Intelligent Management and Artificial Intelligence: Trends, Challenges, and Opportunities

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Wydanie I

Tabel of contents

Preface 5

CHAPTER 1 Modern Cognitive Technologies and AI in Intelligent Management **7**

INTELLIGENT MANAGEMENT OF CONSUMER BEHAVIOUR: THE ROLE OF PACKAGING IN VIRTUAL REALITY SHOPPING ENVIRONMENTS - Małgorzata Wiścicka-Fernando 9

NEUROSCIENCE AND VR TOOLS IN IMPROVING CONCENTRATION IN RETAIL DECISION-MAKING - Konrad Biercewicz, Michał Hendryk 23

VISUAL SHAPING OF BUYERS' PERCEPTION IN ARCHITECTURAL OFFER MANAGEMENT - ANALYSIS USING ADVANCED PSYCHOPHYSIOLOGICAL METHODS - Mateusz Piwowarski, Bogusław Bogdanowicz, Jacek Cypryjański 37

NEUROFEEDBACK AS A DIAGNOSTIC TOOL FOR COGNITIVE AND EMOTIONAL FUNCTIONING: IMPLICATIONS FOR INNOVATIVE MANAGEMENT OF THE ACADEMIC EDUCATION PROCESS - Bartłomiej Piwowarski, Małgorzata Nermend, Alma Shehu Loka, Zdzisław Kroplewski 55

SHAPING INTELLIGENT MANAGEMENT WITH NEUROSCIENCE: MULTIGENERATIONAL PERSPECTIVES FOR THE FUTURE - Marta Starostka-Patyk, Joanna Tylkowska-Drożdż, Marcin Zawada, Helena Kościelniak, Joanna Nowakowska-Grunt 70

USE OF EYE-TRACKING IN THE DESIGN AND OPTIMISATION OF TRAINING MATERIALS FOR FUTURE DRIVERS - Patryk Wlekły, Małgorzata Nermend, Marcin Gryczka, Mariusz Borawski, Halit Shabani 83

EYE-TRACKING AS A METHOD FOR INVESTIGATING COGNITIVE PROCESSES IN THE RECEPTION OF EDUCATIONAL MATERIALS WITHIN THE CONTEXT OF INTELLIGENT MANAGEMENT OF THE DIDACTIC PROCESS - Mateusz Piwowarski, Paula Wiażewicz-Wójtowicz 97

AI-POWERED TAX ATTORNEYS: USING GENERATIVE AI TO ANALYZE TAX LAW TEXTS - Tomasz Strąk, Małgorzata Guzowska Ibish Mazreku 111

AI TOOLS IN THE EVALUATION OF CONTENT MANAGEMENT SYSTEM DATABASES - Artur Kulpa, Grzegorz Wojarnik 120

ANALYSIS OF THE EFFECTS OF APPLYING CLOUD COMPUTING IN ENTERPRISES USING ROUGH SET THEORY - Damian Dziembek, Karol Kuczera, Anna Dunay, Csaba Bálint IllésY 132

ASSESSING LLM'S THROUGH SCENARIO-BASED SOFT SKILLS TASKS FOR MANAGERS: EXPLORATORY STUDIES - Sara Drożdżyńska, Paweł Kucharski 146

AI AND AUTOMATION IN IT: SHAPING FUTURE JOBS AND SKILLS - Magdalena Ławicka, Udaya Mohan Devadas, Ewa Kowalewska 162

HUMAN CAPITAL AS A KEY SUCCESS FACTOR IN SMART ENTERPRISE MANAGEMENT: THE USE OF IT AND AI TOOLS IN BUILDING THE COMPETITIVE ADVANTAGE OF POLISH MANUFACTURING COMPANIES - Barbara Czerniachowicz, Małgorzata Guzowska, Cong Doanh Duong 176

THE IMPACT OF INTELLIGENT MANAGEMENT METHODS ON THE CREATIVITY LEVEL OF EMPLOYEES IN THE CREATIVE SECTOR - Artur Łabuz 195

EMPLOYEE SILENCE AND ORGANIZATIONAL TRUST – THE CONTEXT OF ARTIFICIAL INTELLIGENCE - Marek Kunasz 210

A MODEL APPROACH TO THE RELATIONSHIP BETWEEN EMPLOYEE RELATIONS, AGILITY, AND INNOVATION IN A SMARTLY MANAGED ORGANIZATION BASED ON RESEARCH - Ewa Mazur-Wierzbicka, Agnieszka Rzepka, Dariusz Czerwinskic Magdalena Czerwinska, Jacek Witkowski 223

METHODOLOGICAL FRAMEWORK FOR TEACHING HUMAN RESOURCE MANAGEMENT IN GASTRONOMY: A CRITICAL ANALYSIS OF PROJECT ASSUMPTIONS AND OUTCOME – Katarzyna Brzychcy 239

MIXED-METHODS OF USER EXPERIENCE EVALUATION OF EDUCATIONAL BOARD GAMES DESIGNED WITH 3D PRINTINGTECHNOLOGY – Patryk Wlekły, Małgorzata Nermend, Julia Leżała, Piotr Przetacznik 254

CHAPTER 2 Predictive analytics and real-time decision-making with the use of AI and machine learning 264

APPLICATION OF GENERATIVE PRE-TRAINED TRANSFORMER AS AN EXPERT SYSTEM RECOMMENDING THE TYPE OF HEATING - Filip Majewski, Paweł Ziemba 265

THE FUTURE OF AI IN HRM. A CASE STUDY OF THE HR DECISION-MAKING - Karolina Drela, Anna Grabowska, Małgorzata Brojak-Trzaskowska, Alexandra Bousia 278

DYNAMIC FILLING OF DATA GAPS IN LARGE AIS DATASETS - Dariusz Czerwiński, Adam Kiersztyn, Aneta Oniszczuk-Jastrząbek, Ernest Czermański, Izolda Gorgol, Michał Pluciński 300

AN INNOVATIVE APPROACH TO INTELLIGENT MANAGEMENT OF RETINAL PATHOLOGY RECOGNITION BASED ON DEEP LEARNING AND INTUITIONISTIC FUZZY SETS - Alicja Żmudzińska, Paweł Powroźnik, Maria Skublewska-Paszkowska, Katarzyna Nowomiejska, Paweł Karczmarek 314

AI-POWERED KNOWLEDGE MANAGEMENT AND DECISION SUPPORT FOR IVF WITH PGT: LITERATURE REVIEW AND MODEL PROPOSAL - Małgorzata Skweres-Kuchta, Agnieszka Skweres, Elżbieta Szaruga, Krzysztof Łukaszuk 328

ARTIFICIAL INTELLIGENCE FOR PERSONALIZED RANKINGS OF ARTICLES – NOVEL EMBEDDING METHOD SUPPORTING DECISION-MAKING IN SYSTEMATIC LITERATURE REVIEW - Sebastian Matysik, Joanna Wiśniewska, Paweł Karol Frankowski 344

EFFICIENT AI-POWERED DECISION-MAKING IN SYSTEMATIC LITERATURE REVIEWS USING MULTI-EMBEDDING MODELS - Paweł Karol Frankowski, Joanna Wiśniewska, Sebastian Matysik 366

APPLICATION OF ARTIFICIAL INTELLIGENCE IN BUSINESS PROCESS OPTIMISATION ON THE EXAMPLE OF INTELLIGENT ENERGY PRICE FORECASTING FOR PHOTOVOLTAIC FARMS - Thomas Naprawski, Joanna Kowalik, Anna Pilarczyk-Naprawski 389

A CONCEPT FOR AN INTELLIGENT TELEINFORMATION SYSTEM TO MITIGATE BOTTLENECKS AND OPTIMIZE SALES DURING RECURRING DEMAND PEAKS - Grzegorz Szyjewski, Tomasz Łukaszewski. 407

AI AS DECISION SUPPORT IN THE IMPLEMENTATION OF COURIER SERVICES IN SPATIAL TERMS - Anna Drab-Kurowska, Agnieszka Budziewicz-Guźlecka Joanna Drobiazgiewicz, Michał Kuściński, Katya Antonova 419

LARGE DATABASE OF AIS VESSEL TRAFFIC FOR SMART DECISION-MAKING BASED ON AI IN SHIPPING COMPANIES - Ernest Czermański, Aneta Oniszczuk-Jastrząbek, Janusz Przewocki, Jakub Neumann, Tomasz Borzyszkowski, Elzbieta Szaruga, Michał Pluciński 436

ANALYSIS OF SUPPORT FOR THE DEVELOPMENT OF INNOVATION IN HYDROGEN TECHNOLOGY SECTOR ENTERPRISES IN THE REGIONS BASED ON EMPIRICAL RESEARCH - DECISION PROJECT - Magdalena Kogut-Jaworska, Wojciech Drożdż, Andrea Pizzolante Marzo 455

TOWARD INTELLIGENT PALLET POOL MANAGEMENT – PALLET DAMAGE IDENTIFICATION AND INPUT DATA STRUCTURE IN CAMERA- AND AI-BASED DECISION SUPPORT SYSTEMS - Mariusz Sowa, Katarzyna Kędzierska, Joanna Tuleja 469

SPRINT INTO THE FUTURE: INTELLIGENT MANAGEMENT THROUGH LLM-POWERED COMPUTER SIMULATIONS IN AGILE PROJECTS - Tomasz Wiśniewski, Rafał SzymańskI, Marta Starostka-Patyk 482

CHAPTER 3 Intelligent Management for Sustainable Development 496

ARTIFICIAL INTELLIGENCE (AI) IN LOCAL GOVERNMENTS: HOW DO INTELLIGENT TECHNOLOGIES IMPROVE CITY MANAGEMENT AND RESIDENT COMMUNICATION? - Agnieszka Smalec, Marzena Wanagos, Agata Niemczyk, Eva Benková 497

OPPORTUNITIES FOR THE USE OF ARTIFICIAL INTELLIGENCE IN RAIL TRANSPORT - Arkadiusz Drewnowski, Paulina Dąbrosz–Drewnowska, Krzysztof Małachowski 511

DECISION-MAKING IN URBAN TRANSPORT POLICY AND INTELLIGENT MANAGEMENT: THE CASE OF PAID PARKING ZONES AND TECHNOLOGICAL IMPLEMENTATION IN POLISH CITIES - Artur Pomiannowski, Joanna Sauk 522

THE CONCEPT FOR IMPLEMENTING METHOD OF MULTIDIMENSIONAL COMPARATIVE ANALYSIS FOR ASSESSING ELECTROMOBILITY IN SMART CITIES IN POLAND - Agnieszka Pokorska, Rafał Szymański 540

STUDY OF EMISSIONS, ENERGY CONSUMPTION, AND OPERATING COSTS OF CITY BUS FLEET: EXPLORING THE ROLE OF AI AND TECHNOLOGICAL SOLUTIONS IN SUSTAINABLE URBAN TRANSIT. - Damian Bonk, Norbert Lech 553

TRAVELLERS' MULTICRITERIA DECISIONS AS CONDITIONS FOR SUSTAINABLE URBAN TRANSPORT DEVELOPMENT: THE EXAMPLE OF POLAND - Grażyna Rosa, Artur Pomianowski 571

QUANTIFYING THE CREATIVE CLASS–SUSTAINABILITY LINK: A COMPARATIVE EU ANALYSIS WITH AI INSIGHTS - Aneta Sokół, Petr Hlaváček, Rafał Czyżycki, Agnieszka Gozdek 586

ENHANCING SUSTAINABILITY IN FACILITY MANAGEMENT: DATA-DRIVEN DECISION MAKING THROUGH INTELLIGENT ENERGY MONITORING - Magdalena Malinowska, Paweł Troczyński, Bartosz Marciniak 612

INTELLIGENT SMART CITIES COMMUNICATION MANAGEMENT FOR SUSTAINABLE DEVELOPMENT - Magdalena Kotnis, Małgorzata K. Guzowska, Visar Rrutsemi 631

ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE WINE INDUSTRY: AI-DRIVEN MANAGEMENT IN VITICULTURE, WINE PRODUCTION AND ENOTOURISM - Marta Sidorkiewicz, Karolina Królikowskab, Berenika Dyczek, Edyta Pijet-Migoń, Anna Dubel 645

AI IN SMART MOBILITY - APPLICATION OF SOLUTIONS, DECISIONS, DETERMINANTS AND DEVELOPMENTS ON THE EXAMPLE OF SELECTED CITIES - Joanna Drobiazgiewicz, Agnieszka Budziewicz-Guźlecka, Anna Drab-Kurowska, Katya Antonova 660

AUTONOMOUS VEHICLES AS A TOOL FOR IMPROVING ROAD SAFETY - Tomasz Kwarciński 679

TRANSFORMING CITIES THROUGH SMART MANAGEMENT: ALIGNING ORGANISATIONAL INNOVATION WITH SUSTAINABILITY GOALS - Marta Szaja, Hasibe Aysan 692

THE USE OF AI IN SME's MANAGEMENT IN THE EU COHESION POLICY ON THE EXAMPLE OF POLAND - Jarosław Poteralski 708

AUTOMATION OF TRANSPORT ANALYSIS USING GEOGRAPHIC INFORMATION SYSTEM (GIS) TOOLS FOR INTELLIGENT LOGISTICS NETWORK MANAGEMENT - Sylwia Kowalska, Damian Bonk, Elvis Elezaj 726

Preface

In the face of global digital transformation, increasing complexity of socio-economic systems, and mounting sustainability challenges, the integration of artificial intelligence (AI) with intelligent management approaches has become a critical field of inquiry and application. Contemporary organizations, institutions, and cities operate in a reality where data-driven insights, cognitive tools, and algorithmic support are no longer peripheral innovations, but essential components of effective strategy and governance. Against this backdrop, the second Volume of the monograph "Intelligent Management and Artificial Intelligence: Trends, Challenges, and Opportunities" offers a comprehensive continuation of the reflections initiated in Volume I, extending the thematic scope toward applied, interdisciplinary, and future-oriented perspectives.

This publication is part of the official proceedings of the 28th European Conference on Artificial Intelligence (ECAI 2025), held in Bologna, Italy, on October 25–30, 2025. It includes selected papers presented during the InMan – Intelligent Management Workshop, one of the thematic events accompanying the conference. The workshop brought together scholars and practitioners from a wide range of academic and cultural backgrounds, with contributions from authors affiliated with institutions in Poland, Germany, Slovakia, Ukraine, Bulgaria, the Czech Republic, Italy, Greece, Kosovo, and Turkey. This geographic diversity highlights not only the broad relevance of intelligent management as a research area, but also the shared challenges faced by societies and organizations across different regions of Europe and its neighbouring countries. The multidisciplinary nature of the contributions underscores the need for collaborative, context-sensitive approaches to the design and deployment of AI-based management tools and strategies, especially in domains where ethical, economic, and ecological dimensions intersect.

The structure of Volume II has been designed to reflect the multidimensionality of the intelligent management discourse. The first chapter, "Modern Cognitive Technologies and AI in Intelligent Management," examines the interplay between advanced cognitive methods and managerial practice. Contributions demonstrate how tools such as virtual reality, eye-tracking, and psychophysiological diagnostics enable deeper insights into consumer behaviour, decision-making, and organizational processes. Articles discuss, among others, how packaging and spatial design influence buyer perception in VR environments, how neurofeedback can enhance academic learning and concentration, and how neuroscience perspectives can inform multigenerational workplace management. Alongside behavioural research, the volume includes innovative explorations of generative AI for tax law analysis, database evaluation, and scenario-based soft skills assessment for managers. Studies also highlight organizational dimensions such as employee trust, silence, and agility in the age of AI, showing that intelligent management is as much about human relations as it is about technological progress.

The second chapter, "Predictive Analytics and Real-Time Decision-Making with the Use of AI and Machine Learning," highlights the transformative role of AI in contexts that demand immediacy, precision, and adaptability. Authors analyse generative pre-trained transformers as expert systems recommending energy solutions, deep learning models for retinal pathology recognition, and AI-powered decision support in healthcare processes such as IVF with PGT. Equally important are explorations of AI for systematic literature reviews, multi-embedding models for ranking academic outputs, and innovative teleinformation systems designed to optimize logistics or courier services. Applications in business and energy management, such as intelligent energy price forecasting for photovoltaic farms or hydrogen technology innovation strategies, show the growing importance of predictive analytics for sustainable competitiveness. Collectively, these works emphasize the necessity of context-aware algorithms and the balance between automation and human judgment in high-stakes decision environments.

The third chapter, "Intelligent Management for Sustainable Development," situates AI at the intersection of technology, ecology, and policy. Articles demonstrate how intelligent solutions contribute to smarter urban management, rail transport optimization, and policy-making in areas such as paid parking zones and electromobility. Case studies include AI-supported fleet emission analysis,

multicriteria decision-making in urban transport, and facility management using intelligent energy monitoring systems. Other contributions explore creative economy linkages with sustainability, smart mobility frameworks, and the transformative potential of autonomous vehicles for road safety. By focusing on both local government practices and EU cohesion policy, these papers show how AI can serve as an enabler of sustainability, resilience, and citizen-centric governance.

Taken together, the articles collected in this volume show that artificial intelligence is not only a technological enabler but also a conceptual lens for rethinking intelligent management, governance, and human-centered innovation. The authors do not avoid critical questions concerning algorithmic transparency, data ethics, or societal readiness for AI adoption. Instead, they embrace them as necessary elements of responsible research and application, thereby providing valuable insights for academics, practitioners, and policymakers alike.

The editors of this volume wish to express their sincere gratitude to all contributors whose work is featured here, as well as to the reviewers and members of the Scientific Committee, whose efforts ensured the scientific rigor and editorial quality of the publication. This monograph would not have been possible without the commitment of the international research community. We hope it will inspire further inquiry, cross-sectoral dialogue, and strategic foresight in the evolving landscape of intelligent management and artificial intelligence, encouraging new ways of aligning technological advancement with societal well-being and sustainable development.

Scientific Editors

Karolina Beyer
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CHAPTER 1
Modern Cognitive Technologies and AI in Intelligent Management

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INTELLIGENT MANAGEMENT OF CONSUMER BEHAVIOUR: THE ROLE OF PACKAGING IN VIRTUAL REALITY SHOPPING ENVIRONMENTS

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ABSTRACT

Purpose: *This article presents results from neuromarketing EEG and VR analyses conducted on consumers' purchasing decisions and their decision-making processes in immersive virtual environments.*

Need for the study: *Given the increasing interest in intelligent management of consumer behaviour (IMCB) within marketing strategies, it is essential to understand how packaging influences consumer emotions. This study bridges the gap between traditional consumer research and neuromarketing techniques, offering insights into subconscious decision-making processes in a virtual shop.*

Methodology: *The study employed electroencephalography (EEG) and virtual reality (VR) tools to explore consumer responses to packaged and unpackaged products in a virtual shopping environment. It concentrated on measuring brain waves linked to emotional arousal and cognitive engagement. The VR device simulated a realistic grocery store. The key research question is: How does packaging influence consumer emotion and decision-making in a virtual shop? Basic statistical methods were also applied, including Pearson's correlation coefficient, to assess the relationship between the average holding time of a product category and emotional response.*

Findings: *The results indicate that packaged products evoke higher arousal levels yet are stored for a shorter duration than unpackaged goods. However, packaging alone does not significantly alter the emotional value of the products. These findings highlight the complex relationship between sensory engagement, cognitive load, and consumer trust in virtual shopping environments.*

Practical Implications: *The data obtained can offer valuable insights for companies and researchers studying consumer preferences. It can also utilise neuroscience and virtual reality to create a safe environment for grocery shoppers.*

Keywords: IMCB**,** emotions, consumer behaviour, virtual reality, EEG, intelligent management

Jel codes: M31, D87, L86

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1. INTRODUCTION

Research on consumer decision-making has been conducted for nearly a century and remains a challenge for scientists. This is due to the dynamically changing consumer environment and the complexity of cognitive processes, which are challenging to examine precisely. Technological limitations have hindered the analysis of thought mechanisms and their impact on purchasing behaviour for years. However, the development of modern technologies, such as artificial intelligence (AI), big data, neuromarketing, and digital tools, has revolutionised how consumer behaviour is studied and predicted (Al-Shaikh et al., 2024; Tyagi et al., 2024; Venkateswaran et al., 2023; Zhang & Tan, 2020).

This technology set is called Intelligent Management of Consumer Behaviour (IMCB). It is particularly applied in marketing, where analysing large data sets allows a better understanding of consumer decisions and preferences. As a result, companies can dynamically adjust their strategies to evolving behavioural patterns, leading to more effective marketing efforts and an increased market share (Bhatia & Tishya, 2024; Jiang, 2023; Zhao, 2024). Predictive analytics has become integral to decision-making regarding consumer behaviour. The ability to use machine learning methods provides companies with highly accurate information, allowing them to tailor marketing activities precisely to the needs of various segments and engage with them effectively (Shukla et al., 2024).

With the increasingly complex choices facing today's consumers, understanding how various factors interact in everyday purchasing decisions is crucial. The wide range of available sales channels means the decision-making process is not linear; instead, it results from dynamic interactions between elements of the physical and digital worlds.

Online and offline purchases differ in terms of how information is processed, consumer habits, levels of trust, and decision-making mechanisms. Understanding these interrelationships allows companies to adapt their actions and consumers to make better, more conscious choices.

Neuroscience devices currently support research in this area. Some of the most popular tools for consumer behaviour research include eye tracking, electroencephalography (EEG), galvanic skin response (GSR), and virtual reality (VR).

Eye-tracking technology is becoming increasingly popular in consumer behaviour research. By measuring where and how long users direct their gaze, this method provides essential information about their interests, preferences, and actions. This tool helps analyse behaviour at different points of sale, capture consumer reactions, test the effectiveness of promotional activities or interactions, and research emotions (Alsharif, Salleh, et al., 2021; Bell et al., 2018; Budzanowska-Drzewiecka & Lubowiecki-Vikuk, 2023; Porowska, 2016; Sagan, 2018).

A second commonly used technique in the study of consumer behaviour is electroencephalography (EEG) imaging. As a neuroimaging method, it provides the opportunity to obtain direct information on how the brain responds to various marketing stimuli. The analysis of brain waves enables researchers to gain insights into consumer preferences and behavioural predictions, capturing responses to stimuli or assessing emotional states (Alsharif et al., 2022; Bazzani et al., 2020; Ramsøy et al., 2018; McInnes et al., 2023).

The galvanic skin measurement (GSR) device is convenient because of its size and mobility. This device is beneficial for assessing emotional responses to stimuli, including marketing stimuli. As a result, it offers better opportunities for evaluating consumer decisions in real time. This device has already found its way into commercial products, such as those dedicated to sportspeople, increasing its popularity and providing a large amount of data (Alsharif, Salleh, et al., 2021; Hernandez et al., 2015).

A tool that is also gaining popularity with the development of the Intelligent Management of Consumer Behaviour is virtual reality (VR). This device is particularly favoured by younger generations as it is used for gaming. It has specific features that offer activities in a virtual world that are created in a very realistic manner. It creates immersive and controlled environments to study consumer behaviour and reactions to marketing stimuli. Due to VR's qualities, such as creating a realistic environment and engaging consumers, it is being combined with other neuroimaging devices. Among the most common combinations are EEG fmri devices and eye tracking. An eye-tracking device is often already integrated into VR, making it very easy to study consumer behaviour. Research using combined devices provides even more insight into consumer behaviour, their reactions, and their interactions with products and their packaging (Chen & Zhong, 2024; Kakaria et al., 2023; Kristofferson et al., 2022; Lavoie & King, 2020; Taufik et al., 2021).

Combining neuroimaging devices for research opens up significant opportunities for a deeper understanding of consumer responses and optimising activities in consumer behaviour and beyond.

2. LITERATURE REVIEW

2.1. Packaging and consumer decision-making

The decision-making process regarding packaging is multifaceted, influenced by the number and variety of stimuli that can lead consumers to choose a product. This process takes several forms, including initial attraction through visual appeal, detailed evaluation of functional attributes, and final purchase decisions based on perceived value and sustainability (Peschel et al., 2019).

The role of packaging in consumer purchasing decisions is pivotal. Packaging's primary functions include protection, security, ease of transportation and use, convenience enhancement, and increased sales. This offers a competitive advantage in the fast-moving product market (Rundh, 2005).

The creation of packaging has become a significant aspect of promotional strategies, effectively conveying the product's benefits to consumers. This function is essential in the FMCG sector, where consumers often make impulsive decisions and assess products primarily by their packaging (Rundh, 2009).

Multiple factors influence the selection of packaged products in grocery shops. A study revealed that consumer preferences for packaged products and their associated attitudes are primarily shaped by factors such as preference, ease of use, and prior experience (Rees, 1992). Furthermore, consumers view packaging as a showcase for the product. As a result, the quality of packaging, indicated by its aesthetic appeal, serves as a signal of the product's quality, thereby influencing consumer decisions (Silayoi & Speece, 2007). Additionally, studies have shown that consumers favour food packaging for its ability to reduce cognitive effort during the selection process, enhancing the overall shopping experience (Carroll et al., 2022).

A significant aspect of the consumer experience involves the emotional responses linked to the decision-making process, which continue into the post-purchase phase. The range of emotions experienced is extensive and influenced by the consumer's personality, encompassing both positive and negative feelings.

The Arousal and Valence indices have been identified as potentially useful tools for examining consumer emotions (Moses et al., 2018). These two variables facilitate a deeper understanding of emotions and the analysis of reactions to various stimuli, including products, advertising, and shopping experiences. The Arousal index, in particular, is a valuable metric that assesses the state of arousal, ranging from deep relaxation to high excitement. Conversely, the Valence index refers to the positive or negative nature of the experience. The integration of these two indices forms an active spatial model that is used to analyse emotions (Russell & Barrett, 1999). Applying such a model is particularly beneficial when emotions have an implicit dimension, such as through carefully designed packaging elements that enhance the consumer experience. The analysis can determine which emotions the consumer has experienced and how they can be enhanced; for example, a positive experience can be amplified. Emotions' analysis can be supported using an electroencephalograph (EEG) device.

It is also important to note that during the 2019-2021 period, a significant decline in consumers' sense of security occurred, triggered by the pandemic caused by the novel strain of the virus known as SARS-Cov-2. This unprecedented situation led to changes in consumer behaviour, evidenced by increased purchases of packaged food products (Borawski et al., 2021; Shamim et al., 2021). This shift was driven by health and safety concerns, as well as a reluctance to purchase unpackaged food items. This assertion is supported by research findings from 2021, which specifically addressed grocery shoppers' perceptions of packaging. The study's results indicated that consumers view packaging as safeguarding their food and ensuring its safety (Bou-Mitri et al., 2020; Fernando & Misiak-Kwit, 2023). This finding suggests that consumers may attribute protective benefits to packaging, both physically and psychologically.

As mentioned earlier, consumers' choice of packaged products in grocery stores is influenced by various factors, including convenience, perceived quality, cognitive effort, and the role of packaging in conveying product benefits and ensuring freshness. Emotions are consistently a significant factor affecting consumer decisions. The onset of the pandemic and the following political and social turmoil

of the previous four years have intensified feelings of fear and insecurity. Therefore, there is a strong rationale for researching the impact of emotions on feelings of security and the relationship between emotions and consumer security. The results of this research will be crucial in guiding the development of products, including packaging, and in creating a secure shopping environment.

2.2. Modern methods of consumer behaviour research

As mentioned in the introduction, one area of neuroscience is the Intelligent Management of Consumer Behaviour (IMCB), which, thanks to modern technologies, enables a better understanding of the various factors influencing consumer behaviour. Additionally, it gathers data on the impact of stimuli on consumers. Recently, there has been a significant increase in the support for tools provided by Artificial Intelligence (AI). In the context of emotion research, the use of electroencephalography (EEG) combined with other tools is recommended (Alsharif et al., 2024).

A study conducted in a grocery shop within a virtual reality environment presents an innovative approach to understanding consumer behaviour and decision-making processes in a simulated shopping environment. Utilising virtual reality (VR) technology creates a more precise setting regarding the purchase location, facilitating experimental control (Fang et al., 2021). This technological advancement enables the study of consumers and their purchasing behaviour in a realistic environment (Lombart et al., 2019). This approach addresses the limitations of traditional methods, such as the use of static stimuli or online surveys, by providing participants with a more immersive and authentic experience (Ploydanai et al., 2017). The term ‘static stimuli’ refers to fixed or unchanging elements in the study of participants’ reactions, such as eye-tracking surveys, shop configurations, and product placement scenarios. Virtual reality in this context has been shown to reduce hypothetical systematic errors in choice experiments (Filipe et al., 2017), aligning closely with behaviour observed in physical stores (Egbe et al., 2021). This method overcomes the limitations of conventional approaches, including the reliance on static stimuli or online surveys, thus offering participants a more immersive and realistic experience. Static stimuli denote fixed or unchanging elements that researchers present to study participants to observe their reactions. Examples include eye-tracking surveys, shop configurations, and product placement scenarios. The application of virtual reality in this context has demonstrated an ability to mitigate hypothetical systematic errors in choice experiments, replicating behaviour seen in physical stores. Moreover, studies conducted in this way contribute to a growing body of research on consumer behaviour in grocery shops. These investigations examine various factors influencing consumer choices, including shop characteristics, product variety, environmental determinants, knowledge levels, and shifting habits (Gillespie et al., 2022; Grummon et al., 2023; Nikolaus et al., 2016).

The study’s utilisation of neuroscience technology to comprehend consumer behaviour aligns with emerging research on the application of virtual reality across various fields, including neuromarketing, clinical neuroscience, anxiety treatment, and memory assessment. This interdisciplinary approach showcases the versatility of virtual reality technology in providing insights into human behaviour and decision-making across multiple domains.

In the field of consumer behaviour research, which often uses qualitative methodologies, the use of modern measuring devices such as electroencephalography (EEG), eye tracking, pulse meters (for heart rate measurement), and galvanic skin response (GSR) measurement becomes a viable option. These technologies enable the objective documentation of consumer behaviour data and the identification of behavioural patterns. As a result, contemporary consumer research, aided by neuroscience tools, is becoming increasingly sophisticated and precise, leading to a deeper understanding of customers' preferences and motivations in the context of their interactions with products and services.

The virtual reality grocery shop study represents a novel, interdisciplinary approach to understanding consumer behaviour. Utilising the modern tools of neuroscience, virtual reality technology, and electroencephalography (EEG) to analyse brainwaves, the study not only circumvents the limitations of conventional research methodologies but also significantly contributes to the advancement of knowledge in the fields of consumer behaviour, decision-making processes, and the potential applications of virtual environments (Wiścicka – Fernando et al., 2023).

While emotions significantly influence consumer purchasing decisions, analysing them remains a challenge. They are often assessed based on consumers' declarative statements, which do not always reflect actual reactions. Advances in technology and the increasing application of neuroscience beyond medicine enable a more precise study of consumer behaviour. Examples include measuring

physiological reactions to purchase stimuli, tracking facial expressions to analyse emotions, assessing sentiment based on text, and employing neuroscience techniques to compare the emotional aspects of behavior (Ceccacci et al., 2018; Fici et al., 2024; Kundra et al., 2024; Özmen et al., 2023).

As mentioned, electroencephalography (EEG) has proven to be a valuable tool in neuroscience for assessing the emotional states of research participants. For example, studies conducted by McMahan (McMahan et al., 2015) and Petrantonakis (Petrantonakis & Hadjileontiadis, 2010) utilised the Arousal-Valence Index to quantify emotional experiences. This index defines a two-dimensional emotional space, where one axis represents Arousal and the other represents Valence. Arousal is conceptualised as the degree of emotional intensity, ranging from calm to highly aroused states, while Valence is used to classify emotions along a continuum from positive to negative (Russell & Barrett, 1999). This conceptual framework is visually depicted in Figure 1, where the interaction between Arousal and

Valence allows for a more nuanced understanding of emotional states, making it possible to distinguish between a wide range of emotional experiences and their respective neural correlates. Such measurements offer a deeper insight into the complex nature of emotional processing and how it can be represented through brain activity.

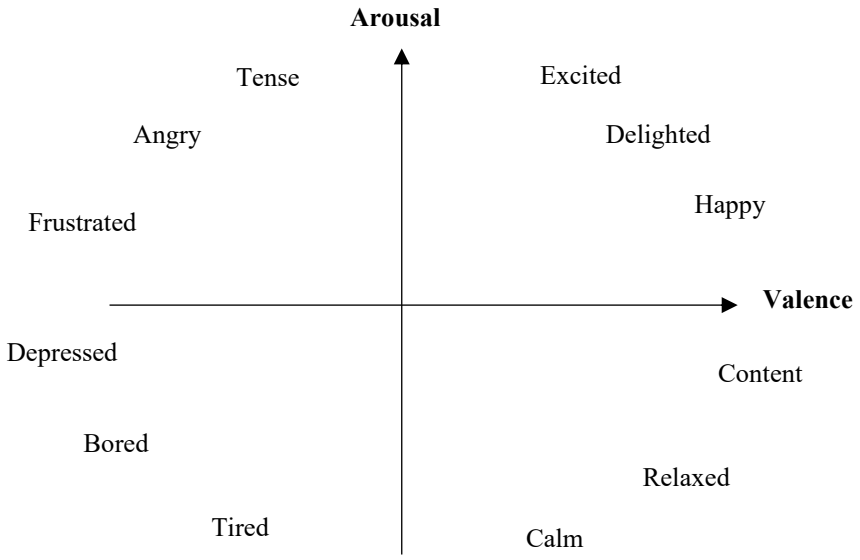


Figure 1. Emotional states and their positions on the Valence/Arousal plane
Source: own elaboration.

Emotions play a vital role in conveying implicit and explicit information, enhancing rapid and optimal decision-making processes (Bechara & Damasio, 2005). Emotions, as a form of influence, can exert a powerful yet fleeting impact on an individual's cognitive and behavioural responses (Frijda, 1994). This underscores the importance of examining the emotional dynamics involved in consumer decision-making, particularly in shopping. Understanding the emotional factors accompanying consumer choices, including those related to sustainable products, is essential for gaining insights into consumer behaviour. Exploring the emotional responses tied to product interest, especially concerning eco-friendly and sustainable products, can reveal key drivers of consumer preferences and inform strategies to enhance consumer engagement with the products.

3. METHODOLOGY

3.1. Materials and Methods

Figure 2 presents the methodology used in the study. A total of 34 participants were selected based on their geographical location. The research question formulated was: What is the role of packaging in consumers' purchasing decisions within a specific virtual reality environment?



Figure 2. Research procedure
Source: own elaboration.

The existing Enzone supermarket shop was utilised and adapted for virtual reality (VR) testing using the Unity engine (*Asset Store*, 2017). This adaptation aimed to accurately reflect the shopping environment for fast-moving consumer goods (FMCG), aligning with consumers' experiences in the real world. Before the study began, participants were informed about its nature and voluntarily consented by signing a consent form. The research received ethics committee approval to proceed with the study.

Participants were shown a brief instructional video demonstrating navigation techniques, item selection, and the overall purpose of the simulation: participating in everyday shopping tasks. Afterwards, the subjects had the opportunity to familiarise themselves with virtual navigation before starting the survey. This preliminary test allowed for the adaptation of the study format and protocol (Li et al., 2020).

The participant preparation process for the study involved donning an EEG (electroencephalograph) cap (Enobio 20), attaching electrodes to the scalp, and wearing a virtual reality headset (HTC Vive Pro Eye). The study utilised a cap equipped with 20 electrodes placed at specific locations, including P7, P4, Cz, Pz, P3, P8, O1, O2, T8, F8, C4, F4, Fp2, Fz, C3, Fp1, T7, F7, and Fpz. These electrodes were positioned according to the 10 -20 system, a widely recognised EEG electrode placement standard. Moistening the electrodes was necessary to ensure optimal conductivity. To verify the contact quality between the EEG electrodes and the scalp, impedance values were measured using Neuroelectrics® Instrument Controller (NIC2) software. The sampling frequency was 500 Hz.

Participants were then given 20 minutes to engage in their daily shopping experience in virtual reality (Beniczky & Schomer, 2020). Before entering the VR shop, respondents viewed a black screen for 60 seconds, which was aimed at calming their emotions and brain waves. The introduction of a time limit was driven by participants' well-being and health considerations.

The virtual shop was divided into three lanes: the first contained fruit and vegetables, with dairy and meat at the end; the second contained pasta, sweets, and seafood; and the third contained bread. Figure 3 illustrates the store’s visualisation in virtual reality.

In the first stage, data was collected from an event file that included information on each product picked up, the time the product was held, and the decision to place it in the basket. It should be noted that each product was assigned to two categories: packaged and unpackaged. Simultaneously, the product's duration in the respondents' hands was used to determine their purchase choices. Subsequently, emotional level indices were calculated based on the Arousal and Valence indices in Table 1. These specific indices were selected for analysis as they are helpful in examining the decisions made by consumers in simulations (Moses et al., 2018; Szymkowiak et al., 2021).

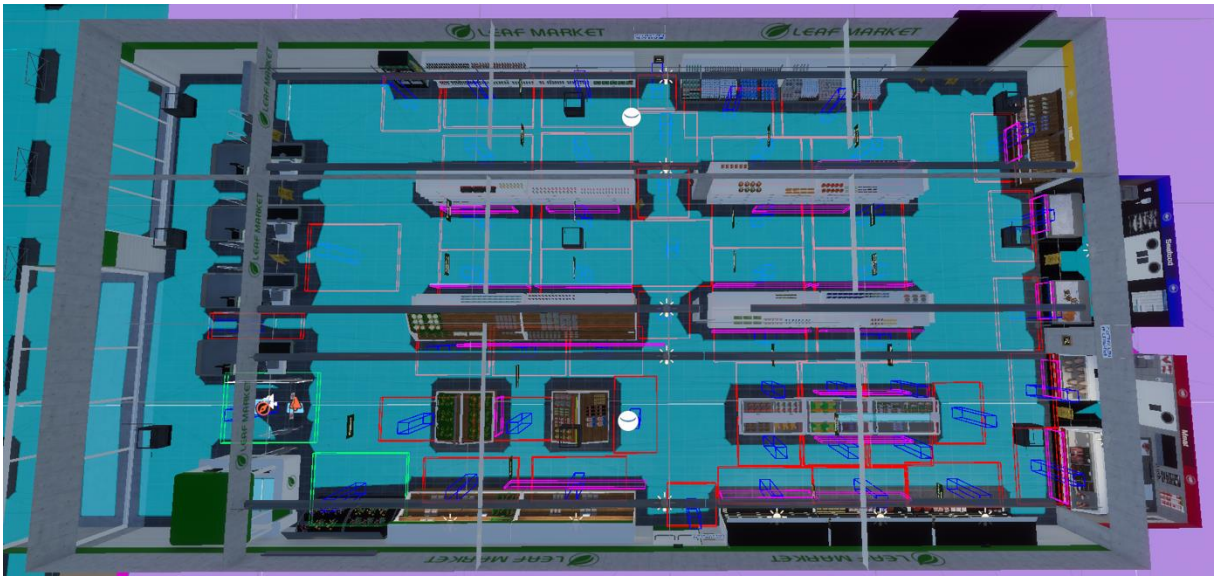


Figure 3. Virtual store plan
Source: own elaboration.

Table 1. Description of formulas used in the study

Index name	Formula	Calculation method
Arousal	$\frac{F3_{Beta}+F4_{Beta}}{F3_{Alpha}+F4_{Alpha}}$	Recording the values of electrodes F3 and F4
Valence	$\frac{F4_{Alpha}}{F4_{Beta}} - \frac{F3_{Alpha}}{F3_{Beta}}$	Recording the values of electrodes F3 and F4

Source: own elaboration.

In the ensuing analyses, Pearson's correlation coefficient was used to ascertain the relationship between the average holding time of a product category and emotion. Analysing this correlation can provide valuable insights for companies. For instance, an extended holding time for a product may indicate its convenience or usability, which could affect users' physical safety.

4. RESULTS

The data were analysed using MATLAB R2019a. The analysis of the electroencephalogram (EEG) signal began with bandpass filtering to eliminate power grid interference, specifically frequencies exceeding 50 Hz. Additionally, the signal was denoised and filtered using the Fieldtrip library. The subsequent analysis of the spectral EEG signal utilised a Morse wavelet, which calculated the average peak frequency of the half-second window (Wachowiak et al., 2018). However, the signal was divided into the corresponding bands – alpha2 (7-13 Hz) and beta3 (13-25 Hz) to calculate alpha and beta frequencies (Tsipouras, 2019).

In the study presented in this paper, indicators were used to determine the emotions experienced by respondents while holding a particular product. In this context, four groups of emotions were identified: satisfaction (positive values of the Arousal and Valence indicators), frustration (positive value of the Arousal indicator and negative value of the Valence indicator), boredom (negative values of the Arousal and Valence indicators), and a feeling of security (negative value of the Arousal indicator and positive value of the Valence indicator).

The recorded time of holding the product and the emotional responses were noted from the moment the product was picked up until it was returned to the basket. Table 2 presents the time, expressed in seconds, that subjects held different products in their hands, categorised into those with and without packaging.

Table 2. Holding time of the product

In the packaging		Without packaging	
Product name	time [s]	Product name	time [s]
Melon	2,59	Lettuce	3,35
Asparagus	3,06	Pineapple	2,44
Carrots	1,51	Leek	8,17
Garlic	4,85	Orange	3,24
Apple	2,76	Courgette	3,84
Salmon fillet	3,75	Strawberries	2,71
Onion	7,04	Tomato	3,73
Cod	4,42	Salmon	5,00
Prawns	6,29	Banana	4,50
Potatoes	2,70	Red pepper	4,04
Meat	3,61		
Average time [s]	3,87	Average time [s]	4,10

Source: own elaboration.

The average time a product is held in hand for packaged items was 3.87 seconds, compared to 4.10 seconds for unpackaged items. Among the unpackaged products, leeks held the longest, at 8.17 seconds, while in the packaged category, shrimp had the longest holding time at 6.29 seconds. Conversely, the products held the shortest were strawberries, which lasted a mere 2.71 seconds without packaging, and carrots, held for only 1.51 seconds when packaged. This variation in holding time suggests that packaging and product type can significantly influence consumer engagement and interest during the shopping process. The final stage of the study was to determine the emotions experienced when holding the product, both with and without packaging (Table 3).

Table 3. Emotions when holding a product in your hand

In the packaging			Without packaging		
Product name	**Stimulation**	**Valencia**	**Product name**	**Stimulation**	**Valencia**
Melon	-0,32798	-0,09773	Lettuce	-0,22659	-0,03798
Asparagus	-0,51801	-0,05289	Pineapple	-0,25376	-0,00304
Carrots	-0,44548	-0,10646	Leek	-0,3081	-0,04458
Garlic	-0,68316	-0,52225	Orange	-0,24402	-0,05279
Apple	-0,39007	-0,06955	Courgette	-0,28833	-0,03462
Salmon fillet	-0,09826	-0,01531	Strawberries	0,381502	-0,23545
Onion	-0,3565	-0,052	Tomato	0,263152	0,15266
Cod	-0,21267	-0,13831	Salmon	1,259015	0,018009
Prawns	-0,43872	0,782404	Banana	0,011121	0,000628
Potatoes	-0,07982	0,029523	Red pepper	0,139198	0,002149
Meat	0,560304	0,008285			

Source: own elaboration.

The results reveal that a significant majority of products (72%) with packaging mainly evoke emotions linked to a sense of security. In contrast, only 50% of unpackaged products elicit similar sentiments. Satisfaction was the second most prevalent emotional response for unpackaged products, observed in 40% of cases. However, this figure was considerably lower for packaged products, at just 9%. These findings suggest that packaging plays a substantial role in shaping consumers' emotional responses, with packaged products predominantly associated with feelings of security. At the same time, unpackaged items tend to evoke more satisfaction-related emotions.

Furthermore, correlation coefficients were calculated between the variables Arousal and Valence and the product held in hand, depending on whether the product was packaged or unpackaged. The results of this study are presented in Table 4.

Table 4. Pearson correlation coefficient between emotions and physically holding a product in the hand

Type of product	Arousal	Valence
In the packaging	0,254739139	-0,0586
Without packaging	0,185814189	0,099528

Source: own elaboration.

The correlation coefficient is a numerical indicator that quantifies the strength and direction of the relationship between the variables under examination. In the case of both packaged and unpackaged products, Arousal demonstrates a stronger correlation with holding the product in hand compared to Valence. Moreover, for packaged products, the correlation between Arousal and holding the product is more pronounced than that for unpackaged products. This indicates that the emotional intensity associated with Arousal significantly influences the consumer's interaction with packaged items.

5. DISCUSSION

The findings from this study offer valuable insights into the role of emotions in consumer decision-making, as well as the impact of packaging on emotional responses. It was noted that emotions play a crucial role in guiding both implicit and explicit decisions, especially in fast-paced, high-stakes situations like shopping. As previous research has indicated, emotions are a significant, though fleeting, influence on consumers (Bechara & Damasio, 2005; Frijda, 1994). In this context, examining the emotional responses connected to product interest is essential, especially when consumers are choosing between sustainable and traditional products. The emotional aspect of consumer decision-making can significantly impact purchasing choices, particularly regarding sustainability, emphasising the necessity for further investigation into how emotions influence consumer preferences for eco-friendly products.

One of the key findings from the data was the role of packaging in influencing emotional responses. Packaged products were found to elicit a stronger sense of security, with 72% of these items evoking emotions related to security, compared to just 50% for unpackaged products. This aligns with the notion that packaging can symbolise reliability and trustworthiness for consumers, providing psychological reassurance that is often absent with unpackaged items. The emotional impact of packaging extends beyond just the security aspect, as it was observed that packaged products predominantly evoke Arousal, indicating heightened emotional intensity, which may affect consumer decision-making processes more strongly than Valence (the positive or negative nature of the emotion). This contrasts with unpackaged products, where satisfaction-related emotions were more common but associated with lower emotional intensity.

The correlation analysis revealed that Arousal demonstrated a stronger correlation with holding a product in hand than Valence, regardless of whether the product was packaged or unpackaged. This suggests that emotional intensity, rather than the positivity or negativity of the emotion, plays a more significant role in the consumer's interaction with the product. Notably, the correlation between Arousal and holding the product was more pronounced for packaged products than for unpackaged items, indicating that packaging enhances consumers' emotional engagement. This insight is crucial for marketers and product designers as it implies that packaging can strategically evoke specific emotional responses, potentially influencing purchasing behavior (Liao et al., 2015).

Additionally, the differences in product holding times provide further evidence of the emotional impact of packaging. Packaged products like shrimp were held for a longer duration (6.29 seconds) compared to unpackaged items such as leeks (8.17 seconds). This extended engagement with packaged products suggests that packaging can capture consumers' attention more effectively, prolonging their interaction with the product. Conversely, unpackaged products like strawberries were held for a significantly shorter period (2.71 seconds), which may indicate a lack of emotional connection or perceived value compared to their packaged counterparts. This may also be because longer holding

times for packaged products result from a greater focus on the message displayed on the package. It takes a bit longer to decode than an unpackaged product.

6. CONCLUSION

This study aimed to identify the emotions consumers experience when choosing packaged or unpackaged products. The analysis showed that both types of products are linked to emotions; however, packaged products tend to evoke these emotions more often.

The first aspect is the relationship between packaging type and the emotions evoked. It turns out that products with packaging evoke greater arousal than those without. This finding may be crucial for companies planning to introduce new products or modify existing ones, especially in encouraging consumers to interact with the product in-store. Greater arousal may translate into increased interest and willingness to purchase the product.

However, product holding time should also be noted. Despite the greater arousal induced by packaged products, the average holding time is shorter than for unpackaged products. This is likely due to differences in how the product is presented and accessed. Packaging may lead to quicker interaction with the product, thereby reducing hand-holding time. Thus, the question arises as to what actually determines the holding time of packaged products. One explanation is that the factors determining sustainability influence consumer reactions. Therefore, it will be interesting to conduct research on emotions related to the identification of packaging for the sake of sustainability (Kardos et al., 2019; Lombardi et al., 2024).

Another important aspect is the emotional value of the products (Valencia) for the consumers surveyed. The analysis results indicate that packaging does not significantly impact the emotional value of a product. Both packaged and unpackaged products evoke similar levels of emotion, whether positive or negative. These findings did not align with the results obtained by other researchers (Carroll et al., 2022). According to the authors, this may be due to the unfamiliarity of the brands offered in the studied virtual shop. It would be interesting to research the impact of a product that is already familiar to the consumer or a well-known brand. Familiar and recognisable products may evoke a different emotional response time. The placement of products featuring recognisable brands could provide additional value. However, it’s important to note that these activities require obtaining a license and the consent of the brand owner, and in the case of grocery stores, the number of brands is quite extensive. This could also lead to increased costs for such research.

Although the EEG tool provides a wealth of real-time data, it still faces challenges in analysis and proper interpretation, as it is a relatively new area of research. The complexity lies in capturing consumers’ emotions since the device primarily detects physiological reactions rather than specific emotions. For this purpose, biometric measurements, such as facial expression analysis, would need to be conducted.

The study’s authors argue that in today's fiercely competitive market, characterised by many products, it is essential to examine emotions individually and their impact on purchasing decisions, particularly since emotions play a crucial role in influencing choices within the fast-moving consumer goods (FMCG) sector. Furthermore, sudden environmental shifts, such as a pandemic or geopolitical instability in Europe, can affect emotions, including consumers' sense of security, impacting their decisions.

Advanced technology allows for precise monitoring of emotions and the situations in which they occur. Access to such data enables managers to take more effective actions, such as optimising shop layout, enhancing product presentation, and improving customer communication. Additionally, the survey results can indicate which actions should be taken to reduce negative emotions and transform them into positive ones.

Additionally, limited uninterrupted shopping time affects consumers. While shopping in physical stores, they encounter more environmental stimuli and unexpected situations. Furthermore, social aspects, such as meeting a friend in the store, can influence consumer behaviour and decisions.

Another limitation of the research conducted is the scope of the study, which was only a pilot study. In order to obtain a representative research sample, it is necessary to expand the sample further.

The authors believe that additional research into the impact of packaging on consumer emotions is crucial for a better understanding of consumer processes and for designing packaging that can effectively shape positive shopping experiences.

The study's findings could be valuable to marketers, enabling them to create more personalised shopping experiences by better understanding and interpreting consumers' emotions. Additionally, these insights can guide decisions to improve products that evoke negative emotions, although further qualitative research to uncover the underlying problem would be necessary. Moreover, big data analytics can enhance customer experience management at the point of purchase, but this process would require integrating artificial intelligence tools.

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NEUROSCIENCE AND VR TOOLS IN IMPROVING CONCENTRATION IN RETAIL DECISION-MAKING

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ABSTRACT

Purpose: *The objective of this research is to investigate the interrelationships between attentional processes, emotional responses, and consumer product selection within an immersive virtual reality (VR) retail environment.*

Need for the study: *Examining the interaction among cognitive attention, emotional reactions, and food-related choices can offer critical insights for marketing professionals, retail strategists, and policymakers. Such understanding could significantly enhance product positioning strategies and consumer engagement practices.*

Methodology: *A VR-based experimental framework was implemented to measure consumer reactions toward distinct categories of food products. Non-parametric statistical analyses, specifically Kruskal-Wallis and Mann-Whitney U tests, were applied to evaluate differences in attention and emotional responses across diverse product categories.*

Findings: *Overall findings indicated no significant differences in attentional focus across various food groups. Nevertheless, a statistically significant distinction emerged between the "fruit" and "vegetable" categories, reflecting the role of emotional engagement and individual preferences in guiding attentional resources. Specifically, vegetables elicited predominantly negative emotional responses, correlating with decreased concentration towards these products.*

Practical Implications: *This research underscores the importance of integrating both cognitive and affective dimensions into consumer behavior analysis. Retailers and marketers can utilize VR technologies strategically to optimize product presentation and consumer interaction. Policymakers may also leverage these insights to encourage healthier dietary selections. Further studies should extend this work by assessing real-world transferability and exploring how contextual factors impact consumer decision-making processes.*

Keywords: Virtual Reality; consumer behavior; EEG; concentration; emotions; shopping

Jel codes: D87; M31; L86

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1. INTRODUCTION

The modern consumer is an individual who shops in two different worlds: the offline world, which encompasses the traditional sphere of consumer choice and purchasing, and the online world, referring to the broader e-commerce environment. According to a 2023 study, 70% of adult Polish consumers regularly engage in online shopping, with forecasts indicating that the national e-commerce market will reach approximately PLN 187 billion by 2027 (Oleksy-Gębczyk et al., 2023; Szczukocka, 2022). Nevertheless, approximately 30% of Polish consumers maintain a preference for traditional retail formats, with senior citizens constituting a substantial portion of this group (Szczukocka, 2022). This aligns with findings from Eurostat (2024), which report that 32% of European Union consumers predominantly engage in traditional shopping, particularly among elderly demographics who represent approximately 25% of traditional shoppers (General Secretariat of the Council, EU, 2024).

Within consumer behavior theory, purchasing decisions are influenced by a spectrum of factors categorized broadly as internal and external. Internal determinants are intimately tied to individual consumer characteristics, including personality traits, cognitive styles, and personal experiences, significantly shaping consumer preferences and motivations Understanding these internal influences is fundamental to analyzing how consumers perceive their needs, prioritize choices, and ultimately make purchasing decisions (Kamińska & Krakowiak-Drzewiecka, 2023). Conversely, external determinants comprise environmental factors, encompassing social influences, economic conditions, marketing strategies, and regulatory policies. These external stimuli generally exert a collective impact on consumer segments, unlike internal factors that vary considerably among individuals. The inherent complexity of internal factors underscores the necessity of employing comprehensive frameworks to adequately understand consumer decision-making processes (Trojanowski, 2018).

From a research perspective, consumer attention is recognized as an essential initial stage in activating the consumer decision-making process. Grounded in foundational psychological theories, such as Maslow's hierarchy of needs, the identification of a need facilitates subsequent cognitive and behavioral processes. Attention serves as a critical component of information processing, influencing how external stimuli affect consumer decisions. At the same time, the environment in which a consumer makes purchasing decisions significantly influences their level of attention. External factors can either enhance concentration or act as distractions, ultimately affecting the decision-making process. The Stimulus-Organism-Response (S-O-R) model provides an effective analytical framework to examine the interplay between external environmental factors (Stimulus), internal psychological states (Organism), and behavioral outcomes (Response) (Mason et al., 2021; Mehrabian & Russell, 1974). This model elucidates how external stimuli interact with internal psychological processes to shape consumer choices, positing that external factors not only elicit specific behavioral responses but also critically depend on the consumer's level of concentration (Mkpojiogu et al., 2024). Retail environmental elements, including product presentation and store ambiance, significantly modulate consumer perception, emotional responses, and engagement levels, thereby shaping purchasing behaviors. The visual arrangement, lighting, colors, and overall atmosphere of a retail space can influence consumer perceptions, emotions, and engagement, ultimately affecting their shopping behavior. At the same time, advancements in data analytics and big data technologies enable a deeper understanding of consumer habits and decision-making patterns. By leveraging large-scale data processing, businesses can identify trends, predict preferences, and generate highly personalized recommendations. Current advancements in big data analytics facilitate an enhanced comprehension of consumer decision-making patterns, allowing for highly targeted marketing interventions (Boardman & McCormick, 2019; Qiu et al., 2023).

2. LITERATURE REVIEW

Recent literature emphasizes the multifaceted nature of the consumer decision-making process, shaped by psychological, social, and contextual factors. These elements interact to form a complex decision-making framework that varies among individuals and market segments.

Attention, a critical psychological construct, significantly influences the depth and effectiveness of consumer interactions with marketing stimuli. In combination with demographic and psychological variables, consumer attention facilitates the development of predictive models regarding consumer

behaviors and decision-making patterns Understanding these interactions allows for more precise predictions of consumer choices and enhances the effectiveness of marketing strategies (Hidajat et al., 2024).

As consumer decision-making processes grow increasingly complex, it becomes imperative to understand the interplay of diverse factors that influence daily shopping behaviors. Contemporary consumers navigate a highly dynamic retail environment, where purchasing choices are shaped by an intricate array of psychological, social, and technological determinants. The proliferation of varied shopping contexts – from conventional brick-and-mortar establishments to digital and hybrid retail channels – indicates that consumer decisions no longer adhere to a linear or uniform trajectory. Rather, these decisions arise from a multifaceted network of interactions involving stimuli from both physical and virtual domains. Consequently, analyzing consumer behavior now necessitates a more sophisticated and context-sensitive approach, accounting for the inherent fluidity and adaptability characterizing consumer engagement within the continuously evolving retail landscape. The increasing complexity of contemporary consumer environments, spanning physical and digital channels, has necessitated sophisticated analytical approaches, exemplified by the Engel-Kollat-Blackwell (EKB) model (Kaur et al., 2024; Punj, 2012). Applying this conceptual model to both offline and online shopping environments facilitates a deeper understanding of how consumers navigate decision-making processes within varying contexts, thereby enabling comparative analysis of purchasing behavior across these mediums. While the fundamental structure of consumer decision-making remains consistent regardless of the shopping channel, differences often emerge concerning consumer interactions and product experiences. These differences primarily result from variations in how consumers engage with products, access information, and respond to external stimuli in physical versus digital settings (Kaur et al., 2024; Zhao et al., 2023). In the context of the Engel-Kollat-Blackwell (EKB) model, stages such as information search and evaluation of alternatives exhibit similar patterns across offline and online environments, supporting the model's applicability to both retail channels. Consequently, analyzing consumer behavior now necessitates a more sophisticated and context-sensitive approach, accounting for the inherent fluidity and adaptability characterizing consumer engagement within the continuously evolving retail landscape.

Research has further highlighted social factors influencing consumer decisions, particularly the Fear of Missing Out (FMO), a psychological phenomenon driven by anxiety related to missing valuable experiences or opportunities. Incorporating FMO into the EKB model enhances its explanatory power by elucidating specific social influences affecting each stage of the consumer journey, thereby providing a more comprehensive understanding of consumer behaviors, especially in online and social commerce contexts (Hettiarachchi et al., 2017).

Zhao's survey findings indicate that consumers often leverage online channels for information gathering and comparison, whereas actual purchases frequently occur offline due to a preference for direct experiences and sensory stimuli (Zhao et al., 2023). The study also highlights that while online reviews influence purchasing decisions, many consumers still seek in-person validation before finalizing their choices. This behavior aligns with the Information Processing Model (IPM), which describes how consumers process information prior to purchasing. Online environments present a higher volume of stimuli, potentially leading to reduced attention and selection filtering, known as 'option overload' (Wang et al., 2021). Conversely, offline information-seeking is characterized by fewer purchase triggers but superior exposure and interaction, strongly influencing decision-making through personal experiences and recommendations, thus fostering a greater sense of security compared to online settings (W. Dai et al., 2019; Harris & Goode, 2010; Qi & Kuik, 2022).

Additionally, the Contemporary Consumer Decision Model (CDM) addresses the integration of advanced technologies, such as artificial intelligence (AI), virtual reality (VR), augmented reality (AR), and sophisticated personalization techniques, into consumer decision-making. These technological advancements enable enhanced user behavior tracking, personalized content adaptation, and automated recommendations, significantly refining the representation of contemporary digital consumer behaviors.

Moreover, the CDM considers the impact of omnichannel strategies, where seamless integration between online and offline touchpoints influences purchasing journeys. It also accounts for the role of social commerce, influencer marketing, and real-time data analytics in shaping consumer perceptions and brand interactions. By incorporating these evolving factors, the CDM provides a nuanced framework for analyzing how emerging digital tools shape consumer engagement, trust, and ultimate purchasing decisions in an increasingly interconnected marketplace.

The existing literature underscores the strategic significance of artificial intelligence (AI) in evaluating consumer preferences and personalizing purchase experiences. Through advanced analysis of extensive datasets, AI algorithms effectively identify consumer behaviors, generating critical insights for tailored marketing strategies (Çakirkaya & Koçyiğit, 2024). Moreover, monitoring consumer interactions with digital content facilitates even more precise alignment of offerings with customer needs (X. Dai & Liu, 2024; Jaiwant & Vazirani, 2024).

Virtual reality (VR) emerges as an impactful technology in the retail sector by creating immersive shopping environments that enhance consumer experiences, subsequently influencing brand loyalty (Loureiro et al., 2019; Mishra et al., 2021). The adoption of VR in research contexts is progressively expanding due to its capability to provide captivating, interactive experiences within highly impressionistic virtual spaces. Cognitive stimulation significantly enriches shopping interactions within VR settings (Yang et al., 2024). Furthermore, purchasing motivation within VR environments is frequently driven by telepresence – the psychological sensation of existing within a virtual space. Telepresence acts as an intermediary between immersive engagement and consumer purchase intent, directly affecting purchasing decisions (Jang et al., 2019). Additionally, VR serves as an effective medium for product evaluation, brand promotion, and direct product interaction, thus enhancing unique consumer experiences and purchase intentions (Johnson et al., 2024; Pizzi et al., 2020). The application of VR technology combined with neuroscientific methods in consumer research represents a powerful tool for intelligent retail management. It enables managers not only to optimize product displays based on cognitive and emotional responses of customers but also to dynamically manage retail environments and personalize shopping experiences. Consequently, store managers and marketers can strategically adapt their retail spaces in real-time according to consumer preferences and behavioral insights.

Augmented reality (AR), another technological innovation rapidly gaining traction, particularly in advertising contexts, effectively captures consumer attention and facilitates product and brand interactions (Pozharliev et al., 2022). The intuitive usability of AR, typically requiring only internet-connected smartphones, significantly contributes to its widespread adoption. The capacity to visualize products within personal environments expedites consumer decision-making, increases engagement, and mitigates perceived risks and uncertainties (Berman & Pollack, 2021; Rauschnabel et al., 2019; Scholz & Smith, 2016). Additionally, AR applications enable not merely visualizations but also real-time tracking of consumer behaviors (Karpagam et al., 2022), a particularly beneficial feature within sectors such as food and beverages, where AR demonstrably enhances consumer interest and purchasing impulses (Fritz et al., 2023).

Integrating AI and AR technologies transforms previously unattainable scenarios into achievable realities, particularly regarding evaluating subjective emotional responses and impressions during product interactions. Such integration substantially augments analytical capabilities concerning consumer reactions, fostering increasingly personalized and immersive shopping experiences tailored precisely to individual preferences. By leveraging AI-based sentiment analyses combined with AR-driven virtual product interactions, enterprises can refine personalization strategies, thus significantly shaping consumer decision-making processes. Consequently, this technological synergy optimizes purchase journeys, enhances consumer satisfaction, and reinforces engagement and loyalty within both online and hybrid retail channels (Rosário, 2024).

Contemporary technologies, including AI, VR, and AR, assume a pivotal role in contemporary consumer purchasing dynamics. These tools not only facilitate precise personalization of product offerings but also enable highly engaging and interactive consumer experiences (Shoaib & Saleem, 2023; Singh et al., 2024). Automated recommendation systems and virtual visualization techniques effectively guide consumer decision-making, creating more intuitive and appealing shopping experiences. The accelerated evolution of these technologies necessitates continuous examination of their impacts on consumer behavior (Zhao et al., 2022).

Emotions critically influence consumer decision-making processes, particularly within immersive digital environments. Research consistently demonstrates that positive emotional experiences enhance customer satisfaction and significantly influence purchasing behaviors (Agarwal, 2023). In virtual shopping contexts, customer emotions are shaped not only by individual predispositions but also by interactive elements such as VR-based experiential engagements and AI-driven customer interactions. Emotional contagion, wherein virtual assistants or customer service personnel transmit positive emotional cues to consumers, further amplifies these effects (Little et al., 2012). Thus, businesses must

actively integrate emotional engagement strategies to optimize consumer experiences within VR and AR environments (Pappas et al., 2014).

The integration of advanced neuroscientific technologies such as electroencephalography (EEG) provides profound insights into consumers' cognitive engagement during decision-making. EEG methodologies offer objective, data-centric measurements of brain activities, capturing implicit emotional and cognitive reactions that traditional self-report techniques might overlook (Dimpfel, 2015; Dimpfel & Hofmann, 2014). By examining concentration and cognitive load levels, researchers gain enhanced understanding of consumers' informational processing and option evaluation preceding purchasing decisions. Notably, concentration within VR contexts mediates emotional responses and subsequently influences product selection, given that immersive environments amplify cognitive engagement and attention (Xi et al., 2022).

Moreover, non-verbal interactions within virtual contexts significantly influence consumer behavior. Spatial proximity, avatar aesthetics, and interface design shape emotional reactions, thereby impacting customer satisfaction and purchase intentions (Lin et al., 2020). Furthermore, emotional labor performed by service personnel within VR environments directly affects consumer experiences, highlighting the imperative for strategic emotional expression management to nurture customer loyalty (Yang et al., 2023).

Ultimately, the convergence of contemporary technology with consumer emotional dynamics highlights the necessity for a comprehensive approach to digital retailing. The collective application of AI-driven personalization, VR-based immersion, and neuroscientific methodologies substantially enhances consumer shopping experiences by fostering engagement, eliciting positive emotional responses, and supporting informed decision-making processes. As businesses continue innovating, understanding cognitive and emotional elements in virtual shopping contexts becomes crucial for crafting successful consumer interactions and fostering sustained brand loyalty.

This article investigates, through VR-based research, the interrelations between consumer concentration, emotional reactions, and product selection. The structure of this paper aligns systematically with its stated research objective. The subsequent section examines VR's application in consumer behavior research, specifically regarding food product selection. Subsequent discussions present empirical findings, key insights, and statistical analyses, accompanied by practical recommendations for enhancing product presentation in immersive contexts. The practical implications underscore integrating cognitive and emotional dimensions within consumer studies, highlighting VR technology's capacity to increase engagement and influence purchasing decisions. The formulated recommendations effectively bridge consumer psychology, marketing, and digital technology domains, providing valuable insights for both academic research and industry practice.

3. METHODOLOGY

3.1. Participants

The study used a structured research procedure, as shown in Figure 1. The sampling process (N=30) was conducted accordingly based on whether people shop at the supermarket once a week. The research problem was then clearly defined, which was presented at the beginning of the Methods section.

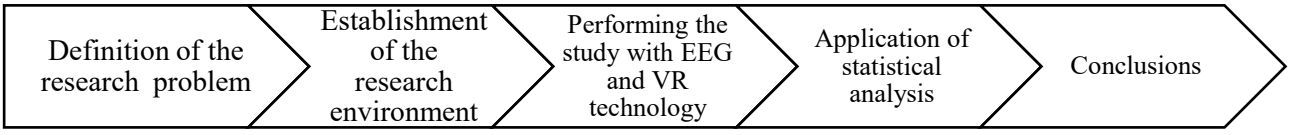


Figure 1. Research procedure
Source: own elaboration.

The current research utilized the pre-existing Enzone store, which was specifically modified to meet the requirements of the study. It was seamlessly integrated into a virtual reality (VR) environment through the Unity engine. The VR setting was meticulously crafted to accurately simulate a traditional

fast-moving consumer goods (FMCG) retail environment, ensuring that it mirrored real-world shopping experiences that participants are likely to encounter. Before the study, participants were thoroughly briefed about the goals and nature of the research, and they provided their voluntary consent to take part in the experiment. Additionally, the study received approval from the relevant ethics committee, ensuring that it adhered to ethical standards.

The subsequent phase of the study involved presenting participants with a brief instructional video. This video provided clear guidelines on how to navigate the virtual environment, and interact with objects, and outlined the study's primary objective, which was to simulate a typical shopping experience. After viewing the instructional video, but before the actual data collection began, participants were allowed to engage in practice sessions within the virtual environment. This practice period allowed them to familiarize themselves with the virtual space, make adjustments to any potential discomforts or disturbances, and ensure that they were adequately prepared for the tasks they would encounter during the study (Li et al., 2020). This step was crucial in minimizing errors and enhancing the accuracy of their responses during the actual experiment.

3.2. Research Protocol and Stimuli

The process of preparing participants for the study involved a series of methodical steps to ensure accurate data collection. Initially, the EEG cap (Enobio 20) was carefully placed on the participant's head, and the electrodes were properly connected to the scalp. In parallel, the HTC Vive Pro Eye virtual reality device was secured and ready for use. The EEG cap utilized electrodes positioned at Fp1 and Fp2 locations, following the internationally recognized 10-20 system for EEG electrode placement (Herwig et al., 2003). To maximize the quality of the signal and ensure proper conductivity, the electrodes were moistened before being placed on the scalp. To confirm the reliability of the electrode-skin interface, impedance values were measured using the Neuroelectrics® Instrument Controller (NIC2) software, ensuring that optimal contact was achieved. The system's sampling frequency was set to 500 Hz to guarantee precise data acquisition during the study. These preparatory steps were crucial in ensuring the accuracy and reliability of the EEG readings throughout the experiment.

Figure 2 presents a comprehensive overview of the virtual store environment. Upon entering the virtual world, the user is positioned at the store entrance, accompanied by an empty shopping cart, ready to navigate the space.



Figure 2. Screenshot of virtual store
Source: own elaboration.

The store layout is designed to resemble a conventional supermarket, incorporating a promotional island and distinct departments dedicated to various product categories, including vegetables, fruits, dairy, meat, baked goods, beverages, fast food, as well as fish and seafood.

Given the spatial constraints of the physical room where the study was conducted, user mobility within the virtual store was facilitated by a teleportation system (Figure 3). This mechanism enabled the participant to move efficiently between different sections of the store.

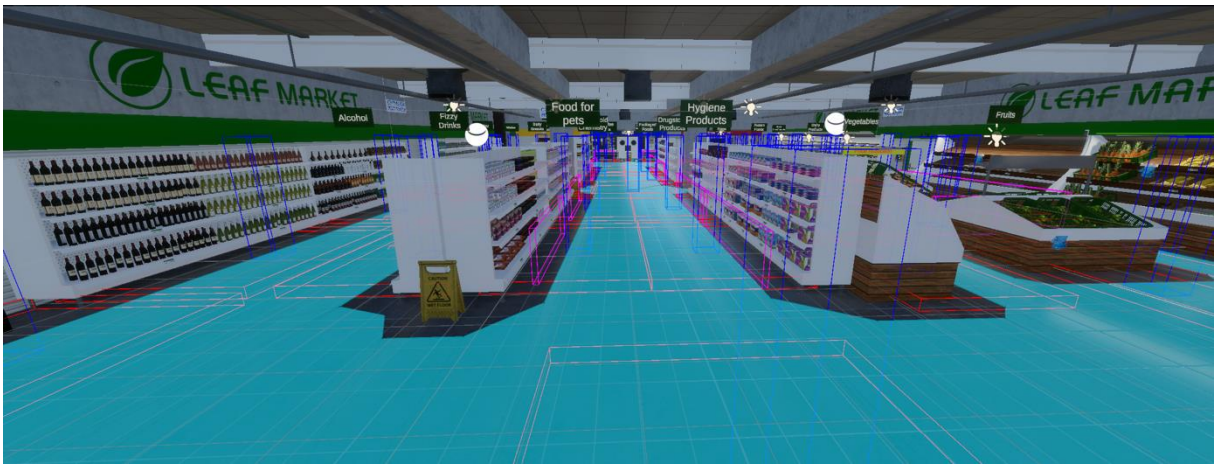


Figure 3. A screenshot of the virtual store. The red rectangle indicates the area where a person can teleport
Source: own elaboration.

Specifically, upon stepping into the designated blue square, available teleportation points were highlighted, allowing the user to choose their next location. Once a destination was selected, their avatar was instantly transported to that location upon confirmation. Additionally, within the red rectangle, the user was permitted to walk freely, ensuring a more naturalistic shopping experience within the virtual setting. This movement method was chosen to overcome spatial constraints and reduce potential disruptions during the experience.

Before entering the virtual store, participants were shown a black screen for 60 seconds. This brief pause was designed to help calm their emotions and synchronize their brain waves in preparation for the study. All participant actions within the virtual environment were continuously recorded and saved in an Excel file using OBStudio software. The collected data was subsequently subjected to further analysis to draw meaningful conclusions.

At the initial stage of the study, all products were systematically categorized into the following groups: fruits, vegetables, dairy, fish, fast food, baked goods, and water. The participants' purchasing decisions were analyzed using data recorded in the event file. This file contained detailed information on each product that was picked up, including the duration for which it was held and whether the product was ultimately placed in the shopping cart, indicating a purchase decision.

3.3. Analysis of Measurement Data

To further assess consumer behavior, the level of concentration during the shopping process was quantified using a specific index, as outlined in Table 1. This measure allowed for an evaluation of the respondent's engagement and decision-making patterns while navigating the virtual store.

Table 1. Description of the indices used in the study

Name of the Index	Formula	Counting method
Concentration (Lee et al., 2010; Lim et al., 2019)	$\frac{Fp1_{Beta}}{Fp1_{Theta}}$	Registration value from electrode Fp1
Arousal (McMahan, Parberry, & Parsons, 2015)	$\frac{F3_{Beta3} + F4_{Beta3}}{F3_{Alpha2} + F4_{Alpha2}}$	Registration value from electrodes F3 and F4
Valence (McMahan, Parberry, & Parsons, 2015)	$\frac{F4_{Alpha2}}{F4_{Beta3}} - \frac{F3_{Alpha2}}{F3_{Beta3}}$	Registration value from electrodes F3 and F4

Source: own elaboration.

The selection of these indicators for analysis is based on their potential applicability in examining consumer decision-making within a simulated environment. These indicators are particularly valuable as they offer insights into the cognitive and behavioral processes that drive consumer choices in virtual settings. By focusing on these specific measures, the study aims to capture a comprehensive understanding of how consumers interact with simulated products and environments, thereby enabling a more accurate prediction of decision-making patterns in such contexts (Moses et al., 2018; Szymkowiak et al., 2020).

4. RESULTS

All data collected from the virtual reality (VR) environment were analyzed using Matlab R2019a. The initial step in processing the EEG signal involved applying a bandpass filter to eliminate interference from the power grid, specifically filtering out frequencies above 50 Hz. Following this, the signal was detrended to remove any linear trends, and further filtering was performed using the Fieldtrip library to refine the data quality.

Subsequently, the raw EEG data underwent a thorough inspection to detect and remove artifacts, such as those caused by muscle activity and eye blinks. Independent Component Analysis (ICA) was then employed to isolate and remove any remaining noise components. Channels with poor signal quality were identified and interpolated based on data from adjacent electrodes to ensure continuity and reduce any gaps in the signal. To minimize reference-related biases, the clean data was re-referenced to a common average.

These preprocessing steps were crucial in ensuring that the EEG signal was of high quality before conducting more in-depth analyses. Once the data were cleaned, spectral analysis was performed using the Morse transform, which allowed for the calculation of the average peak frequency over specific periods of the frame (J. M. Lilly & S. C. Olhede, 2010; Lilly & Olhede, 2012; Wachowiak et al., 2018). To further analyze the brain's activity, the EEG signal was segmented into alpha and beta frequency bands, which are typically associated with different cognitive states. Specifically, the alpha band (7-13 Hz) and the beta band (13-25 Hz) were isolated for further examination (Tsipouras, 2019). This detailed preprocessing and analysis approach ensured the extraction of meaningful and reliable data from the EEG signals for subsequent interpretation.

In the conducted study, specific indices were employed to assess the emotional responses of participants to distinct product sections. The analysis enabled the classification of emotions into four distinct categories: delight, characterized by both positive arousal and valence indices; tension, marked by high arousal but negative valence; disappointment, associated with both negative arousal and valence; and lethargy, which combines negative arousal with positive valence. This categorization

provides a structured framework for understanding consumer affective reactions, offering valuable insights into how product presentation influences emotional engagement and decision-making processes.

The analysis of emotional responses across various product categories reveals significant variability in terms of both arousal and valence. The dairy category stands out with the highest level of variation in arousal, with values ranging from –0.56 to 1.86. This wide range suggests that dairy products elicit a broad spectrum of emotional reactions, from negative to highly positive. In contrast, vegetables tend to evoke more consistently negative emotional responses, as reflected in their arousal values (–0.68 to –0.12) and valence values (–0.52 to 0.07). These values point to a generally neutral or somewhat negative perception of vegetables. Fish, on the other hand, exhibits a higher degree of variability in terms of valence, with values ranging from –0.13 to 0.78, indicating that individual preferences significantly influence emotional responses to this category. Fast food products show relatively low arousal values (–0.15 to 0.29) and moderate valence values (–0.02 to 0.04), suggesting a neutral or emotionally indifferent perception of these items among participants. These findings underscore the varied emotional engagement elicited by different product categories and highlight the complex nature of consumer emotional responses.

Table 2 presents the results detailing the average concentration and emotional values across different product categories. This data provides an overview of how participants' emotional states and levels of focus varied in relation to each specific product category, offering valuable insights into the emotional and cognitive responses evoked by different types of products.

Table 2. Average Concentration, Arousal, and Valence during shopping

Categories	Concentration	Arousal	Valence
fruit	4.678	–0.125	–0.021
vegetables	19.028	–0.198	–0.047
dairy	14.042	0.130	–0.021
fast food	4.940	0.123	0.001
fish	14.199	0.242	0.059
baked	29.857	0.061	–0.092
water	65.394	–0.218	–0.028

Source: own elaboration.

The highest concentration levels are recorded for products within the water category (65.394), while the lowest concentrations are observed for products in the fruit and fast-food categories, with values of 4.678 and 4.940, respectively. Positive emotions are predominantly associated with fast food and fish, whereas emotions of disappointment are most strongly linked to fruit, vegetables, and water. This indicates varying emotional responses across product categories, highlighting the influence of product type on both attention and affective states.

Next, the Shapiro-Wilk test was conducted to assess the normality of the distribution of variables. The results indicated that the variables did not follow a normal distribution, thereby supporting the decision to apply non-parametric tests. The Kruskal-Wallis test ($p = 0.317$) revealed no statistically significant differences in concentration levels across the different food categories. However, the Mann-Whitney U test ($p = 0.0447$) indicated a statistically significant difference in concentration between the 'fruit' and 'vegetables' categories. This suggests that attention levels may differ notably between these two categories, highlighting potential factors influencing consumer engagement with them.

5. DISCUSSION

The integration of immersive technologies, including augmented reality (AR), virtual reality (VR), and mixed reality (MR), has significantly enhanced research on consumer behavior, particularly within the

domain of food selection. These technologies facilitate the creation of interactive and ecologically valid virtual shopping environments, allowing for a nuanced examination of consumer decision-making and the affective processes underlying product selection (Bhavadharini et al., 2023). By replicating real-world shopping conditions with high fidelity, AR and VR methodologies provide valuable insights into consumer engagement with food products, decision-making patterns, and emotional responses to various stimuli.

A central aspect of consumer decision-making involves the role of attention and concentration in evaluating available options. The ability to sustain focus on product attributes directly influences the effectiveness and precision of purchasing decisions. The present study investigated variations in concentration and emotional responses across different food categories, aiming to elucidate the interplay between cognitive engagement and affective reactions in consumer perception. Given that the data did not conform to a normal distribution, non-parametric statistical methods were employed to ensure the robustness and validity of the analyses. Findings from the Kruskal-Wallis test indicated no statistically significant differences in concentration levels across the food categories examined, suggesting that the mere presentation of food items in an immersive environment does not inherently modify consumer attention. However, subsequent pairwise comparisons using the Mann-Whitney U test identified a significant difference in concentration between the 'fruit' and 'vegetables' categories. This result is particularly noteworthy as it implies that specific food groups may differentially engage consumer attention, potentially due to individual preferences, familiarity, or culturally embedded associations

A plausible explanation for this discrepancy lies in the emotional valence attributed to certain food categories. Prior research underscores the pivotal role of affective engagement in modulating attentional processes and shaping consumer choices. In this study, vegetables elicited more negative affective responses relative to other categories, which may have contributed to diminished attentional allocation. Negative emotions, such as aversion or lack of interest, can reduce sustained focus on specific food products, whereas more appealing categories, such as fruit, may naturally command greater consumer attention. These findings align with affective neuroscience research, which has demonstrated that emotional valence and arousal influence attentional dynamics and decision-making behavior. Furthermore, the heterogeneity of emotional responses across food categories underscores the complexity of consumer behavior. The observed variations in arousal levels associated with dairy products, coupled with consistently negative affective reactions toward vegetables, suggest that consumer engagement with food products involves a dynamic interplay between cognitive and emotional components. These findings reinforce the notion that food choices are not merely the product of rational deliberation but are deeply intertwined with personal experiences, cultural context, and intrinsic preferences.

Given the intricate relationship between attention, emotion, and consumer decision-making, future research should further investigate the underlying mechanisms that drive these behavioral patterns. Longitudinal studies could assess the effects of repeated exposure to food products in AR or VR environments on consumer perceptions over time. Additionally, future inquiries could explore how contextual variables – such as branding, packaging, or social influence – modulate attention and affective responses in immersive settings. Such insights would be of considerable value to marketers, retailers, and policymakers seeking to promote healthier consumption habits and optimize consumer engagement through innovative technological interventions. In conclusion, the findings of this study highlight the necessity of integrating both cognitive and affective dimensions when analyzing consumer interactions with food products. The application of immersive technologies in consumer research presents unprecedented opportunities for investigating how individuals perceive, evaluate, and ultimately make purchasing decisions. Leveraging the capabilities of AR, VR, and MR, future research can further unravel the complexities of consumer behavior, paving the way for more effective strategies aimed at influencing purchasing patterns and enhancing the overall shopping experience.

This research also highlights the practical potential for integrating neuroscientific insights into intelligent retail management practices. For example, knowledge about the variability of consumer attention and emotional responses towards different product categories can enable retail managers to employ corrective actions, such as enhancing visual attractiveness or utilizing additional emotional stimuli through augmented reality (AR) or storytelling techniques. Prior studies underscore the effectiveness of AR technologies in managing consumer attention and engagement (Berman & Pollack,

2021; Scholz & Smith, 2016). Thus, incorporating these findings into retail strategy could significantly increase shopping experience quality and effectiveness.

6. CONCLUSION

The presented study employed virtual reality (VR) methodologies to investigate the interrelationships among consumer concentration, emotional responses, and decision-making in retail environments. The results indicate that the virtual presentation of food products does not substantially alter overall levels of consumer concentration; however, significant disparities were observed in attentional allocation toward specific product categories, notably fruits and vegetables. These disparities may result from differences in emotional engagement, individual consumer preferences, and culturally embedded associations.

A crucial finding of this research is the observation that negative emotions elicited by particular food categories, especially vegetables, correlate with diminished concentration and increased likelihood of aversion. This outcome supports existing literature emphasizing the central role emotions play in influencing consumer behavior. Furthermore, substantial variability was identified in emotional responses across diverse food categories, underscoring the intricate nature of decision-making processes involved in food selection.

The outcomes of this study directly support intelligent management practices within the retail sector. Particularly, neurophysiological analytics can be integrated into artificial intelligence (AI)-driven decision-making systems that dynamically adjust product presentations based on consumers' emotional and cognitive responses. Furthermore, concentration and emotional response data could underpin algorithms that intelligently manage product placement and dynamically modify store atmospheres to optimize the shopping experience in real-time. Recent studies emphasize how combining AR and AI technologies significantly enhances consumer interaction and personalization strategies (Çakirkaya & Koçyiğit, 2024; Rosário, 2024), thereby enabling retailers to intelligently tailor shopping journeys.

Nevertheless, the current research exhibits certain limitations. Primarily, the VR-based experimental design, although providing controlled and insightful conditions, may not fully encapsulate the complexity of real-world shopping environments. Additionally, limitations regarding sample size and demographic representation potentially constrain the broader applicability and generalizability of these findings. Future research endeavors should aim to enhance participant diversity, integrate real-life purchasing contexts, and examine further contextual variables influencing consumer decision-making. Another significant consideration emerging from this study pertains to differences inherent in online versus traditional retail environments. Decision-making processes in digital and physical settings vary considerably, influenced by distinct modes of information processing, consumer behavior patterns, trust perceptions, and decisional strategies (Chiu et al., 2019; Niza Braga & Jacinto, 2022; Xu et al., 2021). A deeper understanding of these distinctions may provide valuable insights enabling both retailers and consumers to optimize purchasing outcomes. The results presented in this research may serve as a foundation for intelligent retail management systems, merging VR technology, neuroscience, and artificial intelligence. This integration facilitates a deeper understanding of consumer behavior and allows for dynamic optimization of strategic and operational decisions. Implementing these innovative approaches offers significant competitive advantages for retailers aiming to proactively shape consumer experiences and enhance their operational effectiveness. Future research should aim to bridge the gap between virtual simulations and real-world behaviors, incorporating integrated analyses of both online and offline shopping contexts to achieve a comprehensive understanding of consumer engagement in different environments.

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VISUAL SHAPING OF BUYERS' PERCEPTION IN ARCHITECTURAL OFFER MANAGEMENT - ANALYSIS USING ADVANCED PSYCHOPHYSIOLOGICAL METHODS

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ABSTRACT

Purpose: *This publication presents the results of a study on the impact of unconventional (surreal) architectural visualisation settings on the perception of single-family house design. Particular emphasis was placed on analysing the audience's emotional and cognitive reactions.*

Need for the study: *Research to date does not provide in-depth analyses of the impact of non-standard landscapes, such as surreal mountains or seascapes, on the perception and evaluation of architectural designs. Furthermore, there is a lack of research in this area using psychophysiological methods (EEG, GSR, eye tracking), a significant research gap.*

Methodology: *The study was conducted in a laboratory using advanced methods such as EEG, GSR, eye tracking and facial expression analysis. Participants viewed different variants of house visualisations (daytime and surreal versions). Based on physiological measurement data, metrics were determined to analyse and interpret emotional and cognitive responses.*

Findings: *Analyses have shown that an appropriately chosen environment for architectural visualisations can significantly influence the perception of single-family house designs. It can intensify emotional and cognitive reactions in both positive and negative directions. These effects appeared to depend on the specific design and the type of setting (mountain, sea).*

Practical Implications: *The study's results may be of great practical importance for architects and graphic designers involved in creating architectural visualisations and for people and companies involved in selling single-family house designs. Appropriately designed, unconventional scenery can increase an offer's attractiveness, evoke positive emotions, and improve a design's memorability.*

Keywords: Architectural visualisations; offer management; psychophysiological studies; EEG (Electroencephalography) analyses; GSR (Galvanic Skin Response) analyses; eye tracking analyses; neuromarketing in architecture

Jel codes: M31; D87; C91

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1. INTRODUCTION

A photo of the house exterior is an integral part of every property sales offer. This photo is usually the starting point for house buyers to analyse the offer and it is also the one they focus on for the relatively longest time (Seiler et al., 2012). This shows that the attractiveness of the exterior of a house, commonly referred to as curb appeal, is an important factor influencing the decision to buy a house. This is confirmed both by research results (Bessinger & Jacobs, 2016; Glaeser et al., 2018; Johnson et al., 2020) showing the impact of curb appeal on the selling price of a property, as well as countless websites, blogs and videos advising on how to improve curb appeal. Similarly, the issue of curb appeal arises when we replace house sales offers with house plans offered to those who intend to build their future home. Here, too, we can expect the visualisation of the offered house plan to play an important role. Moreover, while the improvement of curb appeal is limited and costly for an existing house, the possibilities are much wider here. Current house plan visualisations are by no means limited to presenting the building's shape, but place it in a photorealistic scenery of a perfectly designed front yard with an elaborate play of light and shadow. Thus, they can arouse buyers' aesthetic experiences and emotions and, as we will discuss more broadly in the next section, translate into their perception, attention, memory and decision-making. Is this really the case? Can changes in the environment of the building significantly alter the assessment of the house itself, even when the buyer realises that the created setting is fictitious?

As studies on similar topics (Assem et al., 2023; Khaleghimoghaddam et al., 2022; Vecchiato et al., 2015; Weinberger et al., 2021) show, a number of interesting findings on this problem can be provided by research using psychophysiological methods. In the case of architectural visualisations, experiments can be even more reliable because we can place the same building in any chosen setting and thus focus on selected, isolated issues. The aim of the presented research was to analyse changes in the perception of house plans by potential buyers influenced by the transfer of the house from the classic environment of a suburban residence to landscapes of a mountain meadow and a seaside shore, which are unusual for this type of project. In particular, the study examined whether the use of an unconventional landscape (for simplicity, referred to below as 'surreal') increases the level of emotional arousal, influences the direction of motivational responses (approach-avoidance), and shapes the way the viewer focuses their visual attention. Psychophysiological methods such as electroencephalography (EEG), galvanic skin response (GSR), eye tracking and facial expression analysis were used to conduct the research. The use of such techniques is an increasingly common practice in research on human interaction with visual stimuli, as confirmed by previous work on the integration of cognitive neuroscience methods in user experience analysis (Borawska & Mateja, 2024; Niemcewicz, 2023; Zhu & Lv, 2023).

The publication is structured in five parts. Section 2 discusses research on architectural visualisations and their impact on consumers. Section 3 (Materials and Methods) contains a description of the participants, the experimental procedure, the tools, analyses and measurement metrics used. Section 4 (Results) presents the main research results together with statistical analyses. Section 5 (Discussion) discusses and interprets the results. The last part of the paper (Conclusion) contains the final conclusions and practical implications of the obtained results.

2. ARCHITECTURAL VISUALISATIONS AS A FACTOR INFLUENCING HOUSE PLAN BUYERS

The impact of architectural visualisations on buyers is not only due to the obvious role of image in advertising, but also to the human reaction to the built environment. Research conducted over the past decade using psychophysiological methods (a systematic review of which can be found in (Assem et al., 2023; Bower et al., 2019; Lee et al., 2022) clearly shows that the visual properties of built environments cause a range of neural and physiological activities, thus affecting the emotional states of the recipient. In the case of interior spaces, it has been shown that aesthetic judgements are influenced by, among other things: ceiling height, perceived enclosure (open vs. closed), changes in contours (curvilinear vs. rectilinear), interior furnishings (unfurnished vs. furnished spaces), or the photorealism of the spaces presented (Grima Murcia et al., 2019; Vartanian et al., 2013, 2015; Vecchiato et al., 2015). With regard to external architectural spaces, for example, the reactions to familiar and unfamiliar locations or the reactions of experts and nonexperts were compared (Epstein et al., 2007; Kirk et al., 2009). The results of a study by Khaleghimoghaddam, Bala, Ozmen and Ozturk (Khaleghimoghaddam

et al., 2022) on functional magnetic resonance imaging suggest that "the external appearance of an architectural setting can influence the emotional, perceptual, cognitive, beauty judgment, and decision-making (behavioral) process for users to a high degree". Unfortunately, there has been significantly less research on external architectural spaces than on interiors. Moreover, this research has focused on a narrower range of issues, concentrating mainly on aesthetic experiences and emotions, while ignoring their impact on purchasing decisions. In turn, studies analysing the impact of curb appeal on purchasing decisions did not use psychophysiological methods but focused on models for predicting property prices. For example, Bessinger and Jacobs (2016) found that combining objective attributes with curb appeal data allows for more accurate estimates of home prices. However, neither this study nor the studies by Glaeser, Kincaid and Naik (2018) or Johnson, Tidwell and Villupuram (2020) can identify significant environmental characteristics, as in each case the assessment of building photographs was performed using machine learning methods.

Nevertheless, these studies suggest that the same house plan presented in two different settings can evoke different aesthetic experiences and emotions. Our intuition tells us the same thing. Visualisation designers are also aware of this, and consider the elements of the environment and the realism of lighting and objects to be the main factors determining the positive perception of visualisation (Bogdanowicz & Cypryjański, 2017). However, a better understanding of this issue requires focusing on two questions. The first is how to change the environment in the visualisation, which elements of the environment are important and how to present them to evoke positive aesthetic experiences and emotions in the viewers. The second is whether the aesthetic experiences and emotions evoked by these changes have an impact on purchasing decisions.

It is also important to take into account current research in the social psychology and affective sciences when addressing these two questions. With regard to the first question about changes in the environment and their impact on aesthetic experience and emotions, it is primarily about the role of conscious awareness. Bargh (Bargh, 2002, 2022) discusses a series of field experiments that illustrate the wide range of consumer behaviour that is strongly influenced by factors outside conscious awareness. Chartrand (Chartrand, 2005; Chartrand & Fitzsimons, 2011) distinguishes between three areas of unawareness: "consumers are often unaware they have been exposed to an environmental cue that triggers a given consumption behavior, or are unaware of a mental process that is occurring outside conscious awareness, or are even unaware of the consumption-related outcome of such a nonconscious process". Chartrand and Fitzsimons (Chartrand & Fitzsimons, 2011) also emphasise that virtually all consumer psychological processes are on a continuum from highly conscious to entirely unconscious and therefore postulate that the role of unconsciousness should be taken into account in the study of motivation, emotions and consumer decision-making. Also from the work of Bargh (Bargh, 2022) comes a practical conclusion regarding the design of field experiments: since consumers may not be aware of the impact of certain triggers, processes or their effects, they are also unable to self-report them accurately.

With regard to the second question, it should be pointed out that the human mind has long been considered to be a place where two opposing forces clash: rational and deliberate reason, and impulsive and irrational emotions. As a result, emotions have been treated as factors that can interfere with cognitive functions such as perception, attention, memory, and decision-making. However, as the authors of the review (Brosch et al., 2013) of research in the field of affective sciences conclude, the dualism of reason and emotion is not reflected in the architecture of the brain and the functioning of the mind. Emotions and cognition are closely related, and complex human behaviour emerges from the dynamic interactions between multiple processes and brain networks. Emotions determine how we perceive our environment, how we remember it and what decisions we make.

3. MATERIALS AND METHODS

3.1. Participants

Thirty-two participants (15 women and 17 men) aged between 17 and 73 years (M = 32.34; SD = 15.90) participated in the study. The sample comprised people of varying occupational status and educational levels. Participants included students, working people and one pensioner. Participants were randomly

divided into two groups (A1 and A2). Each group completed the same research task, with differences in the variants and order of presentation of the visualisations of the single-family house designs.

The main eligibility criteria for the study were having good or corrected vision and no known neurological disorders that could affect the results of the psychophysiological measurements. One left-handed person was in the study group (3% of the sample), which was considered in the analysis of cerebral asymmetry in the EEG measurements. The structure of the study, the participant eligibility criteria adopted and the results were based on previous analyses and documentation of the research work (Bogdanowicz, 2023).

Before the experiment, each participant was informed about the experiment (without disclosing detailed assumptions) and the measurement tools used. All subjects signed an informed consent to participate in the study and to process their data by RODO regulations. They were also told that they could opt-out at any stage without giving a reason. The study was conducted by the principles of the Declaration of Helsinki (World Medical Association, 2013). The Bioethics Committee of the Regional Medical Chamber approved the research project in Szczecin (Resolution No. 02/KB/VII/2020 of 18 June 2020).

All participants completed the study; however, due to technical problems related to the quality of the EEG signal, the data of 2 subjects were partially excluded from the final analysis. The remaining data from the physiological measurements were used in the analyses.

3.2. Research Protocol and Stimuli

The study was conducted under controlled laboratory conditions, following an established experimental protocol. Each participant entered the study individually, in a neutral environment, which allowed for the minimisation of factors that could interfere with psychophysiological reactions. During the experiment, participants were presented with visual stimuli on a computer monitor, visualisations of single-family house designs. Two different architectural designs were considered, presented from two perspectives (front and back of the building):

- PA - single-storey building with a total area of 135 m2 with a built-in garage and terrace;
- PB - ground floor building with a total area of 126 m2 with large glazed areas and a terrace.

Each house design was presented in two visual options:

- standard version (STD) - realistic visualisation of the building in a typical daytime setting,
- surreal version (SUR) - house design placed in a modified, non-standard setting.

In the surrealist version, two variants were considered, which differed in the type of environment in which the building was located:

- surreal mountain landscape (SUR_M) - a building set in a high mountain setting, characterised by lots of greenery and open space,
- surreal seascape (SUR_S) - a coastal building with open space and the sea in the background.

The following stimulus symbolism was adopted to facilitate the analysis:

- **PA_STD - design A, standard version (fig. 1),**
- **PA_SUR_M - design A, a surrealistic version of mountain scenery (fig. 2),**
- **PB_STD - design B, standard version (fig. 3),**
- **PB_SUR_S - design B, the surrealistic version of marine scenery (fig. 4).**



Figure 1. Project visualisation of house A in standard version (PA_STD)
Source: compiled based on: projekty.muratordom.pl.



Figure 2. Visualisation of house project A in surrealistic version - mountain scenery (PA_ SUR_M)
Source: compiled based on: projekty.muratordom.pl.



Figure 3. Project visualisation of house B in standard version (PB_STD)
Source: compiled based on: projekty.muratordom.pl.



Figure 4. Visualisation of house project B in surrealistic version - marine scenery (PB_ SUR_S)
Source: compiled based on: projekty.muratordom.pl.

Depending on the group to which respondents were assigned (A1 or A2), they were presented with a different variant of the visualisation of the houses - either a standard or surreal version.

The experiment consisted of two main stages: participant preparation and stimulus presentation.

1st Preparation of the participant - briefing about the experiment, obtaining consent to participate in the study and to process data, seating the participant at the test stand, fixing the measuring apparatus and setting up and calibrating the sensors (EEG, GSR, eye tracker).

2nd Visual stimulus presentation - start the study and display successive visualisations of the houses in different variations.

3.3. Research Apparatus

Advanced research equipment was used to record participants' psychophysiological responses and measure physiological parameters. The measurement system included an electroencephalograph (EEG), skin-galvanic response (GSR) sensors, an eye tracker, and a camera for recording facial expressions.

The study of brain electrical activity was carried out using the ENOBIO 20 5G system (Neuroelectrics), equipped with 20 electrodes arranged according to the international 10-20 system (Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, O2). The sampling rate was 500 Hz, and data were transmitted wirelessly to a computer.

Electrodermal activity was recorded using the Shimmer3 GSR+ Unit, which allows measurement of both tonic and phasic GSR activity. Skin conductance sensors were placed on two fingers of the participant's non-dominant hand. The signal was recorded at 16 Hz, and data transmission to the computer was via Bluetooth technology.

Participants' eye movements were monitored using a stationary Tobii Pro X3-120 eye tracker mounted under the monitor screen. The device recorded data at 120 Hz, which allowed precise detection of fixations, saccades, and other visual perception parameters. The eye tracker's calibration was 9-point, and the participants' distance from the monitor was between 60 and 63 cm. Data were wired to the computer via USB 3.0.

Facial expressions were recorded using a Logitech BRIO Webcam 4K, centrally placed above the monitor screen. The camera could record images in 4K Ultra HD (30 fps) or 1080p (30/60 fps). Connection to the computer was via USB 3.0.

All signals were synchronised and recorded using the iMotions platform (*iMotions*, 2024), enabling the integration of EEG, GSR, eye tracking and facial expression analysis data. The system allowed simultaneous processing of multi-channel data and its export for further analysis, including statistical analysis.

3.4. Analysis of Measurement Data

Data analysis involved two main stages: signal pre-processing and the determination of key indicators (metrics). In the preprocessing stage, signal filtering, cleaning and normalisation procedures were applied to eliminate artefacts and improve data quality.

The preprocessing of the EEG signals involved several steps. In the first step, a visual analysis of the signals from all channels was performed. Next, a fifth-order Butterworth filter (range 2 – 45 Hz) was applied to eliminate slow trend and high-frequency interference, e.g., muscular origin. An artefact threshold of ±90 μV was adopted to reject signal fragments with an outlier amplitude. The Welch method was used to exclude interference, in which the EEG data were divided into 1-second time windows with 50% overlap. A Fast Fourier Transform (FFT) was then performed, generating one power spectrum per 0.5 seconds. Hamming time windows were used in the Welch method. The corresponding power spectrum was discarded for signal amplitudes exceeding a threshold value (Heinzel & Rüdiger, 2002; Semmlow, 2012).

Pre-processing of the GSR signal included verifying the quality of the recorded signal and eliminating artefacts. Signal quality was determined by the SNR parameter (signal power-to-noise ratio) expressed in decibels. Signal fragments with SNR values below 10 dB were considered of low quality and excluded from further analysis (Schumm et al., 2008).

The I-VT algorithm was used to analyse the recorded eye-tracking data and to classify fixations and saccades (Olsen, 2012).

After processing the raw signals, key psychophysiological metrics were calculated based on EEG measurements, GSR, eye tracking and facial expression analysis. These enabled the assessment of participants' responses at the physiological level.

The cleaned EEG data were analyzed using power spectral density (PSD) calculations. The PSD values determined the Frontal Alpha Asymmetry (FAA) and the Memorisation Index (MI).

- The FAA was designated according to the formula:

$$FAA = ln\left(P_{alfa\,F4}\right) - ln\left(P_{alfa\,F3}\right) \tag{1}$$

where: $P_{alfa\,F4}$ i $P_{alfa\,F3}$ denote the alpha band power at the respective electrodes.

It has been shown that there is a relationship between asymmetry of cortical activity and motivational-emotional processing. The left frontal part of the brain is more involved in processing stimuli and behaviours associated with a positive attitude (approach motivation), while the right frontal part of the brain is more involved in processing negative stimuli (avoidance motivation) (Allen et al., 2004; Davidson, 1992; Davidson et al., 1990; Pizzagalli et al., 2005).

- MI was derived from the formula:

$$MI = ln\left(P_{theta\,Fp1,F3,F7}\right) \tag{2}$$

where: $P_{theta\,Fp1,F3,F7}$ denotes the power of the theta band at the corresponding electrodes.

The memorisation index was determined according to the Hemispheric Encoding/Retrieval Asymmetry (HERA) model proposed by Tulving and colleagues. The theoretical basis of this model assumes the presence of hemispheric asymmetry in the encoding and retrieval of episodic information.

According to this model, the left cerebral hemisphere prefrontal cortex is more involved in encoding information, and the right cerebral hemisphere prefrontal cortex is more involved in extracting it. (Tulving et al., 1994). The dominant current theories, confirmed by EEG and MEG studies, assume that episodic memory is positively related to theta oscillations (4 – 8 Hz) (Hasselmo & Stern, 2014; Kraus et al., 2013).

Two metrics from the GSR signal were used to analyse the emotional response. The first is the number of GSR peaks, and the second is the amplitude of the GSR peaks (μS). To obtain these metrics, the phase part of the GSR signal was extracted using a median filter within a fixed length time window (8000 ms). The number of GSR peaks determines the frequency of emotional arousal per 1 minute of stimulus presentation. The amplitude of the GSR peaks makes it possible to assess the strength (intensity) of a single response (Benedek & Kaernbach, 2010; iMotions, 2017). The GSR peak was counted if the amplitude exceeded 0.005 μS and if the time between onset and offset was more significant than 500 ms.

Facial expression analysis (FEA) was carried out using the AFFDEX module to identify basic emotions, additional emotional states, and other quantities (Bishay et al., 2022). It was assumed that classification of expression measures would be made for moderately strong facial responses. Threshold values for emotion identification, action units and valence were 50%. When aggregating the data, the time window over which the data were analysed for the participant groups was set to 500 ms.

Analysis of the eye tracking data included the creation of gaze paths for individual study participants, generating heat maps for the study groups considered, and determining metrics for defined areas of interest (AOI). Several key AOI metrics were analysed, such as RC (%) - the percentage of respondents who noticed a given area of interest; FC – the average number of fixations; FFD (ms) – the average duration of the first fixation; DAF (ms) – the average duration of all fixations; TTFF (ms) – the time to first fixation; DT (%) – the percentage time looking at a given AOI; and R – the number of revisits.

Different methods were used for statistical analyses of the data extracted from the physiological measurement, depending on the nature of the data. These included descriptive statistics including Student's t-test (for independent samples).

4. RESULTS

This section presents the results of a psychophysiological study in which the previously discussed methods of EEG analysis, GSR, eye tracking and facial expression enabled the assessment of participants' responses to visual stimuli. Two house designs presented in different visual variations (PA_STD, PA_SUR_M, PB_STD, PB_SUR_S) were analysed to determine the effect of modifications on architectural perception. The results were complemented by declarative surveys, which provided assessments of the visualisation, costing, and functionality of the designs.

The analysis of the results from the physiological measurement began with an examination of whether and to what extent the presented stimuli (variants of the visualisations of the house designs) elicited spontaneous responses linked to emotional arousal. For this purpose, the skin-galvanic response measurement was used, which allows the recording of unconscious bodily reactions reflecting the level of in the reception of the stimulus. Table 1 shows the mean values of the number and amplitude (μS) of GSR peaks per 1 minute for the different visualisation variants. In contrast, Table 2 compares the standard and surreal variants, considering the results of statistical tests and differences in mean values.

Table 1. Average GSR values for individual visualisation options.

Variant	Number of GSR peaks (mean ± SD)	Number of GSR peaks (min-max)	GSR amplitude (mean ± SD)	Amplituda GSR (min-max)
PA_STD	3.55 ± 3.09	1.12 – 6.87	0.052 ± 0.031	0.007 – 0.114
PA_SUR_M	6.43 ± 3.42	2.34 – 9.14	0.079 ± 0.068	0.019 – 0.254
PB_STD	5.08 ± 1.84	3.21 – 7.42	0.063 ± 0.043	0.020 – 0.169
PB_SUR_S	1.84 ± 2.66	0.00 – 4.52	0.098 ± 0.033	0.026 – 0.141

Source: own elaboration.

Table 2. Comparison of GSR values for visualisation options *(* $p < 0.05$)*.

Variants	t	df	p-value	The difference in the average number of GSR peaks	Difference in mean GSR amplitudes
PA_STD vs PA_SUR_M	-2.03	19	0.057	+2.88	+0.027
PB_STD vs PB_SUR_S	2.61	14	0.020*	-3.24	+0.035

Source: own elaboration.

The GSR analysis showed significant differences in emotional arousal depending on the variant of visualisation of the house designs. In the case of the PA design, the surrealist version with mountain landscape (PA_SUR_M) had a higher number of GSR peaks (M=6.43, SD=3.42) compared to the standard version PA_STD (M=3.55, SD=3.09). Analysis by Student's t-test showed that this difference was close to statistical significance (t(19)=-2.03, p=0.057), which may suggest greater emotional involvement of participants in response to this variant of the visualisation. In addition, the amplitude of GSR peaks was also higher in the surreal version (M=0.079 μS, SD=0.068) compared to the standard version (M=0.052 μS, SD=0.031), confirming the higher intensity of the emotional response in the case of an unusual mountain environment.

The results obtained for the PB project indicate the opposite effect. The surrealistic variant with seascape (PB_SUR_S) resulted in a significantly lower number of GSR peaks (M=1.84, SD=2.66) compared to the standard version PB_STD (M=5.08, SD=1.84). The Student's t-test showed that this difference was statistically significant (t(14)=2.61, p=0.020), suggesting that the atypical setting may have influenced participants' emotional arousal reduction. Other correlations were observed for the amplitude of GSR peaks, which was higher in the surreal variant (M=0.098 μS, SD=0.033) compared to the standard PB_STD (M=0.063 μS, SD=0.043).

In the next step, the EEG results were analysed, focusing on the frontal asymmetry alpha (FAA) and the memory index (MI). These analyses assessed whether using different visualisation variants affects motivational perceptual processes and the efficiency of encoding episodic information. Table 3 contains the averaged FAA and MI values for the different visualisation variants, while Table 4 contains the comparison results between standard and surreal variants.

Table 3. Average FAA and MI values of the visualisation options.

Variant	FAA (M ± SD)	MI (M ± SD)
PA_STD	-0.045 ± 0.019	5.13 ± 0.39
PA_SUR_M	0.096 ± 0.025	6.75 ± 0.45
PB_STD	0.036 ± 0.030	3.07 ± 0.26
PB_SUR_S	0.013 ± 0.027	4.18 ± 0.29

Source: own elaboration.

Table 4. Comparison of FAA and MI values for visualisation options *(* $p < 0.05$)*.

Variants	Indicator	t	df	p-value
PA_STD vs PA_SUR_M	FAA	–1.81	30	0.081
PA_STD vs PA_SUR_M	MI	–10.68	30	0.000*
PB_STD vs PB_SUR_S	FAA	0.25	30	0.804
PB_STD vs PB_SUR_S	MI	–11.52	30	0.000*

Source: own elaboration.

The FAA index, which is the logarithmic difference in alpha band power (8-12 Hz) determined for electrodes F3 and F4, indicates the approach or avoidance motivation in direction to the stimulus (visualisation). For design A, the standard version (PA_STD) obtained a mean FAA value of -0.045, while the surreal version in the mountain scene (PA_SUR_M) was 0.096. The Student's t-test showed that this difference did not reach significance ($t(30)=-1.81$, $p=0.081$). For design B, a comparison of the standard variant (PB_STD) where FAA=0.036 with the surreal version in a marine setting (PB_SUR_S) with FAA=0.013 revealed no significant differences ($t(30)=0.25$, $p=0.804$).

The MI, which reflects the efficiency of encoding episodic information and is related to activity in the theta band (4 – 8 Hz) at electrodes Fp1, F3 and F7, showed more pronounced changes. For design A, the standard variant (PA_STD) obtained a mean MI=5.13, while the surreal mountain version (PA_SUR_M) obtained a value of 6.75. Comparison of these values by Student's t-test showed a significant difference ($t(30) = -10.68$, $p<0.001$). For project B, the MI value was 3.07 for the standard variant (PB_STD) and 4.18 for the surreal marine version (PB_SUR_S), which also proved statistically significant ($t(30) = -11.52$, $p<0.001$).

These differences are shown graphically in Fig. 5, which illustrates the mean FAA values with standard deviations for the different visualisation variants, and in Fig. 6, which presents the mean MI values.

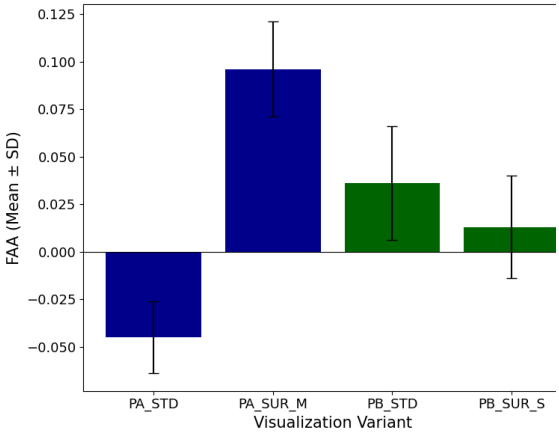


Figure 5. Mean FAA values.
Source: own elaboration.

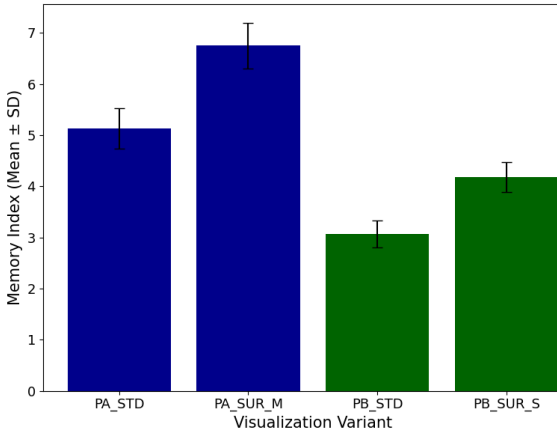


Figure 6. Mean MI values.
Source: own elaboration.

As can be seen, the mountain scenery increased the values of both indicators (FAA, MI) compared to the standard version, while the sea setting slightly decreased FAA and increased MI.

The study of facial expression aimed to determine the valence of emotions, and was a complement to the GSR measurements, which only record the intensity of reactions without determining their direction. The analysis results showed that, in the vast majority of cases, participants presented neutral facial expressions. This is probably related to the fact that the laboratory conditions induced a state of control over their facial expressions (Piwowarski & Wlekly, 2022). Therefore, further analysis of the impact of the visualisations on perception, based on the FEA results, was omitted, and the focus was on more objective measures such as GSR, EEG and eye tracking.

The eye tracking study aimed to determine how participants explore the visualisations of the house designs and which elements attract their attention depending on the visual context. In particular, the analysis of the heat maps made it possible to identify the areas with the highest concentration of fixation and the differences in visual exploration patterns between the standard and surreal versions. As part of the analyses, aggregated heatmaps were generated for two independent groups of participants, allowing a comparison of visual focus patterns under different visualisation conditions.

For the PA_STD variant, fixations were scattered throughout the object, mainly covering windows, doors, the facade and nearby environmental elements such as garden furniture and vehicles. There were no clear points of dominant visual focus, suggesting that participants' attention was evenly distributed across different aspects of the visualisation. For the PA_SUR_M (mountain scenery) variant, a significant change in visual exploration patterns was observed. Fixations were mainly focused on the

windows and doors of the building, while the other elements of the environment (mountains) were scanned in a diffuse manner with no clear focus points. This is probably due to the fact that the mountain range in the background did not contain distinctive elements that could attract the subjects' attention. As a result, attention was focused on the central architectural aspects of the building, which may suggest a greater interest in its structure with limited influence from its surroundings.

The heat map for the PB_STD option showed a strong focus on key elements of the building, including windows, doors and the façade. There were also a number of fixations on surrounding elements, such as vegetation and garden decoration. This variant had a more balanced distribution of attention across the visualisation. For the PB_SUR_S (sea scenery) version, a similar concentration of fixations on windows and doors was observed. Still, an additional area of intense visual focus was the stretch of water visible in the left section of the image. The undulating surface of the sea attracted the subjects' attention, while in the right-hand section of the image, where the water was less visible, this effect disappeared. Compared to the mountain variant, where there was no characteristic focus of attention outside the building, the sea scene seems to generate additional points of interest in the background, which may affect the visual processing of the whole composition.

To determine which elements of the visualisation (e.g., the main body of the building, parts of the background, etc.) evoke which focus of attention of the participants and thus influence visual exploration, areas of interest were extracted, and metrics were counted for them. A graphical representation of the AOIs against the visualisation is available in Appendix A in Fig. A1 – Fig. A4.

Tables 5 and 6 contain the AOI values for house project A in the standard variant and mountain scenery. Tables 7 and 8 also contain AOI values but for project B in the standard variant and sea scenery.

Table 5. Values of AOI metrics for the PA_STD project option

AOI	RC (%)	FC	FFD (ms)	DAF (ms)	TTFF (ms)	DT (%)	R
hs_FR_PA_STD	100.00	7.64	169.34	217.45	476.39	14.34	2.14
hs_BA_PA_STD	100.00	7.13	224.99	214.13	1042.02	13.69	1.93
bh2_BA_PA_STD	13.33	1.00	249.94	249.94	4244.09	2.82	0.00
bh_FR_PA_STD	20.00	1.33	283.29	209.42	8274.25	1.90	0.33
bh_BA_PA_STD	20.00	1.33	175.04	165.10	7548.65	1.26	0.33
ph_FR_PA_STD	13.33	1.00	266.63	266.63	11548.82	2.32	0.00
tr_FR_PA_STD	40.00	3.50	166.48	184.28	2675.63	4.84	1.17
tr_BA_PA_STD	73.33	2.91	248.52	241.13	3656.19	4.60	0.64
bk_FR_PA_STD	13.33	2.00	195.69	233.26	3749.62	2.65	0.50
bk_BA_PA_STD	20.00	2.33	241.62	227.89	5999.29	3.28	1.33

Source: own elaboration.

In the standard variant (PA_STD), the main AOIs corresponding to the building shape, labelled as hs_FR_PA_STD (house shape in front view) and hs_BA_PA_STD (house block in rear view), achieved very high visibility (RC=100% in both cases). For hs_FR_PA_STD, the mean number of fixations was 7.64 and the time to first fixation (TTFF) was relatively short (476.39 ms), indicating that this area was quickly seen. The FFD (169.34 ms) and DAF (217.45 ms) values suggest that participants started to analyse the area fairly quickly and maintained fixations for a moderate amount of time. In contrast, for hs_BA_PA_STD, the FC (7.13) and TTFF (1042.02 ms) values are slightly higher, which may indicate a slightly later start of exploration of the second part of the building, although RC remains at 100%. Additional AOIs, such as areas of vegetation, pathways, terraces or backgrounds (in both views) show significantly lower RC values (ranging from 13.33% to 40.00-73.33%) and longer TTFF times (in the range 3749-11548 ms), indicating that the respondents noticed these areas less frequently and later and that their attention was mainly focused on the shape of the building.

Table 6. Values of AOI metrics for the PA_SUR_M project option

AOI	RC (%)	FC	FFD (ms)	DAF (ms)	TTFF (ms)	DT (%)	R
hs_FR_PA_SUR_M	100.00	9.36	247.33	213.08	997.54	18.29	2.86
hs_BA_PA_SUR_M	100.00	6.27	195.22	209.01	1779.27	11.89	1.60
ph_FR_PA_SUR_M	17.65	1.33	147.25	159.74	4233.36	1.25	0.33
bk_FR_PA_SUR_M	41.18	5.86	186.19	184.19	2869.90	8.68	1.43
bk_BA_PA_SUR_M	23.53	2.00	154.37	142.71	6786.85	2.05	0.25
an_FR_PA_SUR_M	17.65	1.33	577.44	649.62	14609.61	4.27	0.33
an_BA_PA_SUR_M	5.88	1.00	599.96	599.96	2821.52	2.22	0.00

Source: own elaboration.

In the variant with mountain scenery (PA_SUR_M), we observe significant changes in visual behaviour. For the AOI hs_FR_PA_SUR_M (shape of the house in frontal view), the RC is 100%, and the FC increases to 9.36, suggesting that the subjects performed more fixations on this area. At the same time, the TTFF for this AOI was 997.54 ms. This is significantly longer compared to the standard variant, indicating a delayed start of the principal component analysis, but once fixation started, it was maintained longer (DT = 18.29% vs. DT = 4.34%). For the AOI hs_BA_PA_SUR_M (shape of the house in rear view) the RC is 100%, but the FC is lower (6.27) compared to the front view, and the TTFF increases to 1779.27 ms, indicating that the rear view of the building was noticed later. For other AOIs in the surreal variant, such as ph_FR_PA_SUR_M (front path) and background areas on both sides (bk_FR_PA_SUR_M, bk_BA_PA_SUR_M), RC values range from 17.65% to 41.18%, indicating that a smaller proportion of subjects noticed these areas. However, their DT values (from 1.25% to 8.68%) indicate some focus in these areas. In addition, the animal-related AOIs (an_FR_PA_SUR_M and an_BA_PA_SUR_M) received low visibility (RC = 17.65% and 5.88%) and relatively long TTFF times (14609.61 ms and 2821.52 ms), indicating that these items were more difficult to identify quickly and may have required more perceptual effort.

Table 7. Values of AOI metrics for the PB_STD project option

AOI	RC (%)	FC	FFD (ms)	DAF (ms)	TTFF (ms)	DT (%)	R
hs_FR_PB_STD	100.00	9.88	181.82	205.75	1043.91	16.81	2.62
hs_BA_PB_STD	100.00	7.31	250.20	228.34	835.48	15.37	2.06
dc_FR_PB_STD	35.29	2.50	229.21	266.61	4146.91	3.91	1.00
ph_FR_PB_STD	11.76	1.00	149.98	149.98	16137.50	0.50	0.00
ph_BA_PB_STD	29.41	1.00	155.08	155.08	6406.04	1.45	0.00
tr_BA_PB_STD	47.06	2.38	192.77	201.09	3997.28	3.72	0.38
bk_FR_PB_STD	17.65	3.33	152.75	191.58	3358.64	3.08	1.67
bk_BA_PB_STD	23.53	2.25	174.99	237.98	3616.78	3.70	0.75

Source: own elaboration.

In the standard variant of design B (PB_STD), the body of the house was, of course, also viewed. For the area labelled hs_FR_PB_STD (the body of the house in front view), the mean number of fixations was 9.88 and the TTFF was relatively short (1043.91 ms), indicating that this area was noticed quickly. The FFD (181.82 ms) and DAF (205.75 ms) values suggest that participants started to analyse the area fairly quickly and maintained fixations for a moderate amount of time. For hs_BA_PB_STD (the body of the house in the rear view), the FC (7.31) and TTFF (83548 ms) values indicate a slightly later start to exploration of the second part of the building, although RC remains at 100%. Other AOIs, including ambient elements such as the deckchair, paths, terrace and backgrounds, show lower RC values (11.76% to 29.41%) and lower TTFF, FFD and DT metrics. This suggests that a smaller proportion of participants noticed these elements and generally later, and their focus of attention was less intense.

Table 8. Values of AOI metrics for the PB_SUR_S project option

AOI	RC (%)	FC	FFD (ms)	DAF (ms)	TTFF (ms)	DT (%)	R
hs_FR_PB_SUR_S	100.00	7.93	207.38	202.81	1642.40	12.94	1.71
hs_BA_PB_SUR_S	100.00	6.87	204.13	219.48	442.10	15.72	2.13
st_BA_PB_SUR_S	13.33	2.00	241.70	172.27	2950.45	2.26	0.50
se_FR_PB_SUR_S	60.00	3.44	235.75	239.36	1554.47	6.79	1.33
se_BA_PB_SUR_S	13.33	2.50	295.72	263.70	1748.38	8.16	1.00
ph_FR_PB_SUR_S	13.33	2.00	250.00	283.36	8747.98	2.70	0.50
bk_FR_PB_SUR_S	20.00	4.00	202.70	185.52	1844.59	5.47	1.33
bk_BA_PB_SUR_S	13.33	1.50	266.66	252.09	4756.74	3.62	0.00

Source: own elaboration.

In the surreal variant of this design (PB_SUR_S), the building block is viewed by all participants in the study. However, for the area hs_FR_PB_SUR_S (house in front), the average number of fixations dropped to 7.93, and the time to first fixation increased to 1642.40 ms, indicating a delayed start of exploration of the main area. For the rear view of the house (hs_BA_PB_SUR_S), the FC values were 6.87, and the TTFF was 442.10 ms, suggesting that the second part of the building was noticed slightly faster in this variant. The other AOIs in the PB_SUR_S variant include areas associated with the marine environment: stones, sea, path and background. The RC values for these AOIs vary, e.g. the area st_BA_PB_SUR_S (stones) achieved RC = 13.33%, while se_FR_PB_SUR_S (sea) showed RC = 60.00%. Furthermore, the DT, FFD, DAF and TTFF metrics for the sea-related AOIs indicate that although a smaller proportion of participants noticed these areas, the time spent looking at them was relatively long, indicating the additional stimulus provided by the sea element in the visualisation context.

The AOI metric values obtained for the identified areas of interest allowed a detailed analysis of the focus of attention on specific parts of the visualisation. Focus is associated with certain human responses, including interest in a particular visualisation element, but its nature (positive, negative) remains unclear. Therefore, the frontal asymmetry index was analysed for the defined AOIs, based on electrical brain activity (EEG) measurement. EEG recording at 500 Hz enabled dynamic changes in the activity of the hemispheres to be captured, making it possible to determine whether a given area evoked an approach or avoidance motivation. As a result, it was indicated which parts of the building visualisations attracted attention more engagingly, providing valuable information on the mechanisms of visual perception in an architectural context. Fig. 7 shows the FAA values obtained for each AOI, for the modified design options A (mountain scenery) and B (marine scenery).

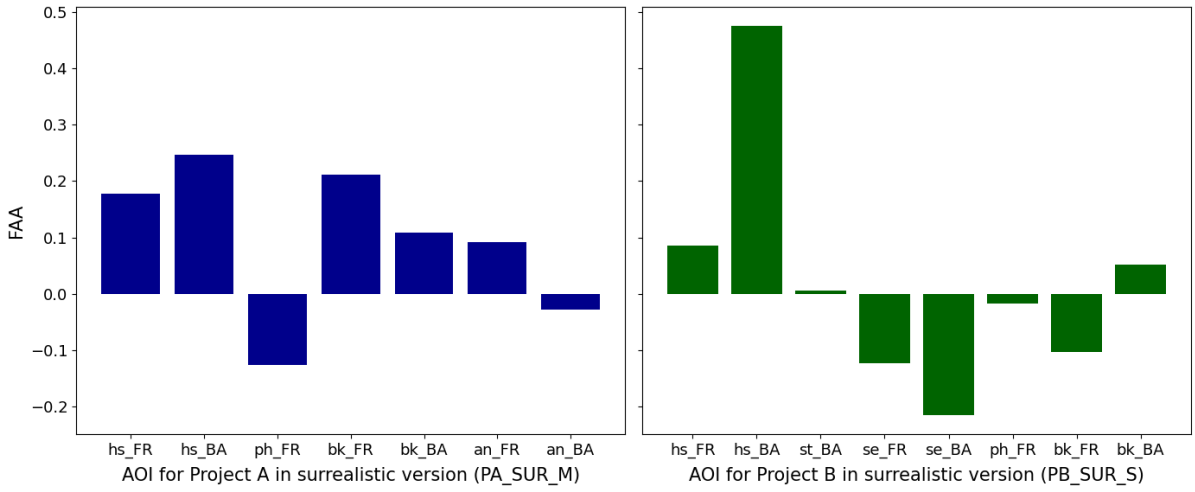


Figure 7. Mean FAA values for AOI in the surrealistic versions of Projects A (PA_SUR_M) and B (PB_SUR_S)

Source: own elaboration.

For project A, the results indicate that in the surreal mountain variant (PA_SUR_M), the respondents showed positive motivational reactions towards the main components of the visualisation, namely the building and the background. The FAA value for the building in front was 0.177, while that for the back was 0.247. For the background, the values were similarly 0.211 and 0.108. In contrast, the AOI corresponding to the path, denoted as ph_FR, had a value of –0.126, indicating a avoidance motivation this part. The FAA values for the animal-related AOIs indicate minimal, almost neutral (0.092) or slightly negative responses (–0.028).

For Project B in the marine scene, the FAA values indicate that the building body evoked an approach motivation in this case. A particularly strong one was registered for the view from the rear, more glazed side, for which FAA = 0.475. A slight positive response (0.052) was still obtained for the marine background from the rear of the building. The other AOIs associated with the aquatic environment showed clear avoidance motivation. Interestingly, the sea's lowest FAA values were obtained: –0.124 and –0.215. Slightly better for the background (sky) visible from the front of the building (–0.103). In contrast, there were relatively neutral values for the AOIs covering the stones (0.006) and the path (–0.017).

The FAA results obtained for both projects suggest that modifying the surrealist variants' surroundings significantly affects how viewers process visual stimuli. In design A, the mountainous environment promotes a more intense focus on the main elements of the building. In contrast, design B induces a clear the other AOIs associated with the aquatic environment showed clear avoidance motivation aspects of the environment while varying the perception of individual parts of the visualisation.

5. DISCUSSION

The results of the analyses indicate that introducing surreal scenery elements can significantly affect the perception of architectural visualisations. However, this effect is not universal. While in the case of the PA project, the addition of a mountainous landscape increased emotional arousal (measured by both the number and amplitude of GSR peaks) and intensified the approach motivation (higher frontal asymmetry index alpha), in the PB project, an analogous modification introducing a marine setting resulted in a decrease in arousal and no significant increase in FAA. Such discrepancies support the assumption that not only the surrealism of the surroundings determines the viewer's engagement but also the specific nature of the design (form of the massing, elements of the surroundings) and the perception of the particular landscape. The literature on visual perception of real estate and neuromarketing (Biercewicz et al., 2022; Borawska et al., 2022; Ogonowski & Piwowarski, 2024; Ramachandram & Hirstein, 2007; Vartanian et al., 2015) repeatedly emphasises that factors such as stimulus novelty, stylistic coherence, or emotion-laden cues can elicit varying psychophysiological responses. Similar relationships have also been observed in research on user interfaces in the context of e-learning, where psychophysiological analysis has identified the impact of visual design on information processing and user engagement (Piwowarski et al., 2024). Our study confirms these findings, showing that a house in the mountains (project PA_SUR_M) was perceived as more expressive or exciting, as reflected in the GSR indicators and higher FAA values. In contrast, the house by the sea (project PB_SUR_S), although intended to be equally intriguing, did not generate a significantly positive response, indicating instead the neutral or calming nature of the seascape as depicted.

Complementing these findings, the eye-tracking results show that in the PA_SUR_M project, respondents were more likely to gaze on the building visualisation (higher FC values) and spend more time on it (DT). This may indicate a clear interest or need to process the visual experience more thoroughly, which correlates with the elevated level of emotional response in the GSR. In the PB_SUR_S project, this phenomenon took the form of reduced interest, although the time to first fixation (TTFF) confirms that the coastal landscape is registered quite quickly. These results are reminiscent of the concept of so-called visual habituation or, conversely, intensification of attention due to a surprising or unique stimulus (Lin & Li, 2023). In our case, the mountains may have had a more substantial surprise effect than the calm sea.

The memory index (MI) analysis revealed significant differences between the variants. In the PA_SUR_M design, the MI value was significantly higher than in the PA_STD, indicating better

encoding of visual information in the presence of a mountain landscape. For PB_SUR_S, the MI value was higher than for PB_STD, although this effect was not as strong as for PA_SUR_M. This may suggest that although surreal surroundings can increase the memorability of a design, its effectiveness depends on the type of landscape and the degree of fit with the building body itself.

It is also worth noting that the analysis of the AOI metrics provides information on visual exploration. The PA_SUR_M variant had a higher percentage of respondents who paid attention to key elements of the building, implying a stronger focus on the architecture in a surreal context. In the case of PB_SUR_S, there was an increased interest in the elements of the surroundings, particularly the water, which may have distracted from the body of the building itself. In addition, FAA analysis for the AOI showed that in PA_SUR_M, areas related to the building body elicited stronger approach motivation than in PB_SUR_S, where the focus of attention was more diffuse.

The higher frontal asymmetry alpha in the PA_SUR_M variant can be interpreted in the context of Davidson's theory (Davidson, 1992, 1993, 2004), according to which greater left frontal hemisphere activity signals an approach motivation, typically to positive or desired stimuli. These observations reinforce the hypothesis that a surreal environment, if visually and emotionally engaging, can enhance the perception of the whole project.

However, it is worth emphasising that the effects discussed do not apply to the whole population, and individual preferences may become apparent on a larger scale. The study included a group of 32 subjects, which is a reasonable starting point for GSR and EEG analyses. Still, in future work, it would be helpful to expand the sample and consider potential moderators (e.g. whether the respondent prefers the mountains or the sea in their daily life and what their aesthetic style is).

Compared to other studies on architectural visualisations, this study focuses on analysing the surreal environment of single-family homes. Furthermore, the applied integration of physiological measurement methods (EEG, GSR, eye tracking, FEA) distinguishes this work from other studies. This is particularly evident in the context of selected indicators such as, for example, EEG frontal asymmetry (FAA), memory index (MI) or eye tracking AOI metrics. The data not only clarify whether surreal surroundings affect perception but also indicate how and why specific modifications can change the emotional and motivational response of the viewer. This approach places the work at the intersection of research fields such as neuroaesthetics, neuromarketing and visual merchandising design. Thus, the presented research complements the subject literature and indicates potentially new research perspectives.

6. CONCLUSION

Research has confirmed that the way architectural visualisations are presented is important to the audience and can influence their emotions, attention, and memory of the design. Using surreal elements in the visualisation environment does not always lead to clear-cut effects. Their effectiveness depends on stylistic consistency with the presented building. Psychophysiological analyses (GSR, EEG, eye tracking) have shown that introducing specific modifications can enhance emotional responses and cognitive engagement. Still, this effect is not universal and depends on the visual context.

The research provided valuable information for architects and property visualisation developers. The right scenery fit can intensify positive emotions, increase viewing time, and enhance design recall. In the context of real estate marketing, this can mean more effective visual materials. However, these effects should be carefully tested, as an ill-fitting setting can undermine a project’s perception. The results also suggest the need to consider individual audience preferences, which may further influence how visuals are perceived and evaluated.

Despite the essential findings, limitations of the study, such as the sample size and the lack of analysis of individual preferences that may shape responses to different settings, should be considered. Future studies should consider a broader range of landscapes (e.g. urban, perhaps more futuristic) and apply more complex statistical analyses to determine the influence of individual factors more precisely. Further exploration of this issue may lead to even more effective architectural visualisation strategies that integrate aesthetics with perceptual psychology and the development of tools to support purchasing decisions in the real estate market.

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APPENDIX A

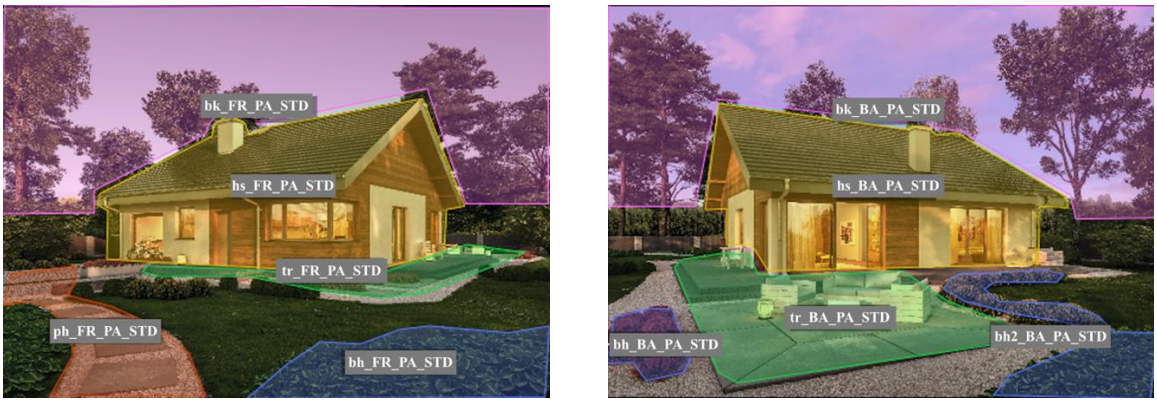


Figure A1. Areas of Interest for the PA_STD project version
Source: compiled from: projekty.muratordom.pl.



Figure A2. Areas of Interest for the PA_SUR_M project version
Source: compiled based on: projekty.muratordom.pl.



Figure A3. Areas of Interest for the PB_STD project version
Source: compiled from: projekty.muratordom.pl.



Figure A4. Areas of interest for the PB_SUR_S project version
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NEUROFEEDBACK AS A DIAGNOSTIC TOOL FOR COGNITIVE AND EMOTIONAL FUNCTIONING: IMPLICATIONS FOR INNOVATIVE MANAGEMENT OF THE ACADEMIC EDUCATION PROCESS

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ABSTRACT

Purpose: *The aim of this publication is to present the potential of neurofeedback as a modern diagnostic tool for identifying cognitive-emotional problems in academia. The relationship between objective EEG indicators and declared difficulties reported by students is analysed, with a particular focus on their relevance to the management of the academic learning process.*

Need for the study: *Declarative self-assessment methods may not reflect actual cognitive and emotional states. There is a need to search for and implement innovative, objective diagnostic tools that can support academic institutions in monitoring and supporting learning processes. Neurofeedback fits into this trend, providing new possibilities for the management of educational quality.*

Methodology: *The study included students for whom data were recorded using neurofeedback. Indicators that dealt with stress, concentration and memory were analysed and then compared with the cognitive-emotional problems reported in the questionnaire.*

Findings: *The data obtained indicate that the students' declarative difficulties are not always consistent with the results of the EEG measurements. Some participants underestimated or overestimated their cognitive-emotional difficulties, which highlights the limitations of self-evaluation. The results confirm that neurofeedback can be a valuable diagnostic tool in identifying cognitive-emotional difficulties.*

Practical Implications: *Integrating neurofeedback into higher education processes can support innovative educational management. Providing more accurate (objective) data to support the identification of students' needs and problems can assist in planning appropriate support. This, in turn, should result in increased learning effectiveness. In the long term, this may translate into better preparation of students for the professional challenges ahead.*

Keywords: Innovative educational management; neurofeedback EEG; cognitive-emotional functioning; neurophysiological diagnostics; stress; concentration; memorization

Jel codes: C91; L15; I20; I23

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1. INTRODUCTION

Nowadays, many people report mental health problems, especially after the COVID-19 pandemic, where a significant percentage failed to cope with the transition into the virtual world and social isolation. In many schools and colleges, teachers and educators have noticed the onset of symptoms such as anxiety, attention problems, fears, withdrawal and depression in pupils and students. In general, this was caused by isolation and reduced social contact. Many of the pupils/students have openly talked about wanting to commit suicide also many have committed acts of physical harm as an extreme form of crying out for attention and help. Nowadays, psychological support is offered in schools and colleges for those who need it.

The problems faced by young people constitute a challenge for academics and future employers in regard to the way they organize work and approach the employee. Human resource management has to face these challenges and properly approach the problems faced by today's society. As early as the primary school stage, school principals point out that previously it was rare for pupils to struggle with an illness such as depression, whereas nowadays more and more pupils are diagnosed with the illness and have therapy and treatment in place. Young people are accompanied by anxiety and fears about the future. There are noticeable mental changes in young people's thinking, with Piagetian abstract thinking and philosophical-existential reflections emerging (Rabindran & Madanagopal, 2020). The combination of the three organic levels, learning to accept changes in one's body, the psychological level - identity formation and social role-taking, leads to the formation of the so-called adult mature personality. As shown by research, the moment of its achievement extends into the later and later years of a person's life. A consequence of this may be a fear of entering adult life, taking on new challenges and meeting employer expectations. This problem affects modern man, where many disturbing behaviours are observed as a consequence of this difficult period, lack of early recognition and implementation of appropriate treatments. Pupils clearly indicated that they needed face-to-face contact with peers, getting out of the house, and interacting with others. It was noted that the increase in symptoms occurred in children who already had emotional problems and were subjected to stressful situations. Almost every person experiences conflicts and reacts with stress in different everyday situations, some more strongly than others, who are able to cope with stress by expressing and overcoming it. From the point of view of developing our knowledge of brain function, it is worth paying attention to the length of time spent under stress and in a crisis situation. The longer the time and the more intense the impression, the more 'havoc' it wreaks on the body of the person experiencing it, whether through shallowed breathing, increased blood pressure and pulse, or through the release of activating substances such as cortisol, noradrenaline and the activation of the sympathetic nervous system. For many people, pandemic was subjectively a very long period and, in addition, the sense of time is also a subjective; for some, an hour is an hour; for a person under stress, it is often an eternity, especially for young people who do not yet have a well-founded temporal (time) perspective. Measures based on promotion, i.e. multiplication, prevention and prevention are effective and efficient. On the other hand, knowledge about how the brain functions is useful for preventing the consequences of improper thinking pattens – demonstrating how influencing the state and the mode of operation of the brain (mood) is actually a health-promoting task.

Among the various naturotherapy methods, there is a method based on biological feedback – biofeedback. Thanks to devices able to visualise natural physiological rhythms, this method is well suited to show the influence of thoughts on the physical functioning of the human body in a different way. Electroencephalographic imaging has been around for more than 100 years and is proving its worth in practice and in self-therapy. Many users of this type of equipment practice, either on their own or under the guidance of a therapist, concentration and meditation, two basic states that stabilise the brain and influence its performance and the experienced well-being. There are more modalities practised, but in the case of neurofeedback, the EEG waveform is used.

Numerous studies and scientific publications confirm observations in the diagnosis of mental disorders caused primarily by forced isolation, i.e. not being able to contact friends and having to stay at home, excessive control or lack thereof or learning problems. The lack of movement and stimulation through visual, sensory contact with different stimuli caused somatic complaints and an increased degree of pain, as well as resentment and apathy, reduced motivation and the adoption of a demanding attitude towards the world. Pupils experienced and were perpetrators of various forms of harm, becoming passive observers or actively supporting the conflicting parties. Physical violence or verbal aggression

are the most commonly perceived forms of manifestation of conflict, while economic, material, emotional and sexual violence are less frequently recorded, but their impact on the psyche can be equal or identical to physical violence, which is worth bearing in mind when analysing the causes of the source and the possibilities of solving the crisis situation. It was and is very important at this time to properly support the student. Not only as a follow-up action, but – above all – through continuous support and health-promoting initiatives that everyone can recognize as an universal good.

Of course, there are many options for dealing with stress and other problems with the help of psychiatrists, educationalists, psychologists, psychotherapists or drug therapy. However, as is well known, the availability of therapies conducted by psychotherapists – which seems to be the most appropriate course of action – in Szczecin, is very limited, due to very long therapy times and prices, which make it difficult for many families to take corrective action. Appointments with psychiatrists are also difficult to arrange, as there are known to be too few psychiatrists, particularly for children. And there are also not many psychologists specialised in this field; in addition, the social stigma associated with attending such appointments seems to have decreased in the recent years, but it is nevertheless present and depends on the level of education and residence of the persons involved.

Therefore, in addition to psychological therapy and psychiatric treatment, the implementation of neurobiofeedback therapy can be proposed at universities. In simple terms, it shows the dependence of the thinking process on the reactions taking place in the human body and offers the possibility of taking control of the physiological rhythms, altering them to become more favourable for the practitioner; learning how to do this can be done at any time in life, through changing social, elemental or emotional events and situations that are reactions to our perception of the consequences of these events.

The aim of this paper is to assess the applicability of neurofeedback as a diagnostic tool in identifying cognitive-emotional problems, such as stress, concentration and memory difficulties, among students. This paper presents the results of a comparative analysis of the indicators obtained from EEG measurements with the statements made in self-assessment questionnaires. This allowed for an assessment of the validity of using neurophysiological data as an objective source of diagnosis. Finally, the potential benefits of using neurofeedback as a tool to support innovative management of the academic learning process were indicated.

The article consists of five sections. Section 2 presents the theoretical basis of neurofeedback, and its applications in the diagnosis of cognitive and emotional functions. Section 3 contains the study methodology used, including the characteristics of the study group, the experimental procedure, the measurement tools used and the data analysis methods. The next section contains the results of the analyses of the EEG indicators derived from the neurofeedback sessions, the self-assessments of the study participants and the statistical analyses performed. Section 5 is devoted to a discussion of the results and an analysis of the applicability of neurofeedback in the diagnosis of cognitive-emotional problems, as well as its role in the innovative management of the academic learning process. The final section includes conclusions, practical implications and directions for further research.

2. LITERATURE REVIEW

Biofeedback is a method of naturotherapy, a therapy which is based on the self-regulation of the psycho-physical state through the use of feedback on changes in selected physiological parameters. Thanks to the feedback, the student knows when their brain activity increases within a particular brain wave frequency band and when bands that have a negative effect on brain function dominate (Frank i in., 2010). The EEG recording, which was first recorded in humans by Hans Berger, is used to read frequency bands (Vergani, 2024). In 1962, Joe Kamiya of the University of Chicago discovered that information given to patients about their Alpha wave status using a sound-emitting device allowed patients to recognise the sound and consciously control their Alpha wave levels (Kamiya, 2011). In the 1960s, Bary Sterman showed that there was a correlation between increased SMR waveforms and increased threshold for seizure excitability (Sterman & Egner, 2006). This discovery allowed the incorporation of SMR training in the treatment of epilepsy. Subsequently, Lubar and Seiferd introduced a new protocol that allowed suppression of Theta frequencies while enhancing SMR. Further research confirmed the effect of wave frequency on concentration. These studies gave rise to much research and the widespread use of neurofeedback today (Marzbani i in., 2016a) e.g. in clinical medicine, psychology

and sport (Paul i in., 2012). When studying the electrical activity of the brain, different types and ranges of waves are distinguished; on average, seven dominant waves are accepted: Delta wave with a frequency of 0.5 – 4 Hz, Theta from 4 – 8 Hz, Alpha from 8 – 12 Hz, SMR 12 – 15 Hz, Beta 1 15 – 20 Hz and Beta 2 from 20 – 34 Hz, Gamma 38 – 42 Hz. These waves are responsible for different functions causing different psychophysical symptoms when the amplitudes of the frequency bands are decreased or increased. There are various captured bands that are characteristic of a state of relaxation, increased concentration or meditation. There are also recordings showing abnormalities, tendencies or disorders, lowered mood or difficulties in decision-making. By selecting appropriate filters and showing prepared training panels, it is possible to influence or help to influence the volitional processes of the person undergoing training and help them learn to steer or control the measured parameters in a conscious way (Marzbani i in., 2016b).

There is a wealth of neurofeedback research. Popular notions highlighted in the literature include:

Delta waves are responsible for efficient brain function and regeneration during sleep. Its low amplitude causes sleep problems, while an elevated amplitude is observed in people with brain injury, people with mental disabilities and autistics.

Theta waves (4 – 8 Hz) are responsible for achieving a state of flow and are associated with relaxation and creativity. Excessive amplitude of this wave in some areas may indicate problems with maintaining attention (Picken i in., 2020). Low levels of Theta waves cause problems with memory and also with achieving a state of flow. People whose Theta is significantly elevated have hyperactivity (ADHD) (Heinrich i in., 2014; Nermend i in., 2022).

The Alpha wave is responsible for, among other things, good mood, relaxation, creativity, feeling calm and relaxed, fast learning. Its increase causes ADD-type attention problems, frequent reverie, excessive fantasising. Its elevated value can also be seen in people who smoke marijuana and take antidepressants. Low Alpha causes a state of psycho-physical exhaustion, reduced creativity, learning problems and lack of relaxation.

The SMR wave in humans induces good resistance to stress, increases the ability to concentrate attention for long periods without effort and, in people with epilepsy, improves resistance to seizures. Its excessive elevation causes excessive concentration issues or even anxiety. On the other hand, its low value causes greater susceptibility to stress, problems with maintaining attention for long periods, psychophysical exhaustion, as well as chronic and prolonged stress.

Another very important wave for normal human functioning is the Beta 1 wave (15 – 20 Hz). This wave is associated with active thinking, concentration and information processing. Excessive Beta 1 wave activity can be associated with a state of over-analysis, irritability and mental tension. When the amplitude of this wave is reduced, there is a problem with attention, mental fatigue, reduced rate of information processing (Jang i in., 2019). In the open-eye test, we register a higher Beta 1 wave amplitude value as in the closed-eye test. If this condition is disturbed, it may indicate fatigue, depression and a problem with concentration.

Beta 2 otherwise known as Hi Beta provides a person with the right amount of energy to work and perform causing peak performance. A decrease in Beta 2 causes a decrease in energy, phlegmaticity, slowness. Excessive amplitudes result in mental tension, stress, anxiety, sleep problems occur. The analysis of the amplitudes in the open-eye and closed-eye tests allows assessment of whether symptoms of excessive tension and excitation are present (Kurimori & Kakizaki, 1995). If the amplitude of the Beta 2 wave in a closed-eye test does not decrease compared to an open-eye test, this is a signal that may indicate chronic stress, sleep problems or anxiety disorders.

As can be seen from the above description, wave frequency disorders cause fatal difficulties in human functioning, while the biofeedback method makes it possible to naturally harmonise individual waves by lowering or raising their percentage of the bands or amplitude by adjusting the level of success and failure in the display showing the range of waves.

In this day and age, where people's mental problems are very noticeable, biofeedback can diminish or offset the effects of long-term stress and its consequences (Schwartz, 2008). In order to diagnose the pupil, the pupil must be interviewed and then an EEG test and QEEG analysis must be performed. The test involves placing EEG electrodes in accordance with the international 10 – 20 system covering the frontal lobes, temporal lobes, central lane, occipital lobes, and parietal lobes.

The QEEG (Quantitative EEG) method is a computerised tool for investigating brain functions and dysfunctions as well as planning biofeedback sessions. The QEEG method enables not only the

recording of the EEG signal, but based on a special computer programme, its quantitative analysiş with a report and suggestions for training.

Biofeedback training is most often based on games that last a few dozen minutes; depending on the ability of the practitioner, the therapist decides on the duration of the entire training. The electrical activity of the neurons is detected through surface electrodes. The activity is then amplified and processed by computer programmes which, by means of a simulation of the game on a computer monitor, induce a conditioned response in the learner, while the therapist teaches techniques and gives tips to facilitate the exercises.

3. METHODOLOGY

3.1. Participants

A group of 44 people volunteered to take part in the scientific experiment. Before taking part in the study, the participants completed a patient interview sheet, in which the strengths of the subject's psyche were noted, as well as those traits that might negatively affect the individual's daily functioning. Through the interview, the therapist also learns about previous illnesses, neurological injuries, medications taken and any mental or physical disorders that may affect brain function. Some neurological conditions, such as severe epilepsy, psychiatric disorders or trauma, may contraindicate neurofeedback therapy. A history helps to detect these before starting the test and planning the therapy.

Individuals who declared taking psychoactive medication and those receiving various forms of psychological and psychiatric therapy were excluded from the study. These persons accounted for 13.64% of the group entering the research experiment (6 persons out of a group of 44). Taking certain psychoactive substances affects brain structures responsible for regulating brain rhythms. Modifying the action of these structures affects the overall EEG profile, changing the amplitudes and dominant frequencies of the waves. Sedative drugs increase the amplitude of slow waves (Theta, Delta) and decrease the amplitude of fast waves (Beta 1). Stimulant drugs increase the amplitudes of fast waves, such as Beta 1, and may decrease the amplitudes of slow waves.

Thirty-eight participants (27 women and 11 men) took part in the laboratory study. They ranged in age from 22 to 26 years, with a mean age of 23.74 years and a standard deviation of SD = 0.79. Each experimental participant was informed about the course and purpose of the study and the apparatus used to record the EEG signal.

The survey was conducted in accordance with the principles set out in the Declaration of Helsinki (2013 version) (World Medical Association, 2013). The scientific experiment was reported to and approved by the Bioethics Committees at Regional Chamber of Physicians in Szczecin. The subjects gave written consent to use the results of the study in the analysis of the scientific paper.

3.2. Research Protocol and Stimuli

The test was carried out in a laboratory room prepared for EEG measurements, enabling the elimination of signal recording interference. The test site was isolated from both external sounds and disturbances originating from the electrical grid and magnetic fields from the operation of electrical equipment.

During the study, participants were provided with a relaxed environment, and external stimuli that could distract the subjects were neutralised. Sets, according to the 10-20 (Marzbani i in., 2016a), electrode attachment sites on the head, were cleaned of dead skin using abrasive paste. This procedure was intended to reduce the impedance of the patient's skin.

Electrode Cz was placed at the main reference (central) point. A reading from this point for a wave in the 12 to 15 Hz frequency range (SMR) is important in diagnosing problems with the subject's concentration and general well-being. Mounting the electrode at the Fz point (frontal area) makes it possible to diagnose a problem with the subject's executive, emotional and attentional functions. The mounting of electrodes in the C3 and C4 sensorimotor area (responsible for motor control and vigilance) supports diagnosis in terms of arousal, impulsivity and attention. In addition, reference electrodes (A1, A2) were mounted on the auricles to reduce interference and ensure signal stability. During the mounting of the electrodes, the impedance value was monitored, trying to keep it below 10 kΩ.

The testing session was divided into two three-minute rounds with a 15-second break between the rounds. The first round of testing was conducted with the eyes open and the second with the eyes closed.

Analysing these two conditions allows us to assess how the brain reacts to different conditions and provides information about the functioning of the nervous system (Barry i in., 2007).

3.3. Research Apparatus

A 4-channel DigiTrack EEG Biofeedback instrument was used in the laboratory study. The device features a high sampling rate of 500 Hz per each of the four channels and 24-bit resolution, which allows for precise mapping of the EEG signal. Its frequency response ranges from 0.1 to 100 Hz, making it capable of recording different types of brain waves. The device uses Ag/AgCl electrodes. Communication with the computer is via a USB 2.0 interface, which simultaneously supplies power, eliminating the need for an additional power source. The DigiTrack is compatible with Windows 10 and above, and its software enables comprehensive analysis of the collected data.

The DigiTrack EEG apparatus tracks brain activity in real time, enabling brainwave analysis diagnosis of neurological disorders and allowing its use in neurofeedback therapy. It works on the principle of feedback, allowing the user to observe their own brain activity and learn to consciously regulate it through appropriate visual or auditory stimuli.

The device consists of five components. The EEG signal recording module, which is responsible for recording and processing the electroencephalographic signals from the connected electrodes. Software whose purpose is to visualise the EEG data in real time, analyse the individual frequency bands and generate feedback in the form of animated therapeutic images or sounds. Four recording electrodes, positioned on the scalp according to the standard 10-20 arrangement. Reference electrodes, mounted on the auricles to stabilise the measurement and reduce noise. A user interface that allows the therapist to control the session, select the training protocol and monitor the patient's response.

3.4. Analysis of Measurement Data

The EEG signal recorded during the study was assessed for undesirable interference and signal recording abnormalities (physiological artefacts, of external and technical origin). The perceived artefacts, mainly muscle artefacts (swallowing of saliva, muscle tensions) and those originating from eye blinking, were manually removed by the investigator.

The cleaned EEG signal was subjected to quantitative QEEG analysis. In this analysis, the amplitude and percentage distribution of brain waves are assessed, allowing potential problems or disorders of the subject to be identified. Each frequency band is characterised by specific activity patterns that correspond to specific mental and physiological states (Sterman, 1996). Based on these results, the therapist makes a decision on further treatment, e.g. neurofeedback training, cognitive behavioural therapy or is a signal for pharmocological solutions.

In a scientific experiment, a diagnosis of QEEG analysis was performed for open and closed eye examination based on brain wave patterns according to Dr. Sterman (Sterman, 1996). The pattern-forming waveform values are used in making diagnoses of patients' emotional disorders. This analysis makes it possible to identify abnormalities that may indicate different emotional states, which is helpful in planning therapy, such as neurofeedback.

Stress is one of the main factors that contributes significantly to health problems (O'Connor i in., 2021). It is defined as the human body's response to external, emotional and psychological stimuli (Giannakakis i in., 2022). Due to the body's individual response to stimuli, its testing and evaluation is extremely difficult (Hou i in., 2015). One method for measuring stress levels is the EEG biofeedback brain test (Dornowski i in., 2024). The diagnosis of stress focuses on the analysis of Beta 2 wave levels (20-35Hz). This wave is associated with high cognitive activity, intense thinking, as well as stress and mental tension. Reduced wave levels are characteristic in cases of reduced cognitive activity and lethargy of the subject.

Concentration is a key cognitive function that is essential for learning and working. It is defined as an individual's ability to selectively focus attention on a stimulus or task, while eliminating factors that are irrelevant to the cognitive process in question (Petersen & Posner, 2012). In studies using neurofeedback EEG, concentration is analysed by observing changes in the rhythms of Theta (4 – 8 Hz) and Beta 1 (15 – 18 Hz) waves. One of the most commonly used indicators for assessing concentration levels is the Theta/Beta wave ratio. Its elevated value is symptomatic of conditions associated with attention deficit disorder.

In classical terms, memorisation is defined as the process of fixing information for later retrieval (Mujawar i in., 2021). Research using EEG biofeedback helps to understand and explain this process. It has been observed that there is a connection between the recorded waves at specific frequencies and cognitive processes such as memory and learning. The Theta rhythm plays a significant role in the formation of long-term memory. Research has shown that there is a correlation between the amplitude values of Alpha (8 – 12 Hz) and Theta (4 – 8 Hz) waves and learning and memory processes. Increased levels of Alpha waves have been shown to be associated with better short-term and working memory performance (Doppelmayr i in., 2002; Klimesch, 1999). A high Alpha/ Theta wave ratio (above 1) indicates a state in which the assimilation of information takes place most efficiently. A predominance of the Theta wave (relative to Alpha) is characteristic of states of meditation and tranquility, which negatively affects memory processes.

4. RESULTS

4.1. Identification of stress problems

Neurophysiological measurements and self-assessment cards were used to assess stress levels among the study group. Two indicators, based on the analysis of the relevant frequency range, were used on the basis of the EEG signal recording:

- Beta 2 wave percentage (20-34 Hz), which is the main measure of emotional arousal, tension, or stress. Exceeding 9% Beta 2 percentage (according to Sterman's table) is interpreted as a state of stress (Syrjänen i in., 2023; Szubert-Czarnocka, n.d.).
- The Theta/SMR index, related to the balance between distraction and emotional stability. It is calculated as the ratio of the amplitude of Theta waves (4 – 8 Hz) to SMR waves (12 – 15 Hz). Values exceeding level 2 may be indicative of stress (Szubert-Czarnocka, b.d.).

The overarching aim of this phase of the study was to test (in addition to identifying the state of stress) whether these EEG indicators can distinguish between people who declare feeling stressed and those who do not.

In the analysis of the first of these indicators, a comparison of Beta 2 wave proportion was made between groups of people who declared a stressful state and those who did not. The mean Beta 2 wave percentage, standard deviation, median and minimum and maximum mean values were determined for both groups. The averaged Beta 2 wave percentage in the group reporting stress was 16.21%, while in the group who did not report stress it was 12.20%. These values are shown in table 1.

Table 1. Descriptive statistics of Beta 2 wave proportion (%) in the groups reporting and not reporting stress

Group	Number of persons	Average	Standard deviation	Median	Range (min–max)
Reported stress	22	16,21	3,31	15,98	11,88 – 24,98
Failure to report stress	16	12,20	2,96	11,04	7,62 – 19,32

Source: own elaboration.

A boxplot (Fig. 1) was used to visualise the distribution of Beta 2 wave proportion in both study groups. It allows the differences between groups to be observed even in cases where the data deviate from a normal distribution. The box shows the middle 50% of the results (between the 1st and 3rd quartiles), the whiskers of the graph show the outliers (close to the limits of a typical distribution) and the visible points are the outliers (atypical or possibly measured incorrectly). The horizontal line inside the box indicates the median.

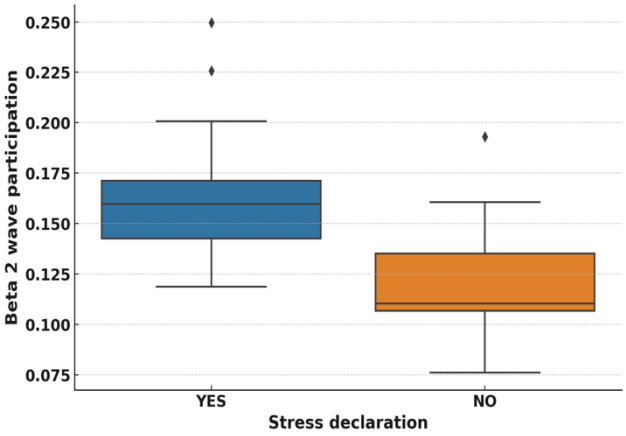


Figure 1. Comparison of Beta 2 wave contribution in the group reporting stress and the group not reporting stress
Source: own elaboration.

The results of the analysis show that the proportion of Beta 2 waves was higher in the group reporting stress, both mean and median (15.98%), than in the group that did not (median: 11.04%). The difference between both groups appears to be significant. To test whether this difference is statistically significant, the Student's t-test for independent samples was used. Before performing the test, assumptions regarding the normality of the distribution and equality of variance were checked. The result of the test concluded that the difference was statistically significant: $t(36) = 3.85$, $p = 0.0005$.

In order to carry out a deeper analysis between the Beta 2 values obtained and the variable determining the reporting or non-reporting of stress, a point-two-tailed correlation test was applied. The obtained result of Pearson's correlation coefficient $r(36) = 0.54$, $p<0.001$ indicates that the relationship is moderate (or moderately strong). This means that higher values of Beta 2 wave share are significantly associated with the declaration of stress. This confirms the previous analysis of differences between groups and thus the role of Beta 2 as an objective neurophysiological indicator of stress occurrence.

For the analysis of the Theta/SMR index to differentiate between the two groups of individuals (stress-reporters and non-reporters), the mean value, standard deviation and median were determined, as before. These values, supplemented by the minimum and maximum values of the Theta/SMR index for both groups, are shown in Table 2.

Table 2. Descriptive statistics of the Theta/SMR index in the stress-reporting and non-stress-reporting groups

Group	Number of persons	Average	Standard deviation	Median	Range (min–max)
Reported stress	22	1,86	0,30	1,83	1,20 – 2,35
Failure to report stress	16	1,90	0,37	1,93	1,28 – 2,50

Source: own elaboration.

Again, a boxplot was used to illustrate the variability of the Theta/SMR index in both groups (Fig. 2). It shows a similar distribution of the Theta/SMR index between the group reporting stress and the group that did not.

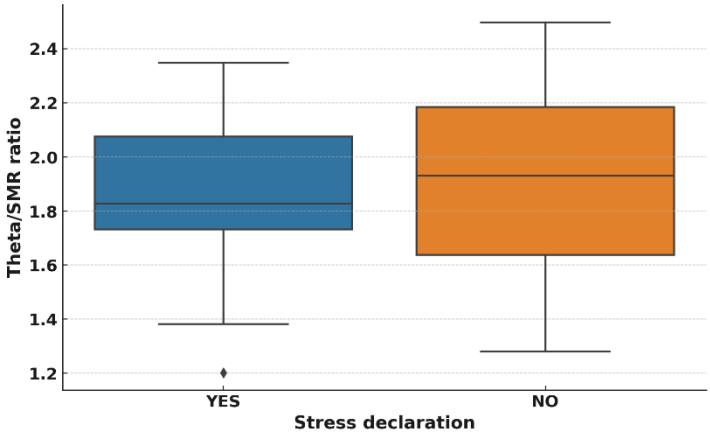


Figure 2. Comparison of Theta/ SMR values in the group reporting stress and not reporting stress
Source: own elaboration.

As can be observed, the mean value of the Theta/ SMR index in the group of people declaring stress was 1.86, while in the other group it had a value of 1.90. The medians also had similar values, respectively: 1.83 and 1.93. The minimum and maximum mean values in the two groups were not significantly different from each other. These data suggest that the distribution of the Theta/ SMR index was similar in both the declaring and non-declaring stress groups. These values were further statistically analysed to check whether they were indeed differences at the level of statistical significance.

A Student's t-test confirmed the lack of statistical significance: $t(36) = –0.33$, $p = 0.7427$, of the mean of the Theta/ SMR index between groups. In addition, a two-tailed point correlation test was conducted between the Theta/ SMR index value and the binary variable, which is the declaration of stress (YES/NO). Pearson's correlation coefficient $r(36) = –0.055$, $p = 0.7427$ indicates a very weak and not statistically significant relationship between the two variables. This means that the Theta/ SMR values do not show any significant trend (increase or decrease) in relation to the stress statement.

4.2. Identification of attention difficulties

Two indicators were used in the analysis of attention problems:

- Index, taking into account the percentages of the Theta and Beta 1 waves. Meeting the two conditions that Theta > 22% and Beta 1 < 9% was interpreted as attention difficulties.
- A complementary indicator also taking into account the percentage of these waves, expressed as their ratio: Theta/Beta 1. Values exceeding the number 3 indicate problems with concentration, a tendency to distraction.

A comparison of the Theta and Beta 1 wave percentage values was made between those who declared problems with attention concentration and those who did not. Mean Theta and Beta 1 wave share values, standard deviations, medians were calculated for both groups and the smallest and largest values were identified. The mean proportion of Theta waves in those reporting attention difficulties was 19.24%, while in those not reporting it was 19.39%. For Beta 1 waves, the values were 11.25% and 11.42%, respectively. Detailed figures are shown in Tables 3 and 4.

Table 3. Descriptive statistics of the proportion of Theta waves (%) in the groups of people reporting and not reporting concentration problems

Group	Number of persons	Average	Standard deviation	Median	Range (min–max)
A problem with concentration was reported	33	19,24	1,80	19,30	14,45 – 23,70
No report of a concentration problem	5	19,39	0,88	19,41	18,03 – 20,20

Source: own elaboration.

Table 4. Descriptive statistics of Beta 1 wave share (%) in the groups of those reporting and not reporting concentration problems

Group	Number of persons	Average	Standard deviation	Median	Range (min–max)
A problem with concentration was reported	33	11,25	1,69	11,14	8,75 – 15,12
No report of a concentration problem	5	11,42	1,23	12,09	9,75 – 12,59

Source: own elaboration.

The detailed analysis started with the first of these indicators. Only 2 people were identified in whom both conditions were met, i.e. in neurophysiological terms, concentration problems appeared. At the same time, 33 people declared in the questionnaire that they had difficulties with concentration, while 5 participants in the study declared that they did not have such problems. Such responses resulted in a clear numerical imbalance between the groups. Furthermore, a significant discrepancy was observed between the statements reported in the questionnaire and the data obtained from the EEG measurements. In the group of people reporting concentration problems, in only 2 people did the first indicator (Theta > 22% and Beta 1 < 9%) confirm a concentration deficit. For the remaining 31 people in this group, this indicator did not confirm problems. In the group of people not reporting difficulties, no problems were detected in anyone on the basis of the EEG reading. In this situation, there was little justification for carrying out statistical analyses to test the significance of differences between groups. Analysis of the Theta and Beta1 wave contribution values in both groups shows that their means, standard deviations and medians are very similar. This therefore confirms that it makes no sense to look for differences or any trends with such results.

The second of the adopted attention/concentration indices (Theta/Beta 1) was treated as complementary. For the group of 38 subjects, the values of this index ranged from 1.16 to 2.66. For those declaring attention problems, the mean value of the index was 1.75 (SD = 0.36). For the group not reporting difficulties, the mean was 1.72 (SD = 0.24). The differences are small and do not indicate that the variation between the groups reaches statistical significance. None of the subjects exceeded a threshold of 3 for Theta/Beta 1, indicating a lack of detection of attention problems at the level of brain activity.

4.3. Identification of memory problems

The Alpha/Theta index, calculated from the proportion of EEG waves, was used to analyse memory difficulties. It reflects the ratio of activity related to a state of relaxation and internal information processing (Alpha waves) to activity related to remembering and recalling information (Theta waves). Higher values of this index indicate better mental performance, especially in terms of memory and concentration (Egner & Gruzelier, 2004). The analysis used a division into three categories of the Alpha/Theta index, labelled as: normal level, for values ≥ 1.00 (a sign of optimal cognitive performance), borderline level, for values 0.90-0.99 (a warning signal but still acceptable), and reduced level, for values < 0.90 (potential memory problems) (Zhuang i in., 2009).

In the sample analysed (n = 38), the largest group of subjects (52.63%) obtained values in which the Alpha/Theta index indicated reduced working memory performance and difficulty in focusing attention (reduced level). The category defined as normal level was assigned to 34.21% of the subjects, while 13.16% of the subjects were in the reduced level category. The values of the Alpha/Theta index, together with other descriptive statistics calculated for the three interpretive categories, are presented in Table 5.

Based on the data obtained from the questionnaire, it was found that 16 study participants (42.11%) reported experiencing difficulties with memorisation. The remaining 22 (57.89%) reported no problems in this area.

Table 5. Descriptive statistics for the three categories of the Alpha/Theta index

Category Alpha/Theta	Range of values (thresholds)	Number of persons	Persons (%)	Average	Median	Range (min–max)
Normal level	≥ 1,00	13	34,21	1,18	1,10	1,00 – 1,81
Borderline level	0,90–0,99	5	13,16	0,92	0,92	0,90 – 0,94
Reduced level	< 0,90	20	52,63	0,74	0,74	0,63 – 0,87

Source: own elaboration.

In order to check the subjects' declared memory difficulties against the values of the Alpha/Theta index, an analysis of the distribution of this index was carried out in three categories: normal level, borderline level and reduced level. A visual representation of this distribution is shown in Fig. 3. The graph shows boxes representing 50% of the results (between the 1st and 3rd quartiles), outliers (whiskers), outliers and the median (horizontal line in the boxes). This presentation allows an assessment of the spread of data within each group.

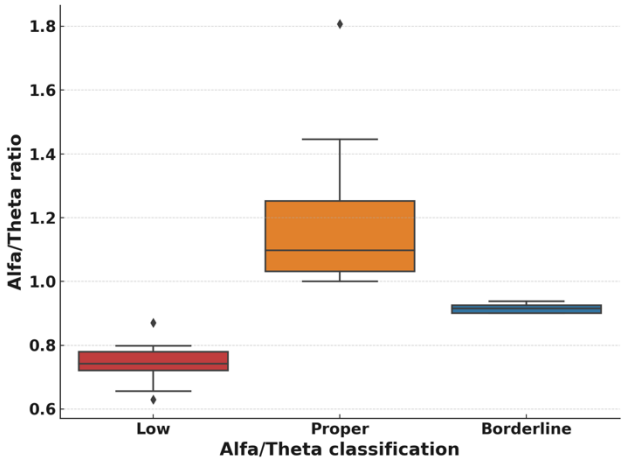


Figure 3. Distribution of the Alpha/Theta index (wave share) across the three value categories
Source: own elaboration.

To test the significance of the differences between the groups, an analysis was performed using the Mann-Whitney U test. The median Alpha/Theta index for the group of subjects reporting memory problems was 0.92, while for the others it was 0.79. This difference was not statistically significant ($U = 202.00$; $p = 0.451$), meaning that there was no significant relationship between self-report and EEG activity. Some subjects with a low Alpha/Theta ratio did not perceive memory problems. Similarly, some subjects, with an index in the normal level category, declared a memory problem. These results suggest that the declarative assessment of memory problems may be unreliable and not fully reflect the actual state of cognitive function.

To assess whether the reporting of memory problems is related to the category of the Alpha/Theta index, an independence analysis was performed using the chi-square test. Three categories of subjects were compared: those with a low index (< 0.90), those with a borderline value (0.90 – 0.99) and those with a normal level (≥ 1.00). The analysis was intended to show whether reports of memory problems were significantly more frequent in any of these groups. The test result turned out to be statistically insignificant ($\chi^2(2) = 1.16$; $p = 0.560$). This means that no correlation was found between the Alpha/Theta category and reported memory problems. However, it is interesting to note that the highest percentage of reported problems appeared in the group of people with the highest Alpha/Theta index (normal level). This may indicate greater cognitive sensitivity or higher levels of self-awareness in those with optimal cognitive performance. In contrast, memory problems may have gone unrecognised or considered insignificant in some of those with lower Alpha/Theta scores.

The Alpha/Theta analysis was complemented by an analysis of the recorded EEG values from the Beta 1 frequency range. This is responsible for activity associated with the processes of attention,

vigilance (speed of reaction to stimuli) and information processing. The mean Beta 1 amplitude in the study group was 6.32 μV. It was therefore within the typical range for healthy individuals. However, cases were identified in which people with low Alpha/Theta ratios had at the same time quite high Beta 1 activity. This may indicate that, despite problems with memory and concentration, people are showing increased mental effort. This may be an attempt to cope with the difficulty in remembering. Such a pattern, i.e. low Alpha/Theta and elevated Beta 1 values, may be an indication that working memory overload is occurring and difficulties with sustaining attention are emerging. Although the analysis of values in the Beta 1 range was not the primary aim of the study of memory problems, its inclusion allows a better understanding of the processes involved. This can be helpful, for example, when planning individual neurofeedback training, which will be better adapted to the participant's condition.

5. DISCUSSION

The aim of the study was to compare the problems reported by the subjects in the questionnaires in terms of their cognitive-emotional functioning with objective data obtained by neurofeedback measurements. A detailed analysis of the results indicated discrepancies between the two ways of obtaining information.

The greatest convergence was observed in the context of the stress test. Those who declared a problem with stress were characterised by higher Beta 2 wave activity, and this indicates an increase in arousal, emotional tension, i.e. stress (Dornowski i in., 2024). In contrast, among the majority of people who did not report stress problems, the proportion of Beta 2 waves was relatively low. It is noteworthy that no elevated values of the Theta/SMR index were observed in this group, which further confirms the significant coincidence of the declarations with the brain activity reading.

In the case of attention, the analyses carried out showed a much lower correspondence between self-assessment and brain activity readings. Out of 38 subjects, as many as 33 declared difficulties with concentration, but EEG measurements confirmed this problem in only two subjects. The low relevance of self-assessment is confirmed by studies which found that individual assessment of cognitive function often deviates from the results of neuropsychological tests (Mosiołek, 2014). It is noteworthy here that in the vast majority of subjects, the activity of the Theta and Beta1 waves was within the normal range. This suggests that processes related to attention were normal, despite the different declarations of the subjects.

Interesting analytical results were also obtained in the context of memorisation. The Alpha/Theta ratio, which is considered a proxy for working memory performance (Doppelmayr i in., 2002; Klimesch, 1999), and thus the ability to process information in short-term memory, was below normal in the majority of people interviewed. This is in contrast to the declarations of the individuals, where not all overtly confirmed problems in this area. At the same time, for some of the subjects, the Alpha/Theta index did not indicate memory problems, and yet individuals reported difficulties in this area. The analyses carried out in this area also confirm that self-assessment is not always a reliable measure of actually occurring cognitive problems.

The results of the data analysis carried out (declarations and EEG activity readings) take on particular significance in the context of learning management. This means that one should not rely only on students' declarations regarding their current cognitive-emotional state. The use of EEG as a diagnostic tool allows access to hidden information that is inaccessible to those potentially involved. Considering the aspect of university management, the integration of neurofeedback-type tools with classical systems for monitoring student progress, can contribute to improving personalised forms of educational support. Importantly, the use of EEG in the diagnosis of emotional and attentional responses is already being validated in other research areas. An example is the research on the effectiveness of social campaigns, in which EEG was used to measure the level of engagement, attention and emotion of the audience, revealing information not available in the declarative reports of participants (Piwowarski, 2018). As in education, here too the EEG signals obtained allowed for an in-depth diagnosis and optimisation of the message, confirming the usefulness of this type of data in designing effective communication and decision-making strategies.

6. CONCLUSION

The research carried out showed that subjective declarations made by students using a questionnaire (interview sheets) regarding cognitive and emotional difficulties are not always consistent with objective indicators obtained by EEG (neurofeedback) measurements. The largest discrepancies concerned concentration and memory problems. The majority of subjects reported difficulties that did not find confirmation in neurophysiological data. In contrast, in the case of stress, a concordance was observed between self-assessment and EEG indicators.

The results of the study suggest that the use of neurophysiological methods in academic learning can support the diagnoses of cognitive and emotional barriers that are not possible through self-assessment. This approach makes it possible to improve academic learning management processes by introducing measures that support monitoring and enhance the effectiveness of student learning.

It should be noted that the study had its limitations. The number of participants was relatively small, which may affect the generalisability of the results. Further research would benefit from considering larger samples, longer measurement sessions and analysis of the dynamics of change over time. Another direction for future research could be the integration of EEG data, acquired from neurofeedback sessions, with other data sources, such as the measurement of electrodermal activity or facial expression analysis.

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SHAPING INTELLIGENT MANAGEMENT WITH NEUROSCIENCE: MULTIGENERATIONAL PERSPECTIVES FOR THE FUTURE

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ABSTRACT

Purpose: *The article explores the integration of neuroscience and intelligent management in the context of a multigenerational workforce. It aims to examine how Generations X, Y, and Z perceive the applicability and usefulness of neuroscience tools and techniques in managerial practice.*

Need for the study: *In the face of rapid technological advancement and increasing generational diversity in the labor market, there is a growing need to understand how modern management tools — particularly those grounded in neuroscience — are received across generational cohorts. The literature lacks studies that combine neuroscience, intelligent management, and generational differences, creating a gap that this article addresses.*

Methodology: *A quantitative survey was conducted using the CAWI method on a sample of 423 Polish respondents representing Generations X, Y, and Z. The questionnaire measured awareness, perceived usefulness, and willingness to apply eight neuroscience tools and techniques in intelligent management. Nonparametric statistical tests (Mann–Whitney U) were used to identify generational differences.*

Findings: *The results indicate significant generational differences in the perception and acceptance of neuroscience tools. Generation Y rated neuroeducation and neuromarketing highest, while Generation Z showed greater openness to neurofeedback and neuroadaptive decision-support systems. Generation X demonstrated more familiarity with neuroleadership and neuroeconomics but expressed more skepticism toward newer tools.*

Practical Implications: *These insights suggest that organizations should adapt the implementation of neuroscience-based management tools to generational preferences. Doing so can enhance employee engagement, learning effectiveness, and leadership development. Customized training and communication strategies may support smoother adoption of intelligent management innovations across age-diverse teams.*

Keywords: Intelligent Management; Neuroscience; Tools and Techniques; Generation X, Y, Z

Jel codes: M12; M15; O33; J24; D83

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1. INTRODUCTION

In the face of dynamic technological, demographic, and social changes, contemporary organizations are confronted with the challenge of redefining their management approaches. Traditional management models are proving insufficient in addressing the growing complexity of the work environment, the multigenerational structure of the workforce, and the need for rapid and accurate decision-making (Chiwisa & Mpundu, 2024). In response to these challenges, increasing attention is being directed toward neuroscience-based approaches and so-called intelligent management, which combine knowledge of human brain functioning with modern decision-support systems.

Neuroscience offers valuable insights into the mechanisms of perception, learning, motivation, and decision-making, which form the foundation of effective leadership and the development of human resource management strategies (Butler et al., 2016). In turn, intelligent management relies on the use of artificial intelligence, data analytics, and adaptive systems that support managers in steering organizations (Berente et al. 2021). The integration of these two fields creates a unique foundation for a new management model grounded both in hard data and in the understanding of human nature.

At the same time, generational diversity in the workplace is gaining importance. Modern work environments bring together representatives of as many as three generations – Generation X, Y, and Z – who differ not only in values and expectations, but also in communication styles, work approaches, and technological preferences (Berkup, 2014). The integration of neuroscience and intelligent management systems may serve as an effective tool for fostering intergenerational collaboration and unlocking the potential of every employee.

The aim of this article is to present current and future opportunities for neuroscience-inspired intelligent management, considering how they are perceived by different generations. The considerations presented here fill a gap in the literature, as research on intelligent management and neuroscience from a multigenerational perspective – Gen X (born in 1965–1980), Gen Y (born in 1981–1996), and Gen Z (born in 1997–2012) – has not been conducted to date.

The article presents a theoretical section discussing the issues of intelligent management and neuroscience, as well as various neuroscience techniques and tools used in intelligent management. Then, methodology based on the survey questionnaire, research results made with advanced tools, and discussion and conclusions where similar research and this paper's main achievements are pointed out as well as the future research directions are mentioned.

2. LITERATURE REVIEW

Intelligent management is a concept that has evolved from the need of modern organizations to make rapid, flexible, and informed decisions in complex and dynamic environments. A key feature of intelligent management is an organization's ability to self-regulate, learn, and adapt — enabling continuous adjustment to changing market, technological, and social conditions. This approach leverages data, artificial intelligence, and knowledge management techniques to support accurate, analysis-based decision-making (Dayal, 2004).

The contemporary understanding of intelligent management refers to the use of advanced technologies – such as artificial intelligence, big data, and decision-support systems – to enable dynamic, predictive, and self-adaptive decision-making within organizations. Intelligent management not only streamlines operational processes but also allows companies to anticipate changes, respond to them in real time, and design data-driven strategies. Research indicates that intelligent management systems focus on transforming data into knowledge and knowledge into effective business decisions (Tweedale et al., 2016).

The concept of intelligent management originates from earlier approaches such as information management, expert systems, and learning organizations. The contemporary perspective has gained prominence in the context of digital transformation, the development of the Internet of Things (IoT), big data, and advanced analytical technologies (Szelągowski & Lupeikiene, 2020).

Intelligent management integrates core managerial functions — planning, organizing, leading, and controlling – with decision-support systems and intelligent technologies, taking into account the organizational context and the need for dynamic adaptation to changes in the economic environment (Sun, 2016). In the face of increasing organizational and business environment complexity, the role of

knowledge- and data-driven management systems is becoming crucial. As a result, artificial intelligence, machine learning, and predictive modeling not only support decision-making processes but also transform the way strategies are formulated and organizational performance is managed (Usmani et al., 2023).

At the core of intelligent management lies the ability to operate effectively under conditions of uncertainty, foster innovation, and build stakeholder engagement. In line with Deming's systems thinking approach, further developed by contemporary scholars, intelligent management requires viewing the organization as a whole, where interdependencies and feedback loops play a crucial role (McElheran & Brynjolfsson, 2016). This holistic understanding is reflected in the integration of digital technologies and artificial intelligence, which enable strategic decision-making that not only strengthens the organization's legitimacy but also contributes to the creation of long-term value (Mayer et al., 2012; Bresciani et al., 2021).

Contemporary models of intelligent management are largely based on emotional intelligence, collective intelligence, and ethical reasoning (Goleman et al., 2013; Woolley et al., 2015). Additionally, the convergence of neuroscience and management sciences has significantly enriched the understanding of decision-making processes, stress regulation, motivation, and cognitive biases. Intelligent management involves the ability to switch between analytical and empathetic neural networks, enabling more flexible and human-centered leadership. This neurobiological perspective is essential for understanding how leaders can develop self-awareness, empathy, and adaptability — qualities that are crucial in multigenerational work environments (Boyatzis et al., 2014).

As a result, intelligent management is not limited to analytical capabilities but represents a multidimensional competence encompassing emotional, cognitive, ethical, and technological aspects. As the work environment becomes increasingly diverse and digitally interconnected, the ability to manage intelligently in both multigenerational and technological contexts become a key factor in achieving sustainable success.

This is precisely why there is an urgent need to integrate the concept of intelligent management with the achievements of neuroscience, in order to respond more effectively to the challenges faced by modern organizations (Aithal & Satpathy, 2024). Neuroscience provides tools and knowledge that enable a deeper understanding of decision-making mechanisms, learning processes, motivation, adaptation, and stress response in the workplace (Daw & Shohamy, 2008). The integration of these findings into management practice makes it possible to develop more conscious, empathetic, and flexible leadership. This not only optimizes internal processes but also helps shape a work environment that fosters the development of individual and team potential – regardless of generational affiliation. In doing so, it becomes possible to build future-ready organizations that are resilient, innovative, and genuinely human-centered.

Neuroscience, as an interdisciplinary field, studies the functioning of the nervous system at various levels – from the molecular level to complex cognitive and behavioral processes. Modern neuroscience develops in close connection with mathematical theories, computer science, and computational modeling, allowing for the creation of coherent theoretical frameworks to understand how the brain works (Kaygısız, 2022).

In recent years, particular attention has been paid to the need for developing consistent neuroscientific theories that can integrate the vast datasets generated by modern neuroimaging and neuroinformatics technologies. Theory in neuroscience serves three primary roles: descriptive, mechanistic, and normative. Each corresponds to a different level of abstraction – from describing observed phenomena, to explaining mechanisms, and ultimately to formulating rules that enable prediction and control of neural processes (Levenstein et al., 2020).

Contemporary management approaches increasingly incorporate findings from neuroscience research, leading to the development of so-called brain-inspired intelligent management. The core idea is to use knowledge about how the human brain functions to design more adaptive, flexible, and effective management systems and decision-making processes (Cucino et al., 2022).

The application of neuroscience in management can contribute to a deeper understanding of intelligence in the organizational context. Knowledge about how the brain functions may lead to more precise definitions of intelligence and better-tailored tools for assessing employee competencies, taking into account the context of specific roles and tasks (Becker et al., 2015). Neuroscience can also significantly support talent management by identifying employee motivation, engagement, and

development mechanisms. The integration of neuroscience with HR policies may enhance the effectiveness of human capital management strategies (Agrawal & Shree, 2021). There are also intelligent economic forecasting systems based on neural mechanisms that simulate how the brain adapts to changing environments. As a result, neuroscience-inspired structures can predict economic changes using minimal input data (Mengov & Nenov, 2020).

A broader look at the relationship between neuroscience and artificial intelligence — a key component of intelligent management – reveals that many contemporary AI algorithms have been directly inspired by the brain's cognitive structures and processes. An example of this is neural networks, which mimic cortical structures and utilize learning mechanisms similar to synaptic plasticity (Hassabis et al., 2017). Neuroscience also plays a significant role in the development of modern AI-based management systems, such as working memory models, decision-making systems, and the analysis of large organizational data sets (Macpherson et al., 2021).

Various neuroscience techniques and tools are used in intelligent management. Table 1 presents eight of the most relevant ones from the perspective of implementing intelligent management processes.

Table 1. Neuroscience tools and techniques used in intelligent management

Tool / Technique	Description	Application in Intelligent Management
Neuroleadership	Application of neuroscience knowledge to enhance leadership competencies and optimize human resource management. It draws on research on brain functioning to better understand decision-making, motivation, empathy, stress regulation, and effective communication in organizations.	Supports leadership development, improves emotional intelligence, reduces stress, and facilitates organizational change.
Neuromarketing	A field that uses neuroscience techniques to analyze consumer responses to advertisements, products, and sales strategies. Neuromarketing research relies on methods such as EEG, fMRI, and eye-tracking to identify which stimuli most influence purchasing decisions.	Enhances marketing effectiveness by aligning strategies with subconscious consumer responses; supports data-driven decision-making in sales and product design.
Neuroeconomics	An interdisciplinary field combining neuroscience, economics, and psychology to study the mechanisms behind economic decision-making. It analyzes how emotional, cognitive, and neurological factors influence financial choices and market behaviors.	Supports strategic and financial decision-making, improves understanding of risk perception and consumer behavior, and enhances behavioral forecasting.
Neuroadaptive DSS	Technologies that use neurophysiological data (e.g., EEG, stress measurements) to optimize decision-making processes. These systems adapt to the user by analyzing their responses and supporting accurate, real-time decision-making.	Enhances managerial decision-making under pressure, personalizes support systems, and improves performance in complex environments.
Neuroeducation	The application of neuroscience knowledge to improve teaching and learning methods. It explores how the brain processes, retains, and engages with information to adapt educational systems to natural cognitive mechanisms.	Enhances employee training and development, supports personalized learning strategies, and improves knowledge retention in organizational contexts.

Neuroethics	A field that examines the ethical, legal, and social implications of using neuroscience, particularly in relation to manipulation of the human brain, privacy, and influence on decision-making. It also addresses issues of moral responsibility and the impact of technology on individual autonomy.	Guides the ethical implementation of neuro-based technologies in organizations, supports responsible innovation, and protects individual rights in data-driven environments.
Neurofeedback	A technique that enables conscious control of brain activity through real-time feedback. Users can learn to regulate their mental states, such as reducing stress, improving focus, or enhancing creativity.	Supports mental well-being, increases productivity, improves cognitive performance, and enhances leadership effectiveness.
Neural Networks	Artificial intelligence systems inspired by the structure and functioning of the human brain. They are used to analyze large data sets, recognize patterns, and make decisions based on self-learning algorithms.	Enables predictive analytics, enhances strategic planning, automates complex tasks, and supports data-driven decision-making.

Source: own elaboration based on Antonopoulou, 2024; Abou Hashis, 2024; Bratinau & Staneiu, 2024; Grubov et al., 2024; Shahmoradi et al., 2019; Fafrowicz et al., 2012; Vincent, 2018; Shahmoradi et al., 2019; Yue et al., 2020.

The use of neuroscience tools in intelligent management opens new opportunities in decision-making, team leadership, data analysis, and the optimization of organizational processes. Integrating knowledge about human brain functioning with modern technologies (such as artificial neural networks or neuroadaptive systems) enables the development of solutions more tailored to user needs, thereby increasing the efficiency and flexibility of management (Radtke Caneppele et al., 2022). These tools support, among other things, better understanding of employee behavior, predicting consumer responses, and fostering leadership competency development.

At the same time, it is important to emphasize that the growing role of neuroscience in management calls for the maintenance of high ethical standards. Technologies such as neurofeedback, EEG analysis, or the application of artificial intelligence in workplace environments require not only precise regulations but also greater awareness among management regarding their responsible use (Khaneja & Arora, 2024). Further research in this area should focus both on verifying the effectiveness of individual tools and on developing ethical frameworks for their implementation in organizational contexts.

3. METHODOLOGY

In the theoretical background, the concepts of intelligent management and neuroscience were presented. However, the main objective of this paper is to emphasize the perspective of these phenomena from the point of view of Generations X, Y, and Z – that is, how individuals belonging to each generation perceive the potential for using neuroscience tools and techniques in intelligent management processes.

To achieve the research objective and fill the identified research gap – the lack of a multigenerational perspective in this area – individuals from Generation X (born in 1965 – 1980), Generation Y (born in 1981 – 1996), and Generation Z (born in 1997 – 2012) were selected. This choice is justified by the fact that representatives of these generations are currently active in the labor market.

Based on comprehensive literature studies related to intelligent management and neuroscience tools and techniques – particularly neuroleadership, neuromarketing, neuroeconomics, neuroadaptive decision support systems (DSS), neuroeducation, neuroethics, neurofeedback, and neural networks – a quantitative survey in the form of a questionnaire was developed. The questionnaire included 15 main questions using a Likert-type scale, as well as a confidential section (including questions on gender and generational affiliation). A pilot study was conducted with a sample of 10 participants to eliminate any ambiguities and ensure that respondents clearly understood all questions.

In the first quarter of 2025, the main study was conducted among Polish participants using the CAWI method (Computer-Assisted Web Interviewing – an online survey distributed via a link). The condition

for participation in the study was the declaration of birth between 1965 and 2012 – confirming inclusion in Generation X, Y, or Z (Fig. 1).

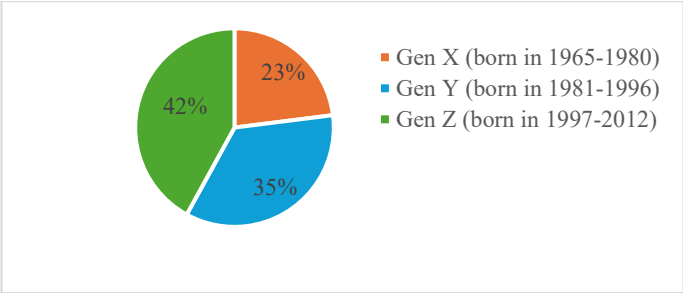


Figure 1. Distribution of respondents by generation.
Source: own elaboration.

The study was conducted on a sample of 423 randomly selected individuals, with a 6% margin of error and the use of positional measures, which constitutes an appropriate sample size. The sample included 60% men and 40% women. Regarding educational background, 34% of respondents held a degree in Logistics, 26% in Management, 20% in other fields, 10% in Finance and Accounting, and the remaining participants had studied Administration or Economics. Nearly 90% of respondents are professionally active, holding positions as specialists (35%), managers (17%), administrative staff (9%), or other roles (39%).

4. RESULTS

In the conducted study, basic descriptive statistics were initially applied. These revealed that respondents, when presented with the following definition of neuroscience – *Neuroscience is the study of the structure and functioning of the nervous system, with particular focus on the brain. It combines knowledge from various fields such as biology, psychology, medicine, physics, chemistry, computer science, and engineering to understand how cognitive, emotional, and behavioral processes work* – indicated that neuroscience may have a significant (60%) or very significant (34%) impact on intelligent management.

Respondents also believed that neuroscience is currently being applied in intelligent management to a large extent (48%) or to a very large extent (10%). However, 18% of respondents felt it is applied only to a small extent, and 2% believed it is not used at all.

When asked about the listed neuroscience tools and techniques – neuroleadership, neuromarketing, neuroeconomics, neuroadaptive decision support systems (DSS), neuroeducation, neuroethics, neurofeedback, and neural networks – the most well-known were neuromarketing and neural networks, while the least familiar were neuroethics and neurofeedback. The remaining tools received relatively balanced responses in terms of recognition.

At the same time, all the listed neuroscience tools and techniques were recognized by the respondents as potentially useful in supporting intelligent management from a managerial perspective. They were assessed as useful or very useful.

Respondents were also asked which neuroscience tools and techniques they would use in management processes if they were in managerial roles (Fig. 2).

In this part of the study, respondents most frequently indicated neuromarketing, neuroleadership, neuroeducation, and neural networks as the neuroscience tools and techniques they would be most likely to use in managerial roles. The least frequently chosen was neuroethics.

A total of 89% of respondents confirmed that neuroscience tools and techniques should be further developed in the future to better support intelligent management. Similarly, 91% of participants believe that within the next 10 years, the use of neuroscience in management processes will increase significantly.

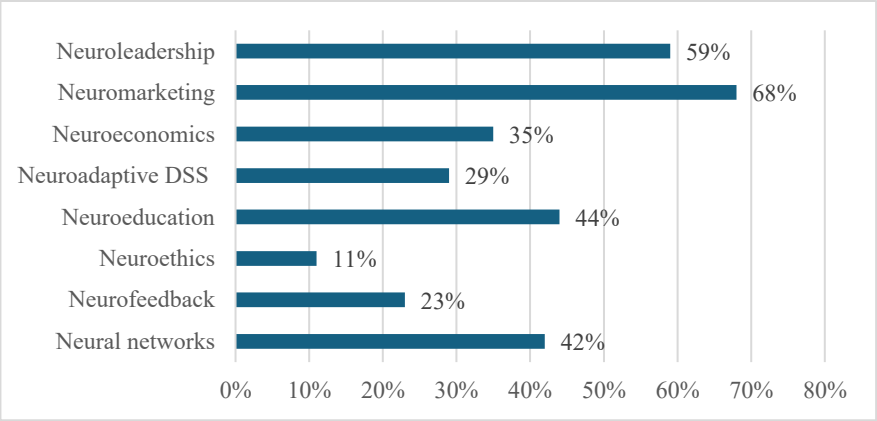


Figure 2. Preferred neuroscience tools and techniques for use in management
Source: own elaboration.

The above descriptive statistics confirm the positive perception of neuroscience applications in intelligent management. In the next phase of the study, the generational perspective in this area was examined.

Using the Mann-Whitney U test (a nonparametric test for assessing differences in central tendency), comparisons were made between two independent groups – in this case, representatives of Generations X, Y, and Z. The null hypothesis in this test assumes that the samples come from the same population (i.e., there are no significant differences between them), while the alternative hypothesis assumes that the compared samples come from different populations (i.e., they differ significantly).

The results of the Mann-Whitney U test verifying how each generation evaluated the potential of neuroscience tools and techniques to support intelligent management are presented in Table 2.

Table 2. Evaluation of the potential support of neuroscience tools and techniques for intelligent management by generation

	Gen X / Gen Y		Gen X / Gen Z		Gen Y / Gen Z	
Variable	**Z**	**p**	**Z**	**p**	**Z**	**p**
Neuroleadership - a neuroscience-based approach to leadership	0.544	0.586	0.339	0.734	–0.249	0.804
Neuromarketing - a technique that examines consumer reactions to products and advertisements	–2.373	0.018	–1.337	0.181	1.157	0.247
Neuroeconomics - a methodology for studying decision-making processes in economics and business	–1.097	0.272	–0.134	0.893	1.140	0.254
Neuroadaptive DSS - systems that use neurophysiological data to optimize managerial decisions	–1.673	0.094	–0.036	0.971	1.669	0.095
Neuroeducation - a brain-based approach to learning and development	–3.739	0.000	–1.356	0.175	2.844	0.004
Neuroethics - analysis of ethical aspects of using neuroscience in management	–0.664	0.506	0.130	0.897	1.022	0.307
Neurofeedback - technology that enables monitoring and training of brain activity	–0.909	0.363	–0.257	0.797	0.761	0.447

Neural networks - artificial computer systems inspired by the brain, used for data analysis and decision support	–1.575	0.115	–1.658	0.097	–0.018	0.986

Source: own elaboration.

Respondents from Generation Y rated the potential of neuromarketing to support modern management significantly higher than those from Generation X ($Z = –2.373$; $p = 0.018$). Additionally, Generation Y participants assessed the usefulness of neuroeducation in modern management significantly higher than both Generation X ($Z = –3.739$; $p < 0.001$) and Generation Z ($Z = 2.844$; $p = 0.004$). The remaining comparisons were not statistically significant.

Table 3 presents the results of the Mann-Whitney U test evaluating the perceived usefulness of key activities related to each neuroscience tool or technique for intelligent management, depending on the respondents' generational affiliation.

Table 3. Evaluation of the usefulness of key activities related to each neuroscience tool/technique for intelligent management by generation

	Gen X / Gen Y		**Gen X / Gen Z**		**Gen Y / Gen Z**	
Variable	**Z**	**p**	**Z**	**p**	**Z**	**p**
Neuroleadership						
improving leadership skills	–0.139	0.889	0.198	0.843	0.410	0.682
team management based on neurobiological mechanisms	–0.804	0.422	–0.321	0.748	0.528	0.597
reducing stress and making better decisions	–3.356	0.001	–2.398	0.017	0.991	0.322
Neuromarketing						
optimizing advertising campaigns	–1.030	0.303	-0.030	0.976	1.119	0.263
analyzing consumer preferences	–2.087	0.037	–1.766	0.077	0.315	0.752
designing more effective customer interactions	–3.100	0.002	–2.004	0.045	1.252	0.211
Neuroeconomics						
better understanding of investor, customer and manager behavior	–0.457	0.648	0.384	0.701	1.063	0.288
optimization of business strategies based on decision neurobiology	–0.509	0.610	0.871	0.384	1.524	0.128
analysis of risk and decision-making in business	–1.887	0.059	–1.354	0.176	0.612	0.541
Neuroadaptive decision support systems (DSS)						
optimization of managerial decisions	0.708	0.479	3.088	0.002	3.114	0.002
improvement of work efficiency in dynamic environments	0.377	0.706	2.331	0.020	2.405	0.016
automation of decision-making processes in organizations	0.344	0.731	2.132	0.033	2.493	0.013

Neuroeducation						
creating more effective training and education programs for employees	–1.456	0.145	–0.435	0.664	1.001	0.317
increasing the effectiveness of learning through methods adapted to the functioning of the brain	–3.104	0.002	–1.261	0.207	2.026	0.043
personalizing teaching methods in organizations	–6.186	0.000	–4.152	0.000	2.532	0.011
Neuroethics						
protection against abuse in neuromarketing	–0.313	0.755	–0.046	0.964	0.232	0.817
regulations regarding the use of neurodata in recruitment or business	0.173	0.862	1.069	0.285	0.990	0.322
analysis of the ethical boundaries of using neuroscience in management	–2.626	0.009	–1.961	0.050	0.579	0.563
Neurofeedback						
concentration training for managers	–2.293	0.022	–0.052	0.959	2.106	0.035
improving mental resilience and adaptability at work	–3.770	0.000	–3.383	0.001	0.124	0.901
reducing stress levels	–4.537	0.000	–4.102	0.000	0.466	0.641
Neural networks						
business process automation	–1.680	0.093	–0.283	0.777	1.420	0.155
data analysis in management	–3.771	0.000	–1.271	0.204	3.055	0.002
supporting managerial decisions by forecasting trends and optimizing business strategies	–2.507	0.012	–0.515	0.606	2.556	0.011

Source: own elaboration.

Respondents from Generation X rated the usefulness of neuroleadership activities in intelligent management – particularly in terms of stress reduction and making better decisions – significantly lower than those from Generation Y ($Z = –3.3561$; $p = 0.001$) and Generation Z ($Z = –2.398$; $p = 0.017$). A similar pattern was observed for neuromarketing, specifically in designing more effective customer interactions ($Z = –3.100$; $p = 0.002$ and $Z = –2.004$; $p = 0.045$), as well as in the personalization of learning methods within organizations (neuroeducation), ethical analysis of the boundaries of neuroscience applications in management (neuroethics), enhancement of psychological resilience and adaptability at work, and stress reduction (neurofeedback).

Generation X also rated the usefulness of consumer preference analysis (neuromarketing) lower compared to Generation Y ($Z = –2.087$; $p = 0.037$). Similar observations apply to increasing learning effectiveness through brain-based methods (neuroeducation) ($Z = –3.104$; $p = 0.002$), as well as the perceived usefulness of data analysis in management and decision-making support through trend forecasting and business strategy optimization (neural networks), and concentration training for managers (neurofeedback).

Compared to Generations X and Y, Generation Z rated significantly higher the optimization of managerial decisions and automation of decision-making processes in organizations (neuroadaptive DSS), as well as the personalization of learning methods in organizations (neuroeducation).

Generation Z also rated higher than Generation Y the usefulness of decision-making support through trend forecasting and strategy optimization ($Z = 2.556$; $p = 0.011$) and data analysis in management (neural networks) ($Z = 3.055$; $p = 0.002$), concentration training for managers (neurofeedback) ($Z = 2.106$; $p = 0.035$), and increasing learning effectiveness through brain-based methods (neuroeducation) ($Z = 2.026$; $p = 0.043$).

In the final stage of the study, a test assessing the significance of differences between structural indicators (percentages) of awareness of neuroscience tools and techniques across Generations X, Y, and Z was conducted. The results are presented in Table 4.

Table 4. Results of the test comparing structural indicators of neuroscience tool and technique awareness by generation

	Gen X / Gen Y		Gen X / Gen Z		Gen Y / Gen Z	
Tool / Technique	**U**	**p**	**U**	**p**	**U**	**p**
Neuroleadership	2.427	0.008	3.627	0.000	1.367	0.086
Neuromarketing	–1.699	0.045	–3.904	0.000	–2.398	0.008
Neuroeconomics	3.626	0.000	2.653	0.004	–1.224	0.110
Neuroadaptive DSS	1.445	0.074	2.557	0.005	1.246	0.106
Neuroeducation	1.566	0.059	–0.144	0.443	–1.988	0.023
Neuroethics	1.242	0.107	–0.813	0.208	–2.355	0.009
Neurofeedback	1.931	0.027	0.564	0.286	–1.580	0.057
Neural networks	0.448	0.327	0.308	0.379	–0.171	0.432

Source: own elaboration.

The vast majority of respondents from Generation Z identified the concept of neuromarketing. This result is significantly higher compared to respondents from Generation Y ($U = –2.398$; $p = 0.008$) and Generation X ($U = –3.904$; $p < 0.001$). However, a large majority of Generation Y respondents also recognized the term, and their result was significantly higher than that of Generation X ($U = –1.699$; $p = 0.045$). Generation Z also demonstrated significantly greater awareness of the terms neuroeducation and neuroethics compared to Generation Y ($U = –1.988$; $p = 0.023$ and $U = –2.355$; $p = 0.009$, respectively).

A significantly higher percentage of Generation X respondents identified the concept of neuroleadership compared to those from Generations Y ($U = 2.427$; $p = 0.008$) and Z ($U = 3.627$; $p = 0.000$). A similar pattern was observed for the identification of neuroeconomics ($U = 3.626$; $p = 0.000$ and $U = 2.653$; $p = 0.004$, respectively). Generation X also showed greater familiarity with the term neurofeedback compared to Generation Y ($U = 1.931$; $p = 0.027$), and rated neuroadaptive DSS more highly than Generation Z ($U = 2.557$; $p = 0.005$).

The results of the test comparing structural indicators of the willingness to use selected neuroscience tools and techniques in intelligent management, depending on generational affiliation, are presented in Table 5.

Table 5. Results of the structural indicator comparison test on the willingness to use selected neuroscience tools and techniques in intelligent management by generation

	Gen X / Gen Y		Gen X / Gen Z		Gen Y / Gen Z	
Tool / Technique	**U**	**p**	**U**	**p**	**U**	**p**
Neuroleadership	–0.878	0.190	–0.376	0.353	0.590	0.278
Neuroeducation	–1.520	0.064	–2.896	0.002	–1.564	0.059
Neural networks	–0.748	0.227	1.136	0.128	2.160	0.015
Neurofeedback	–1.966	0.025	–3.396	0.000	–1.753	0.040

Neuromarketing	1.507	0.066	2.352	0.009	0.968	0.167
Neuroeconomics	–1.282	0.100	0.209	0.417	1.739	0.041
Neuroethics	0.942	0.173	–1.673	0.047	–2.944	0.002
Neuroadaptive DSS	1.295	0.098	3.183	0.001	2.077	0.019

Source: own elaboration.

Respondents from Generation Z indicated significantly more frequently than those from Generation X the potential use of neuroeducation (U = –2.896; p = 0.002), neurofeedback (U = –3.396; p = 0.000), and neuroethics (U = –1.673; p = 0.047) in management. At the same time, they indicated significantly less frequently than Generation Y respondents the potential use of neural networks (U = 2.160; p = 0.015), neuroeconomics (U = 1.739; p = 0.041), and neuroadaptive decision support systems (DSS). They also less frequently pointed to the potential use of neuromarketing (U = 2.352; p = 0.009) and neuroadaptive DSS (U = 3.183; p = 0.001) in management compared to Generation X.

Respondents from Generation X indicated significantly more frequently than those from Generation Y the possibility of using neurofeedback in management (U = –1.966; p = 0.025), while at the same time indicating it significantly less frequently than respondents from Generation Z (U = –1.753; p = 0.040).

5. DISCUSSION

The conducted study confirms that neuroscience-based tools and techniques are perceived as valuable components of intelligent management, particularly in the context of managing a multigenerational workforce. The analysis revealed statistically significant differences in how Generations X, Y, and Z perceive and intend to use specific neuroscience tools, suggesting generationally driven variability in openness, familiarity, and expectations regarding innovation in management.

Generation X, while more familiar with traditional concepts such as neuroleadership and neuroeconomics, appeared more skeptical toward emerging tools like neurofeedback and neuroadaptive decision-support systems. Generation Y expressed the highest levels of support for neuroeducation and neuromarketing, highlighting their focus on professional development and customer-centered approaches. Generation Z, the youngest group, showed the greatest openness to neuroethics, neurofeedback, and decision automation tools, reflecting their comfort with technology and interest in well-being and ethics.

These results align with broader literature on generational traits in the workplace – where older generations prioritize structured, proven methods, while younger ones are more inclined toward innovation, flexibility, and personalization. Importantly, the tools assessed in this study – particularly neuroeducation, neural networks, and neuroadaptive DSS – are closely linked to the emerging need for cognitive adaptability and rapid learning in dynamic business environments.

Moreover, the generational differences observed suggest that universal implementation strategies for neuroscience-based tools may not be equally effective across all age groups. For example, training programs based on neuroeducation may yield better outcomes among younger employees, whereas leadership development initiatives may resonate more with Generation X when framed through the lens of neuroleadership and emotional intelligence.

Finally, the ethical aspect of neuroscience applications – particularly in areas such as neuromarketing and neurodata usage – was more emphasized by Generation Z, signaling a rising awareness of privacy and responsible innovation. These findings underscore the importance of integrating ethical frameworks alongside technological advancements.

6. CONCLUSION

This study provides empirical evidence supporting the relevance of neuroscience-informed intelligent management in the era of multigenerational organizations. The key finding is that while

neuroscience tools are generally perceived as useful, the degree of awareness, perceived effectiveness, and willingness to use them differs significantly between generations.

From a practical perspective, this means that organizations aiming to implement such tools should adopt tailored approaches that reflect the generational composition of their teams. Customization of communication, training, and application strategies can improve adoption and enhance organizational outcomes.

The research contributes to theoretical discussions by introducing a generational lens into the study of intelligent management. It bridges the gap between neuroscience and management theory and highlights the need to factor in demographic variables when designing future-oriented managerial solutions.

Limitations of this study include its national scope (limited to Polish respondents) and reliance on self-reported data. Future studies should explore cross-cultural comparisons and apply mixed-methods approaches to deepen the understanding of generational dynamics and neuroscience adoption in the workplace.

Ultimately, the study supports the notion that the integration of neuroscience into intelligent management has the potential to foster more adaptive, empathetic, and effective organizations — provided that these innovations are implemented in a way that aligns with generational expectations and ethical standards.

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USE OF EYE-TRACKING IN THE DESIGN AND OPTIMISATION OF TRAINING MATERIALS FOR FUTURE DRIVERS

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ABSTRACT

Purpose: *This study examines the effectiveness of multimodal educational materials for driver training, focusing on how users perceive and process road signs. The research explores the impact of visual design, text placement, and the integration of multimedia elements on comprehension and retention.*

Need for the study: *With the increasing use of digital learning in driver education, optimising materials for better knowledge retention and practical application is essential. Prior studies (Shimazaki et al., 2017; Zhang et al., 2022) show that multimodal content enhances learning, but the ideal design for driver training remains underexplored.*

Methodology: *Eye-tracking technology was used to analyse gaze patterns and attention distribution while participants interacted with training materials. Fixation duration, saccadic movements, and heatmaps were evaluated to identify key engagement areas. The study tested different layouts, emphasising variations in text structure, image prominence, and highlighted sections.*

Findings: *Results indicate that users prioritise visual elements like road signs before engaging with text. Highlighted content (bold, colour-coded text) significantly improves comprehension. Findings align with research by (Petzoldt et al., 2013; Makowska, 2021), emphasising the role of structured visual cues in learning.*

Practical Implications: *Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged.*

Keywords: multimodality, traffic sign perception, eye tracking, training materials, visual communication, information processing, learning process

Jel codes: I21, C80, O32

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1. INTRODUCTION

Good, multi-faceted driver preparation - encompassing theoretical knowledge and practical skills - is an issue of global importance (Atchinson, n.d.; Sethi et al., 2007). Educational systems and examination forms vary from country to country, as evidenced by numerous studies and regulations (Simpson, 2003; Shimazaki et al., 2017; Rodwell et al., 2018; Elvebakk et al., 2020). The requirements for obtaining a driving licence, both in terms of candidate preparation and examination, are essential in shaping road safety.

In the EU countries, there are high requirements for obtaining a driving licence, which include a medical examination, completing a certain number of hours of a course and passing a driving test. In Poland, the examination consists of a theoretical part, where the candidate must obtain at least 68 points out of a possible 74, and a practical part, which includes driving on a manoeuvring area and in city traffic (*How long does a driving licence course take in Poland.*, 2022; *Driving test in Poland - the course.*, 2025). In Denmark, in addition to 28 hours of theory and 7 hours of first aid course, the candidate must receive training in slippery driving and driving in difficult conditions, including slalom driving in reverse (Olito, 2018). In Germany, 21 hours of theory and 12 hours of driving under special conditions, such as night driving, are required for category B. In some countries, such as France, there is a requirement to drive 3,000 kilometres under the supervision of an instructor before being certified (*Driving tests around the world (2022)*, 2022). The level of difficulty of the examinations also varies in Asia - in Japan they are considered among the most difficult (pass rate of around 35%), while in India or Indonesia the procedures are much less demanding (Olito, 2018; *Driving tests around the world (2022)*, 2022).

Regardless of the region of the world, the increase in the number of vehicles and the volume of traffic make proper driver preparation a key issue. This is particularly true regarding knowledge of road rules and the formation of correct habits and behaviour. European data show that up to 14% of fatal accidents involving young drivers (18 – 24 years) may be due to inadequate training and bravado (Rodwell et al., 2018; Martín-delosReyes et al., 2019). For example, the pass rate statistics for the theoretical exam in Poland in 2020 fluctuated around 57%, in Germany it was around 70%, and in the UK it even dropped to 48% (Driver training and licence acquisition in Germany., 2013; *Driving tests around the world (2022)*, 2022; Theory Car Pass Rates by Gender and Age of Candidate: Great Britain., 2025).

One possible explanation for this situation is the quality and delivery of knowledge. The development of training materials, including the growing popularity of digital resources and e-learning platforms, means that videos, animations or interactive materials increasingly supplement traditional printed textbooks. (*A free book for learning theory for driving licence.*, 2022; *Free digital theory driving course – low-quality*, 2022; *Example of a free driving theory course - demo version*, 2023; *Example of a theory textbook for a driving licence*, 2024; *Example of e-learning platform for learning the theory of driving licence*, 2025). The COVID-19 pandemic has further accelerated this trend, forcing the search for more effective forms of distance learning (Saha et al., 2022). As studies have shown, multimodal methods (e.g. text, video, interactive exercises) can significantly reduce reaction times to potential hazards (Shimazaki et al., 2017), and drivers trained in this way were better able to identify dangerous situations on the road (Horswill et al., 2021).

However, multimodality alone does not guarantee effective learning – graphic design, logical positioning of elements and appropriate narration are also crucial (Leszkowicz, 2012). Therefore, the presented article aims to demonstrate the usefulness of modern physiological measurement methods (eye tracking, facereading) for studying the effectiveness of the reception of digital training materials. The research presented in the following section (Chapter 4) focuses on how different content layouts and forms of presentation affect the audience's attention span and the emotions evoked. The article also presents the potential of such methods in improving educational materials, including those related to traffic regulations.

In addition to physiological measurement methods, the future development of driver education materials may increasingly rely on artificial intelligence (AI). AI-based systems have the potential to support both the design and evaluation of educational content by dynamically adapting materials to individual learner profiles, analyzing performance patterns, and suggesting optimizations based on real-time data et al., 2015). Intelligent learning environments, integrating eye-tracking data and AI

algorithms, could personalize training paths by identifying areas where learners struggle and adjusting the complexity or form of presented content accordingly. Furthermore, AI can contribute to automating the evaluation of visual design elements, such as layout consistency, information hierarchy, and clarity of multimodal materials, thus enhancing their educational effectiveness (Chen, 2010; Zhang et al., 2022b). Considering the dynamic development of digital technologies and the growing demand for individualized, high-quality learning experiences, the integration of AI tools into the creation and refinement of driver training materials appears to be a promising direction for future research and practical applications.

The following chapters provide an overview of information design and visualisation issues (Chapter 2) and describe the data used, measurement techniques and research methods (Chapter 3). Chapter 4 presents the experiment's results, together with a discussion, and the whole is summarised with conclusions arising from the analyses. The results can contribute to developing more effective and learner-friendly educational tools, which will translate into improved road safety.

2. LITERATURE REVIEW

Creating educational materials for future drivers requires a professional approach to effectively convey knowledge without excessive cognitive load (Leszkowicz, 2012; Sorapure, 2019; Makowska, 2021; Mateja et al., 2025). Developing such materials should be based on scientifically validated pedagogical principles and consider cognitive psychology insights to optimise learning outcomes. One of the most crucial aspects is structured learning frameworks that progressively build knowledge and skills, ensuring that learners are neither overwhelmed by excessive information nor discouraged by a lack of engaging content.

The most common approach is to use multi-modal materials – combining text, graphics, video and often voice-over narration (Goliasz, 2009; Sorapure, 2019; Makowska, 2021; Pei et al., 2022). This multi-modal approach aligns with Mayer's Cognitive Theory of Multimedia Learning, which suggests that people learn more effectively when information is presented through visual and auditory channels rather than relying on one modality alone. By integrating different media formats, educational materials can cater to a broader range of learners with varying preferences and cognitive styles (Ho & Tai, 2020; Sorapure, 2019).

The key here is to maintain content consistency, minimise distracting elements, and appropriate selection and placement of information and logical integration (Shen et al., 2019; Pei et al., 2022). Studies have shown that learners retain information more effectively when educational content follows a clear, structured layout with well-defined sections and transitions (Shepherd, 2018). For example, Makowska and Sorapure emphasise that keeping text to the bare minimum, supported by highlighting (bold, colour, underlining) and clear graphics, increases the accessibility of the message (Sorapure, 2019; Makowska, 2021). This method allows learners to focus on essential information without cognitive overload. At the same time, Goliasz, Ho and Tai point out that adding voice narration in video materials helps the listener focus on the image and understand the message, reinforcing learning outcomes (Goliasz, 2009; Ho & Tai, 2020).

In the design process, it is important to avoid splitting attention - e.g., by unnecessarily dividing related content into different slides or arranging text and images too tightly (Leszkowicz, 2012; Yamada & Kobayashi, 2018; Shen et al., 2019; Heaton et al., 2020; Makowska, 2021). Instead, the aim should be to create a single, coherent message in which text, video and illustrations complement each other (Goliasz, 2009; Leszkowicz, 2012; Shepherd, 2018). This ensures that the cognitive load remains manageable and does not exceed the learner's working memory capacity, which is crucial for effective knowledge retention. The problem of excessive cognitive load (so-called cognitive fatigue) occurs when material is overloaded with too many elements at once (Ho & Tai, 2020; Pei et al., 2022; Mateja et al., 2025). For example, simultaneously using multiple animations, interactive elements, and detailed text can overwhelm the learner rather than support comprehension.

Careful selection of content, appropriate placement of graphics and videos, and skilful accentuation of the most important parts facilitate learning (Shepherd, 2018; Sorapure, 2019; Makowska, 2021; Pei et al., 2022). Research has shown that chunking information into small, manageable units improves comprehension and recall. By dividing instructional content into shorter, focused sections with clear

objectives, learners can process information more efficiently and retain key concepts (*Free digital theory driving course - low-quality*, 2022; Wildfeuer & Stamenković, 2022).

Different categories of educational aids are available on the market: from paper textbooks, electronic books, and static graphics to advanced e-learning platforms with tests, videos, and instructor interaction(Benta et al., 2015; *A free book for learning theory for driving licence.*, 2022; *Free digital theory driving course – low-quality*, 2022; *Example of a free driving theory course - demo version*, 2023; *Example of a theory textbook for a driving licence*, 2024). Traditional textbooks provide a fundamental knowledge base, while e-learning platforms offer dynamic and interactive learning experiences. Blended learning approaches, which combine digital and traditional materials, have been found to be particularly effective in driver education as they allow for self-paced learning and reinforcement of key concepts through repetition. (Heaton et al., 2020; *Example of e-learning platform for learning the theory of driving licence*, 2025).

Free materials are sometimes truncated or low-quality (e.g., unclear graphics or lack of knowledge tests) (*Free digital theory driving course - low-quality*, 2022). In contrast, paid platforms often provide well-structured, high-quality multimedia content that positively impacts learning effectiveness ((*Example of a free driving theory course - demo version*, 2023; *Example of e-learning platform for learning the theory of driving licence*, 2025). High-quality multimedia content often includes real-life driving scenarios, interactive simulations, and gamification elements that enhance engagement and motivation (Chen, 2010; Zhang et al., 2022).

To verify the effectiveness of such materials, eye trackers are increasingly being used to track which elements attract the eye (heat maps) and how the learner combines stimuli into a single message (Sviličić, 2010; Mealha et al., 2012). Research by Zhang et al. (Zhang et al., 2022) showed that a video showing the gaze path of an experienced driver increases young learners' ability to perceive hazards by guiding their visual attention to critical areas of the driving environment. In contrast, Petzoldt et al. (Petzoldt et al., 2013) proved that animations better support the response to dangerous situations than static images. By using animations to depict complex traffic scenarios, learners can better understand potential hazards and appropriate responses in real-world driving situations.

This analysis can be complemented by the use of face reading techniques, which record facial expressions and emotions while using materials (Hildebrandt et al., 2015; Kostyra et al., 2016; Yu & Ko, 2017; van Bommel et al., 2020; Pichierri et al., 2021). These techniques provide insights into learner engagement and emotional responses to specific content elements, helping designers refine instructional materials to enhance motivation and reduce frustration. Emotional engagement plays a crucial role in learning; therefore, materials that evoke positive emotions, such as curiosity and excitement, tend to be more effective in retaining learner attention and promoting long-term knowledge retention (Hildebrandt et al., 2015).

Combining such measurement methods with thoughtful content design can create more engaging and effective driver training programmes, resulting in higher-quality education and road safety. Future advancements in adaptive learning technologies and artificial intelligence-driven content personalisation could further enhance the effectiveness of educational materials by tailoring instruction to individual learner needs, optimising learning pathways, and providing real-time feedback. These innovations have the potential to revolutionise driver education, making it more accessible, engaging, and impactful for learners worldwide.

3. METHODOLOGY

3.1. Participants

Fifty-two people participated in the survey, including 26 women and 26 men. They were studying, studying and working. The age of the subjects ranged from 17 to 57 years, with a mean age of 25.55 and a standard deviation of SD = 10.77. For men, the mean age was 26.92, SD = 8.61, and the mean age for women was 24.19, SD = 8.55. Of the total group, 22 subjects did not hold a driving licence (11 women and 11 men), and the rest had held a licence for varying lengths of time (15 women and 15 men). All subjects voluntarily participated in the study and gave their consent to the processing of personal data. Before the start of the test procedure, the participants were informed about the general course of the test procedure (without giving details) and the measuring equipment used.

The survey consisted of several stages. At the beginning, participants completed a pre-test questionnaire, including a metric and general questions linked to the specifics of the study. The following stages included training materials with different structures (content blocks) and different ways of distribution. The content was developed based on different ways of presenting information: text, graphics, and video. The first one concerned the presentation of material on traffic signs, the second one on issues related to crossing intersection rules, and the third one concerned the revision of traffic regulations. Each stage was concluded with a test to check the knowledge of the previously presented area. The tests' structure varied from single-choice to multiple-choice questions, marking the correct answers (e.g. indicating priority at junctions) and writing values in text boxes (e.g. justification of rules of the road at junctions).

The structures of the training materials considered in the study (multi-modal structures) are shown in Figure 1. They were developed along the lines of the existing materials for learning traffic rules listed in Section 2 of this study.

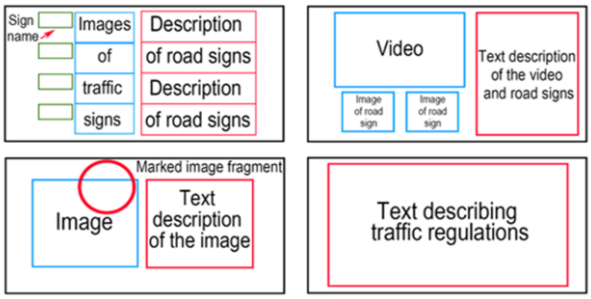


Figure 1: Structures of training digital materials used in the study
Source: own elaboration.

The study analysed how participants read and visually process multimodal materials that combine text, video and graphics in different configurations and structures. In particular, it was verified how participants visually scanned text distributed, for example, across a page, adjacent to graphics or near other blocks of text, but also in combination with video material.

In addition, the role of attention-getting elements (e.g., circular marks, arrows), which can facilitate tracking key pieces of content, was analysed. Finally, different material layouts were compared with the learning and memory effect, assessed in knowledge tests. In this way, it was possible to determine which combinations of forms and structures of content presentation best support the learning process and, consequently, could be applied in developing more effective learning tools.

3.3. Research Apparatus

The research was conducted using a combination of specialized hardware and software designed for detailed analysis of participants' visual attention. The primary device employed was the Tobii Pro X3-120 stationary eye tracker, a high-precision tool optimized for studies requiring detailed gaze data in controlled environments. The Tobii Pro X3-120 operates at a sampling rate of up to 120 Hz, which ensures a high temporal resolution suitable for capturing both fixation patterns and rapid saccadic movements. The system utilizes infrared light reflection off the cornea and pupil to determine the gaze point with high accuracy. The eye tracker was installed below the monitor, allowing for unobstructed observation of natural viewing behavior. The device's calibration process involved a standard 9-point procedure to ensure high precision in gaze data collection across the full screen area (*Tobii X3-120 Manual*, 2016).

Data acquisition and analysis were carried out using the iMotions research platform – a comprehensive software suite that integrates biometric sensors and facilitates the synchronization of eye-tracking data with stimulus presentation. iMotions enabled real-time recording of gaze patterns, automated detection of Areas of Interest (AOIs), and generation of various visualizations, including heatmaps, gaze plots, and fixation metrics (e.g., time to first fixation, total fixation duration, number of revisits) (*Imotions Software*, 2025).

3.4. Analysis of Measurement Data

The leading indicators in the eye tracking method are fixations and saccades. During fixation, the eye remains almost stationary, allowing the perception and processing of information from the stimulus being analysed. The opposite is saccades – rapid eye movements between successive fixation points, during which information is not absorbed (Makowska, 2021). From the raw eye movement data, fixation maps and heatmaps were generated. Heatmaps visually represent the duration of gaze on particular areas using a color scale, facilitating the identification of the most attention-attracting and neglected elements of the multimedia materials (Mealha et al., 2012; Makowska, 2021; Mateja et al., 2025).

An additional technique for eye-tracking analysis is in areas of interest (AOI), which researchers have designated as key sections of material. AOI analysis provides quantitative information about the number of people paying attention to a particular fragment and the time spent viewing it. These methods make it possible to accurately assess the effectiveness of visual material reception and the degree of attention (Makowska, 2021; Mateja et al., 2025).

In addition to qualitative visualizations, several quantitative eye-tracking metrics were analyzed (Skaramagkas et al., 2021; Azam et al., 2022; Pei et al., 2022b). *Fixation Count* – the total number of fixations made on a specific Area of Interest (AOI), reflecting how thoroughly an area was inspected. A higher number of fixations is often associated with either greater interest or increased complexity of the information. *Revisit Count* - the number of times an AOI was re-fixated after the gaze initially left it. Higher revisit counts can indicate cognitive difficulty, ambiguity of content, or its particular relevance for the user. *Time to First Fixation (TTFF)* - the time elapsed (in milliseconds) from the stimulus onset to the participant's first fixation on a given AOI. Lower TTFF values suggest that the element quickly attracted visual attention due to perceptual salience. *Dwell Time* – the total amount of time (in milliseconds) that a participant spent fixating within a particular AOI across all visits. Longer dwell times are interpreted as signs of deeper cognitive engagement or processing difficulty. *Duration of Average Fixation* – the mean duration of fixations within an AOI. Longer average fixation durations are typically associated with increased cognitive load or complexity of the viewed information.

In summary, eye-tracking methods such as fixation maps, heat maps, and AOI analysis provide detailed information about how multimedia materials are received, enabling the optimisation of their educational effectiveness.

4. RESULTS

Figure 2 shows the results obtained for four different combinations of digital materials. Each was analysed using the method of generating heat maps based on fixation maps, and areas of AOI interest were created for each. The analyses presented for each sign follow the following steps: First, the heat map generated for the material is analysed, and then the heat maps generated for it are analysed.

The first is an image of 4 graphics depicting the road signs together with their name in smaller text and a description as a paragraph. The distribution is shown in Figure 2 below. A heat map is shown in the exact figure opposite.

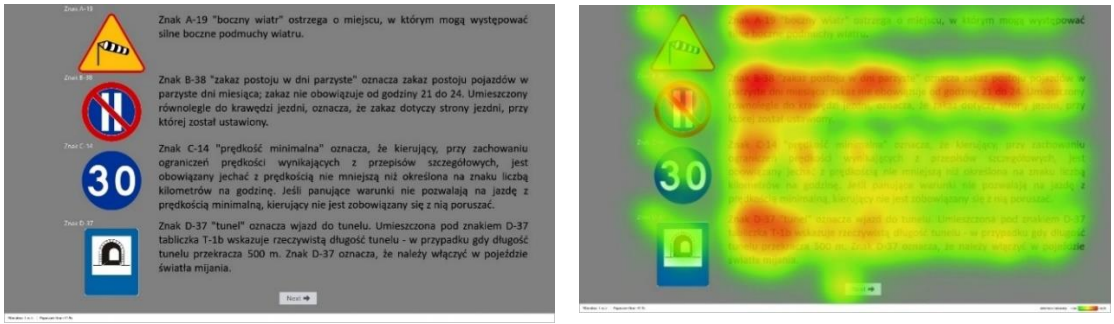


Figure 2: Structure of 4 road signs (left) and the obtained heat map

Source: own elaboration.

The strongest focus on the text occurred mainly on the description of sign B-38, which was analysed very closely; moreover, the sign attracted attention significantly compared to other signs. This may be

evidenced by this sign being unpopular in Poland. Moderate interest in the text occurs when describing signs C-14 and D-37 (third and fourth). The least interest in terms of text was shown for the description of sign A-19. A table with the description and statistics of the areas of interest generated for this stimulus is shown below in Table 1.

Table 1: Results obtained during the analysis of areas of interest - structure 1

Name of AOI	Revisit count	Fixation count	TTFF (ms)	Dwell time (ms)	Duration of average fixation (ms)
Sign A-19	1.11	2.75	4518.27	544.19	191.15
Name of sign A-19	0.35	1.82	2617.75	433.64	219.30
Text A-19	2.13	18.39	645.51	3442.02	177.44
Sign B-38	2.90	5.52	7724.71	1129.67	217.52
Name of sign B-38	0.59	2.29	18439.57	656.88	294.89
Text B-38	4.36	49.41	3533.18	9586.98	188.76
Sign C-14	0.97	2.41	21526.26	399.91	175.88
Name of sign C-14	0.32	1.59	27824.15	413.02	255.73
Text C-14	3.53	44.85	14582.82	8268.76	181.18
Sign D-37	1.24	2.89	34049.73	572.26	200.82
Name of sign D-37	0.32	1.96	50212.35	464.96	216.82
Text D-37	2.78	36.74	26856.27	6680.65	181.96

Source: own elaboration.

Sign A-19 (‘side wind’) had an average of 18.38 fixations on its description, suggesting a moderate interest in its textual explanation. The average fixation time was 177 ms, indicating that the respondents browsed vaguely. Respondents moderately returned to the text area after leaving it (about 2 times). The sign graphic attracted attention for an average of 544 ms viewing time. The averaged fixation time of 191.15 milliseconds is higher than for the text, suggesting a longer scanning time, but the number of fixations is small.

Sign B-38 (‘no parking on even days’) received many fixations (5.52 on average), the average fixation time was 217 ms, and the average dwell time in the area was 1130 ms. This means that the respondents focused the most attention on this sign of all. Additionally, the highest number of revisits of all the signs suggests that this was a beautiful object to them. The text describing the sign was also the longest analysed of all (9587ms), which may be because it was the longest text. The highest number of fixations, revisits, and mean fixation times for all sign texts indicates a high interest in sign-describing text. It may indicate a higher time to analyse and assimilate information from the area due to its length and the complexity of the definition of the sign itself.

Sign C-14 (‘minimum speed’) was noticed by respondents, but its name and its graphics did not arouse much interest (1.59 and 2.41 fixations). In contrast, its description was intensively read (44.85 fixations), making it the second most frequently analysed text describing the definition of the sign. It was also the second longest reading time for the sign description (8268 ms), which, together with the average time of a single fixation and its number, indicates that the text also required a longer focus to analyse it and assimilate the information. Respondents also returned to the text frequently, as evidenced by the high number of revisits (3.53).

The sign D-37 (‘tunnel’) attracted moderately high attention at the icon level (mean observation time of 572 ms), as did the number of fixations (2.89) and their duration (201 ms). Its textual description was analysed in average detail (36.73 fixations), as further evidenced by the short time of a single fixation (182 ms). The reading time of the text was a mere 6681 ms, which indicates that participants here already paid less attention to this cue than to the others. This is because this sign’s description was similar to the other sign on this digital material, but its text was scanned almost 3 seconds shorter.

Averaged times to first fixation in a given area (TTFF) indicate that the subjects scanned the entire material from top to bottom, one item at a time.

The second digital material described is the F-17 sign material, consisting of graphics, text, and two markings for the listed and described elements – a circular marking and an arrow, both in red. The digital material and heat map can be found in Figure 3. A table with an analysis of the areas of interest can be found in Table 2.



Figure 3: Structure of road sign F-17 and the obtained heat map
Source: own elaboration.

The heat map indicates that respondents paid the most attention to the F-17 sign, particularly the central part of the sign - the area with the red ellipse, which symbolises the end of the lane. The intense red spot means that participants' gaze stayed longer in this area, suggesting this was the key visual information. A smaller but clear focus of attention is also seen on the arrow indicating the end of the lane shown on the sign. This is consistent with the expected perceptual pattern: drivers first process traffic signs that directly influence their driving decisions. The explanatory text attracted attention on average compared to the sign itself; it can be seen that most parts are green, i.e. of lower interest.

Table 2: Results obtained during the analysis of areas of interest - structure 2

Name of AOI	Revisit count	Fixation count	TTFF (ms)	Dwell time (ms)	Duration of average fixation (ms)
Road lane	0.85	2.71	9340.91	684.32	247.85
Marking Arrow	0.93	2.88	6966.27	671.98	234.79
Text of sign F-17	2.06	33.22	579.56	6183.79	181.32
Marked sign F-17	2.24	5.11	1228.59	1200.56	231.70

Source: own elaboration.

Mark F-17, marked by an ellipse, had a mean fixation count of 5.11, a mean Single fixation time of 231.70 ms and a total fixation time of 1,200.56 ms, indicating a high interest in the area and scanning it. This is the most important area for the respondents, as confirmed by the intense red spot on the heat map and the area of interest analysis.

Participants in the study read the text before 6200ms on average, with a fixation count of 33.22 and an average single fixation time of 181ms, which speaks to the relatively low density of fixations across the entire area consisting of 5 lines of text.

The arrow helped participants direct their gaze to the mark, but the time of its first fixation indicates that it was noticed later than the other elements – a TTFF of 6966ms. The focus time on its area was only 672ms, which is the area of the arrow alone.

The statistics look similar for the area of the lane to which this arrow points – the average dwell time in its area was 684 ms, and the number of fixations was 2.71 vs. 2.88 for the arrow. In both cases, the number of re-visits is less than 1, which means that not everyone looked at the arrow or lane area again.

The third digital material described is a description of the revision of the traffic regulations, consisting of three paragraphs of text. The digital material and heat map can be found in Figure 4. A table with an analysis of the areas of interest can be found in Table 3.

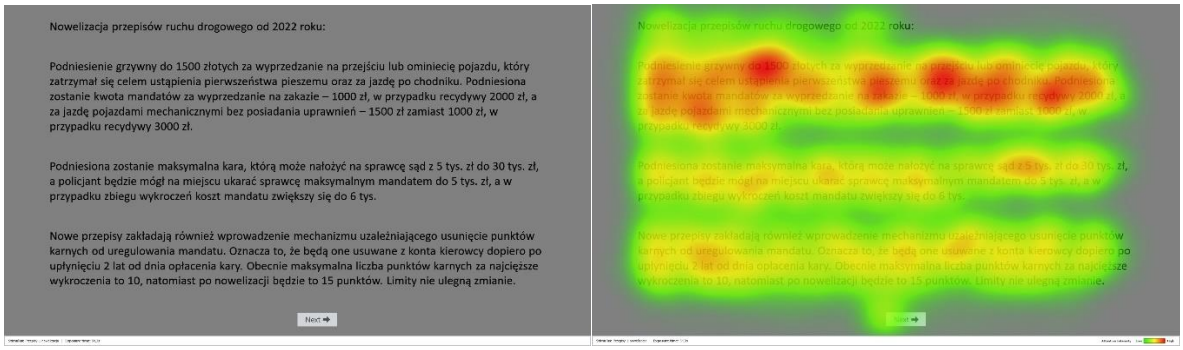


Figure 4: Structure of novelisation of road law regulations and the obtained heat map
Source: own elaboration.

The first paragraph attracted the most attention, as can be seen by the density of the red colour. The middle paragraph attracted moderate interest, and the last paragraph attracted the least interest. The heat map shows that the amount of 1500 and other numerical values, e.g. 2000, 3000, attracted the most interest.

Table 3. Results obtained during the analysis of areas of interest - structure 3

Name of AOI	Revisit count	Fixation count	TTFF (ms)	Dwell time (ms)	Duration of average fixation (ms)
Paragraph 1	2,88	75,17	907,26	14418,20	179,38
Paragraph 2	1,94	36,18	14787,60	6897,48	184,37
Paragraph 3	1,21	42,07	30673,13	8171,03	180,49

Source: own elaboration.

The first paragraph attracted the most attention, as evidenced by the high values for fixation (75.17) and total focus time (14418.19 ms). This is further evidenced by the high value of single average fixation (179 ms). This paragraph also had the highest number of revisits, i.e., they often returned to this passage.

Users paid less attention to this passage than to the first paragraph, reflected in fewer fixations (36.18) and a shorter total focus time (6897.48 ms). The lower values of the analysed data indicate a decrease in interest and reading of the subsequent paragraphs of the text.

The third paragraph was the least engaging in the first moments (high TTFF – 30673 ms). The total focus time (8171 ms) suggests that although users did not focus on it immediately, they spent some time on it after reading the previous paragraphs.

Users focused on specific figures related to fines and penalty points. The first paragraph had the highest number of fixations and total focus time, indicating that users were reading this passage closely. Paragraphs 2 and 3 had lower focus – users moved through these passages more quickly, looking for the most important information.

The last digital material described comprises a video animation, text and two road signs. The material was divided into the three main sections: the start of traffic, the entrance to the intersection and the exit. Figure 5 shows a photograph of sequence 1 – the beginning of traffic. The analysed section is approximately 7 seconds long. The analysis will be presented in photos, and a table for the selected sequence will be shown below. Data analysis will be performed for all sections.

Sequence 1 - beginning of animation. Participants' main attention was directed towards the animation and textual content, suggesting that dynamic elements are crucial in processing visual information. Vertical signs (e.g. A – 7, D – 1) attracted less attention, indicating that users did not perceive them as crucial for understanding the situation at the intersection. The respondents read the text only in fragments.

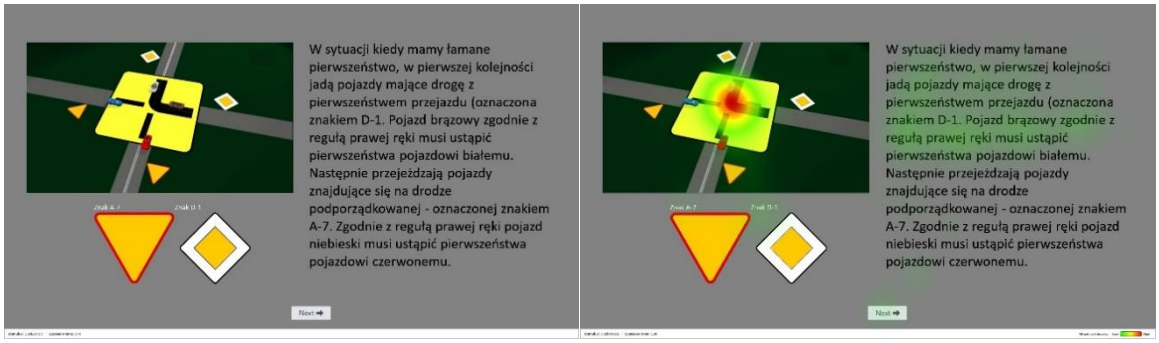


Figure 5: Structures relating to driving rules at intersections and the obtained heat map
Source: own elaboration.

Table 4. Results obtained during the analysis of areas of interest – structure 4 – sequence 1

Name of AOI	Revisit count	Fixation count	TTFF (ms)	Dwell time (ms)	Duration of average fixation (ms)
Start of movement	4,01	20,02	1795,43	5949,62	292,71
Sign D-1	0,48	1,84	8477,98	284,62	156,37
Name of sign D-1	0,11	1,11	13026,72	272,48	225,32
Name of sign A-7	0,00	1,13	10281,66	255,37	239,78
Sign A-7	0,23	1,74	6238,81	234,44	124,55
Text	4,02	40,76	526,98	6868,28	166,52

Source: own elaboration.

Animation attracted the most interest (average number of fixations: 20.02, viewing time 5950 ms). Text was also heavily scanned (over 40 fixations), but the time was very short (166 ms). Surprisingly, as the animation was the central element of the slide, the respondents focused on the text first (TTFF – 527 ms). The A-7 sign and the name of the D-1 sign attracted much less attention, suggesting that users focused more on the dynamic elements and textual content than the signage.

Sequence number 2 – The most important element in the analysis was the traffic situation itself, rather than the signage. Text was again critical, suggesting users relied on it to interpret the situation. Road signs are still in the background and are noticed late, which may mean their location or appearance does not attract enough attention. The 'entering the intersection' manoeuvre alone attracted the most attention (6 fixations, average viewing time 4560 ms), suggesting that users were focused on analysing the traffic situation. The text was also seen first (544 ms) in this case. Traffic signs (D-1, A-7) still did not attract much attention – the D-1 sign had only 1.8 fixations, 263 ms viewing time, and the A-7 sign had even lower values (1.33 fixations, 160 ms viewing time).

Sequence number 3 – Attention was directed to the exit manoeuvre and the text, indicating prioritising the traffic situation. Road signs were analysed even less frequently than in the previous sequences, which may suggest that their meaning was evident to the participants or that they did not pay sufficient attention to them. The moment of exit from the intersection attracted the most attention (mean 19.36 fixations, mean area viewing time 5013 ms). The text was again intensively analysed (39.83 fixations, dwell time - 6924 ms), indicating that participants relied on description. The text was again first noticed; this may be because it was read before the section analysis started.

5. DISCUSSION

The educational materials analysed had varied delivery forms, affecting how they were assimilated and how effectively the participants remembered the information. The eye-tracking analysis and knowledge test results indicate that users assimilated the content best when presented visually, with additional graphic markings aiding the information processing.

Material analysis - Four road signs. When analysing the material depicting the four traffic signs, the sign B-38 (‘no parking on even days’) attracted the most attention from the participants. The eye tracking results confirmed this – the highest number of fixations and the longest time spent analysing the text, and by the knowledge test results. The respondents had to answer questions related to signs. The first was straightforward, as it asked whether sign number 4 required the driver to switch on their dipped headlights; the second question related to sign number 1 asked them to choose the correct graphic for the sign informing of lateral wind gusts. Question number 3 referred to sign number 3 on the slide and was complicated as it asked about the specific behaviour of the driver when seeing the sign. Question number 4 was a reference to sign number 2 and was also complicated for the respondents, due to the detailed question asking for an explanation of its meaning. Participants showed a high level of recall of sign information, as confirmed by the test results: 88%, 92%, 73% and 77% correct answers for individual signs. The best results were obtained for signs commonly used or requiring special attention on the road. The slightly lower score for the D-37 sign suggests that its meaning was more intuitive, which may have resulted in shorter analysis time and less cognitive engagement.

Material analysis – Sign F-17. For the material relating to the F-17 sign, eye tracking analysis showed that the greatest concentration of participants' gaze occurred in the area of the lane end, marked by the red ellipse. The arrow and the sign attracted attention, although to a lesser extent. The text was analysed intensively, suggesting that users relied heavily on visual interpretation. Respondents had to answer a question linked to the text shown in Figure 2, which concerned the meaning of the sign shown. The test score for this material was 79% correct answers, indicating a good uptake of the information, although slightly lower compared to the signs discussed in the first material. This may mean that the sign was so intuitive that it did not require detailed processing, but a partial misunderstanding of its meaning may have led to incorrect answers.

Material analysis – Revised traffic regulations. The text on the revision of traffic regulations showed the most significant focus on the first paragraph. This passage had the most fixations and eye returns, suggesting that users were trying to assimilate key information at the beginning. Subsequent paragraphs were analysed more quickly and to a lesser extent, which may indicate that participants were looking for specifics, such as figures for fines and penalty points. The test questions related to the new fine rates and the new recidivism penalties (questions 1 and 2), the new maximum fine rate (question 3), the new number of maximum penalty points per offence and the time of their deletion (questions 4 and 5). Test scores for this material were very high (up to 94%), suggesting that the numerical information and the hierarchical structure of the text allowed for effective learning. However, the decrease in interest in successive paragraphs indicates the need for better highlighting key passages in longer texts.

Material analysis – Three sequences of crossing an intersection. When analysing the three crossing sequences, participants focused most on the dynamic elements, indicating that animation was a key source of information. Text also played an important role, especially in interpreting the traffic situation. The eye tracking analysis showed that users focused on the text first, followed by the traffic flow at the intersection. Traffic signs attracted the least attention, suggesting that their presence was perceived as less important. The test results indicated that 40 out of 52 people correctly identified the sequence of vehicle movements, indicating the high effectiveness of this learning format. However, it is possible that greater integration of signs with animation could have improved their perception and recall.

6. CONCLUSION

The study provided important information on the effectiveness of the reception of multimodal training materials, especially in the context of road signs and their use in the driver education process. Eye tracking allowed a thorough analysis of users' focus areas, which provides valuable insights into the design of effective teaching materials. The results indicate that a key factor influencing the effectiveness of content perception is how text and graphics are arranged and their visual hierarchy.

It was observed that the study participants first directed their gaze to the graphic elements, such as pictograms of road signs, and only then focused on their textual descriptions. This is due to humans' natural tendency to process images faster than text, which is in line with the findings of Shimazaki, Ito, Fuji, and Ishida. Ensuring consistent and transparent integration of image and text in learning traffic rules is crucial to facilitate learning and improve memorisation.

Another important finding of the study is the role of visual differentiators, such as colour, bold, and tick marks, which significantly impact directing the audience's attention. The results indicate that items highlighted this way were identified more quickly and held the respondents' gaze longer. Similar conclusions are drawn from the work of (Sorapure, 2019; Makowska, 2021), who emphasise that an excess of text without adequate visual division can lead to cognitive overload and impede effective information assimilation.

Eye tracking has also been used to assess the effectiveness of different visual layouts in training materials. The results of a study by (Zhang et al., 2022b) suggest that young drivers who learned using video depicting real-life traffic situations showed better perceptual skills and reacted faster to hazards. This confirms the validity of using dynamic content to educate future drivers. Also, a study by (Petzoldt et al., 2013) showed that interactive animations are more effective than static images in learning traffic rules, indicating the need to modernise the didactic methods used in driving courses.

It is also worth noting the potential practical applications of the results of this study. Analysis of gaze paths and areas of interest can be used to optimise digital training materials, which are particularly relevant in this era of increasing popularity of e-learning. As the study by (Martín-delosReyes et al., 2019) shows, using driving simulators and interactive learning methods significantly improves road safety by enabling a more realistic and engaging learning experience.

In conclusion, the study highlights the key role of the appropriate design of driver education materials. To be effective, they must consider natural perceptual mechanisms, such as the prioritised processing of graphic elements, highlighting key information, and integrating dynamic content. The study's results indicate that modern teaching technologies, such as eye tracking or multimedia driving simulators, can significantly improve teaching effectiveness and road safety. In the future, it is worth considering further research into the impact of interactive training methods on user perception, which could lead to even more effective learning tools in driver education.

In terms of future developments in driver education, artificial intelligence (AI)-based technologies have great potential to revolutionise how future drivers learn traffic regulations, recognise hazards or make decisions in dynamic traffic situations. AI can analyse a student's progress in real time – e.g., learning speed, areas of difficulty, most common mistakes – and tailor educational content to the student's individual needs. AI could also generate complex but comprehensible learning reports, showing, for example, areas mastered, progress over time, concentration problems (e.g., based on eye tracker data), which can help students and instructors improve the learning process. The use of modern AI in driving simulators could allow the generation of realistic, dynamically changing traffic scenarios that respond to the trainee's behaviour. Simulations could teach through unusual or dangerous situations (e.g., pedestrian intrusion, sudden weather changes), giving immediate feedback.

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EYE-TRACKING AS A METHOD FOR INVESTIGATING COGNITIVE PROCESSES IN THE RECEPTION OF EDUCATIONAL MATERIALS WITHIN THE CONTEXT OF INTELLIGENT MANAGEMENT OF THE DIDACTIC PROCESS

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ABSTRACT

Purpose: *The article introduces a research approach based on eye tracking metrics to analyse cognitive processes during the reception of teaching materials in three different visual versions.*

Need for the study: *There is a lack of comprehensive research demonstrating how various presentation formats influence visual attention and cognitive load.*

Methodology: *A laboratory experiment using eye tracking allowed us to identify indicators that reveal the dynamics of attention and challenges in content integration.*

Findings: *Analyses showed that different versions of the materials distinguish cognitive responses; metrics based on time and number of fixations proved to be particularly sensitive to visual attention, while indicators of distraction and returns better reflected cognitive effort.*

Practical Implications: *The results obtained form the basis for developing guidelines for designing educational content and may support the development of intelligent systems for managing the learning process.*

Keywords: eye-tracking in education; cognitive load; attention processes; design of educational materials; intelligent management of the didactic process

Jel codes: I23; C91; D83

1. INTRODUCTION

Contemporary education undoubtedly presents a challenge not only for children and their families but also for teachers, curriculum developers, textbook authors, and educational resource producers. For many years, fairs, stands, and educational promotions aimed at popularising and selling tools that make learning and teaching more enjoyable and easier have appeared in everyday social rituals and public

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events, aligning with the rhythm of school life. Sellers assure us of their effectiveness, entrepreneurs count their profits, and interested parties assess the efficacy of the educational and teaching aids they have purchased. But are these tools necessary? In the face of the expanding virtual space of life and ubiquitous artificial intelligence, are other teaching methods still required? Psychological and pedagogical research on the creation and quality of the teaching process demonstrates how vital it is to use correctly selected methods and properly developed tools in implementing educational programmes. This is crucial for the effectiveness of the teaching process, as it depends on the quality of the message created, which provides information gathered in the form of individual knowledge of the participant in education.

Since the invention of printing and its introduction into mass communication, numerous scientific studies and experiments have been carried out, leading to the development of various theories and concepts related to interpersonal communication. In light of emerging technological innovations and advancements in IT, accumulated observations and experience contribute to the formulation of diverse recommendations for educational content development. Due to the rapid growth and progress of new media, ongoing research, monitoring, and updating are essential in the fields of psychophysiology of vision and information perception.

One of the latest methods used to gather precise data on perception and information processing is eye tracking. This study enables the collection of numerous quantitative physiological measurements related to information processing in a relatively short period. Once analysed, the collected data allows for identifying the most effective ways of presenting knowledge, thus creating conditions for developing reliable research results, formulating recommendations and guidelines for creating prompts (commands) used in GPTchat-type tools, and subsequently applying them as guiding principles for developing teaching tools in intelligent IT management using AI.

This article presents a research method using eye-tracking metrics to investigate cognitive processes involved in learning with teaching materials. The study examined three visually distinct versions of the duplicated content, which enabled the identification of attention focus, distraction, and cognitive load mechanisms.

The article is divided into several sections. The theoretical part outlines the evolution of learning theory, focusing particularly on the role of visual materials and methods of analysing them within the educational process. Next, it presents the methodology employed, which is based on eye-tracking measurements and analysing their results, followed by a comparison of three versions of teaching materials. The final section of the article discusses the interpretation of the results and their implications in the context of intelligent management of the teaching process.

2. LEARNING THEORIES AND THE ROLE OF VISUALISATION IN CONTEMPORARY EDUCATION

The learning process, as a key activity in human life, is essential and relies on cognitive functions and memory, which humans develop according to their physiological abilities and simultaneously acquire skills to broaden their horizons throughout their lives during education. Learning is not only about gathering necessary information, but also about building competencies that shape human life. Psychological research on cognitive functions and learning reveals many factors that influence the quality of learning and knowledge acquisition. Most of these include common elements such as innate individual characteristics and the educational environment, which provides developmental stimuli and affects the quality of the educational process. However, the most significant impact on the effectiveness of acquiring knowledge and intellectual growth is achieved by organising the immediate environment in a way that fosters opportunities for personal development.

One of the most renowned learning theories at the turn of the 19th and 20th centuries is constructivism, with key figures being (Bruner, 1966; Vygotsky, 1980). The foundation of constructivist ideas in education is the belief that knowledge is not merely transmitted by the social environment but is independently constructed by the learner through actively building cognitive structures tailored to their individual abilities and needs, based on understanding fundamental concepts and problems. The recommended teaching methods emphasise problem solving and autonomous discovery of the laws governing reality. Social interaction and collaboration are crucial in this process, fostering critical

thinking, discussion, and problem-solving skills. Constructivism in education is a perspective grounded in the theory of learning by doing and John Dewey's concept of the school of work (Dewey, 1938), while also aligning with research on neural networks emerging in the social sciences, as exemplified by Seymour Papert and Marvin Lee Minsky (Papert, 1993). The principles of this approach are not entirely new; they are rooted in the 16th-century general didactics theory articulated by the European reformer and pedagogue Jan Amos Komensky (Komenský, 1956).

In the second half of the 20th century, cognitive sciences exerted a strong influence on educational sciences, leading to the emergence of new ideas and directions of development in both pedagogy and education. An example of such a concept that significantly impacted general education is A. Paivio's dual coding theory (Paivio, 1990), which emphasises the importance of imagery, visualisation, and verbal associations in enhancing the effectiveness of the learning process. Similarly, John Sweller's cognitive load theory (CLT), which posits that to maximise learning effectiveness, teaching methods and tools should avoid overloading memory (Sweller, 1988), has profoundly influenced reflections on the teaching process in Europe.

The development of civilisation in the 21st century and the rapid pace of change in the world demand that the average member of modern society remains constantly prepared to adapt to new conditions and pursue lifelong learning. The geopolitical events of the past decade have heightened the necessity to develop the ability to learn continuously, based on independently acquired knowledge, such as through educational platforms, online courses, e-learning, visualisation, and, in recent years, the utilisation of artificial intelligence. Therefore, the concepts of educational constructivism continue into the 21st century through new research and ideas by scientists like Jean Lave and Etienne Wenger (Lave & Wenger, 1991), known for learning by doing or situated learning theory and communities of practice, as well as in the theory of learning in the digital age – connectivism, proposed and developed by George Siemens (Siemens, 2004) and Stephen Downes (Downes, 2008).

Assuming, in accordance with the postulates of nineteenth- and twentieth-century pedagogy (Vygotsky, 1980), that learning as a process involves actively constructing knowledge based on fundamental principles and concepts (Bruner, 1966), teaching materials and educational aids are designed to support experimentation and independent discovery of knowledge (Dewey, 1938). Twenty-first century pedagogy therefore not only incorporates the good practices proposed in nineteenth and twentieth-century education but also emphasises interactivity (Papert, 1993), multimedia, and the simultaneous integration of visual and verbal materials (Mayer, 2009). Another postulate of contemporary social expectations is the creation of access to multiple sources, the ability to connect to other online resources, and network information (Downes, 2008), while combining words and images in teaching materials (Paivio, 1990). An important factor determining the quality of a teaching tool in 21st-century education is aesthetics and readability, which promote concentration and a positive attitude towards learning (Arnheim, 1954; Norman, 2013).

Visualising information has become an essential part of the educational process, now standard in both traditional and multimedia teaching settings. In response to societal needs and market demands, principles for designing visual and digital materials have been established. The core idea of visualisation is the principle of data hierarchy, which involves organising content logically so that information is arranged by importance, with the most significant elements highlighted through size, colour, or placement within the visual layout (Itten & Lisiecka, 2020; Ware, 2013). This relates to the need for intentional selection of information – the principle of purposefulness (Kupisiewicz, 1994; Okoń, 2003) – and entails removing elements that do not support the main message (‘chart junk’), excess data, and overly complex graphical features (Tufte, 2001). Minimalism is particularly recommended when developing teaching materials, as it enhances layout clarity and helps focus learners’ attention on key visual elements that aid memory (Paivio, 1990). Memory performance is also improved by thoughtfully positioning and organising data, such as placing related information close together to create groups. Grouping, based on the Gestalt principle, and using consistent formatting structures enhance readability and facilitate understanding of conveyed messages (Ware, 2013). The principle of contrast, involving the use of contrasting colours, shapes, fonts, and spacing, significantly improves the quality and effectiveness of visual educational materials by emphasising selected message elements. Additionally, it is vital to adapt content to the recipient. The chosen visual materials should consider the age, knowledge level, and visual preferences of the target audience, thereby increasing the likelihood of successful knowledge transfer (Bruner, 1966; Vygotsky, 1980).

When evaluating the effectiveness of visual materials, the methods used to analyse perception and processing are critically important. Among these, data analysis and eye tracking are predominantly utilised. Data analysis collects information about how users interact with educational materials, including the time spent on a particular piece, the number of repetitions, and, most significantly, their level of understanding after completing the task. In contrast, eye tracking – a technology that monitors eye–movements – enables analysing the visual attention directed towards different elements of the teaching materials and identifying which parts attract viewers' gaze. This method also measures how long viewers' eyes focus on specific fragments of visual content. Such data helps determine which information captures attention most easily, is absorbed effectively, or requires modification. Research indicates that eye tracking can significantly enhance the design of visual materials, allowing content to be customised to meet the actual needs of the educational audience. In Poland, these topics have been examined by Janusz Morbitzer (Morbitzer, 2012) and Mirosław S. Szymański (Szymański, 2014).

The above experiences clearly show that visual materials currently play a vital role in the learning process by helping understand content, supporting memorisation, and engaging different senses. Thanks to modern methods of perception assessment and intelligent management of the teaching process, teachers can more effectively tailor materials to meet students' needs. In the digital age, the ability to design effective visual materials is becoming an essential skill for teachers, educators, and lifelong learners (Łukasik et al., 2021; Szymański, 2014). Adapting projects to the audience's needs and considering principles of effective information visualisation can significantly improve teaching effectiveness. Intelligent management of education using artificial intelligence, based on data about visual perception and information creation principles, is increasingly common in modern schools and educational platforms. With the technological capabilities of IT tools, personalising teaching aids for individual learners is straightforward. A well-designed platform distributing educational materials can, based on user preferences, offer different versions of the same content created from eye-tracking analysis data. Additionally, intelligent management in education enables providers to give learners real-time feedback, allowing quicker responses to educational challenges and facilitating instant adaptation of teaching materials to learners' needs.

3. METHODOLOGY

3.1. Participants

A total of 45 people took part in the study, including 23 women and 22 men. They were adults, mostly students in various research fields and working professionals. The average age in the sample was M = 22.40; SD = 3.95. Participants were assigned to one of three groups. Group 1 included eight women and seven men (M = 22.10; SD = 4.46), group 2 comprised seven women and eight men (M = 22.35; SD = 4.20), and group 3 consisted of eight women and seven men (M = 22.25; SD = 3.70). The selection of participants reflected typical recipients of teaching materials at the academic level, enabling analysis of perception processes in conditions similar to real-life teaching management scenarios.

Each participant took part in the study voluntarily, having previously given their written consent to both participation and the processing of their data. Before the psychophysiological tests began, they received general information about the course of the experiment, the research equipment used, and how it operated. However, no details were disclosed about the stimuli presented on the screen. The experiment was conducted in accordance with the provisions of the Helsinki Declaration (2013 version) (World Medical Association, 2013) and after obtaining the opinion of the Bioethics Committee at the Regional Medical Chamber in Szczecin.

3.2. Materials and Research Procedure

The research experiment was carried out under controlled laboratory conditions at a specially equipped university facility. After a brief introduction, the participants underwent eye tracker calibration, followed by the start of the actual study. Stimuli (screens with educational content) were displayed on the computer, with the presentation order predetermined and identical for all participants. Once the research session was complete, the measurement data was prepared for analysis, including eye tracking metrics and statistical assessments. Specifically, indicators related to visual attention, distraction, and cognitive load were analysed.

The study used teaching material corresponding to one module of classes (two thematic lessons), aimed at supporting the instruction of one of the academic subjects. The structure of the module included the following components:

- introduction;
- several theoretical issues (content), presented using various types of elements: text, bullet points, numbering, mixed lists, tables, charts, graphic elements, and videos;
- interactive quizzes as exercises;
- final evaluation exam.

Some screens (similar to presentation slides) displayed various combinations of these components, arranged differently. Overall, the module included 112 screens, with 20 containing quizzes.

To compare how different presentation styles affect audience perception, three versions of the course materials were created. Each version was identical in content but varied in visual design and resource organisation. Version 1 (classic) featured a layout with a moderate use of visualisation for screen elements. Version 2 was more detailed, with graphic elements emphasising key information, such as various types of bulleted and numbered lists, highlights, captions for graphics, and diverse content arrangements. Version 3 adopted a minimalist layout, with limited graphic elements deemed unnecessary, although other highlighting methods were employed. The aim was to reduce cognitive load and promote more even scanning of the screen content.

A schematic outline of the research procedure, considering the three versions of the analysed educational materials, is shown in Fig. 1.

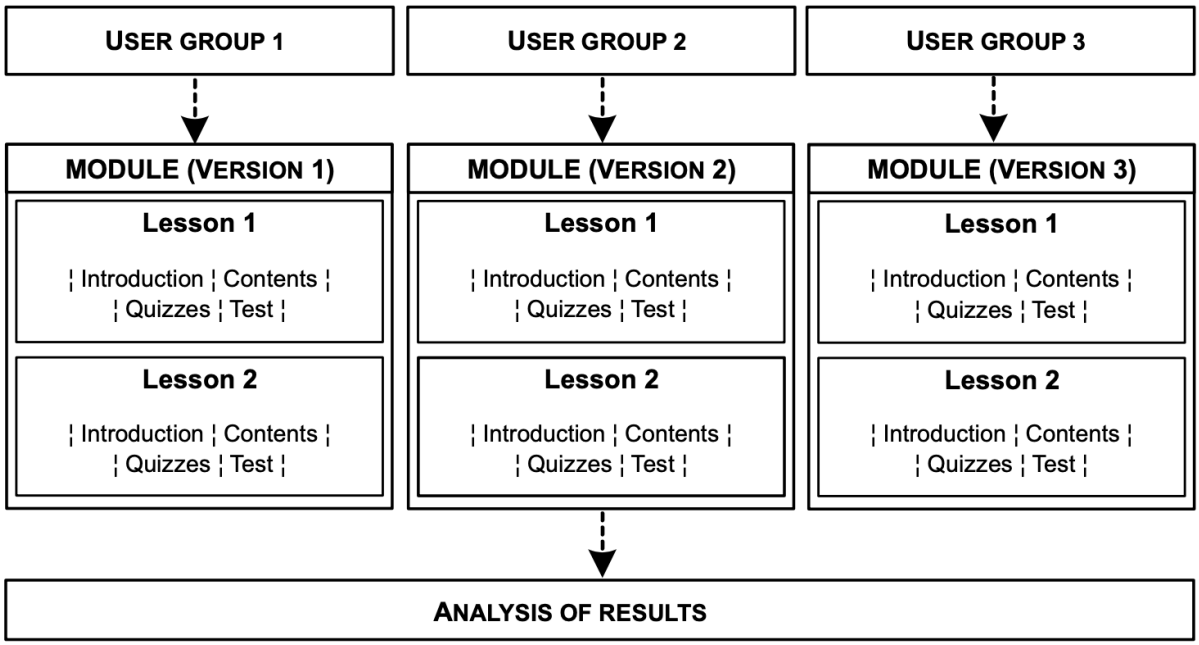


Figure 1. Procedure for testing different versions of educational materials
Source: own elaboration.

The module was created in three different versions not only to assess how the content was received, but also to identify the most effective solutions for intelligent management of the teaching process by optimising perception and reducing cognitive load.

3.3. Apparatus and Indicators for Evaluation

A stationary Tobii Pro X3-120 eye tracker was used to record visual activity. It was mounted at the bottom of the laptop screen, approximately 60 cm from the subject. The recorded data was further processed using the I-HMM (Hidden Markov Model) fixation identification algorithm. The minimum fixation duration was set at 60 ms, and the maximum interval between successive fixations at 75 ms. A moving average filter was employed to reduce noise, while missing data were supplemented through interpolation (intervals ≤ 75 ms).

The data analysis concentrated on gaze paths and, mainly, on indicators (metrics). These facilitated the assessment of the perception process, specifically the focusing and dispersing of visual attention, as well as the analysis of cognitive load. These metrics were computed for areas of interest (AOI) defined within individual screens. Table 1 displays a set of metrics used in the analyses (Guo et al., 2016; Hessels & Hooge, 2019; Mahanama et al., 2022; van der Laan et al., 2015; Wedel & Pieters, 2006).

Table 1. AOI metrics and their interpretation included in the analysis

Abbr.	Name	Metric description	Interpretation and application
TTFF	Time to First Fixation	Average time from the start of exposure to the first fixation in the AOI (ms)	**Focusing visual attention**: the speed at which gaze is attracted to the target element. **Visual attention dispersion**: also used in the analysis to assess the smoothness of transitions between consecutive content segments (e.g., list points, text sections, screen elements), indirectly indicating lower or higher attention dispersion.
FC	Fixation Count	Average number of fixations in the AOI	**Focusing visual attention**: a higher number of fixations may indicate a more thorough examination of content. **Visual attention dispersion**: when fixations are spread across multiple subareas or involve backward shifts, higher FC shows greater search effort and less smooth gaze focus.
TFD	Total Fixation Duration	Total fixation time in the AOI (ms)	**Focusing visual attention**: longer TFD on key content indicates stronger and more sustained attention. **Cognitive load**: : in analysis, considered as an indicator of processing effort (e.g., in tables, figure captions, video headers).
FFD	First Fixation Duration	Duration of the first fixation in the AOI (ms)	**Focusing visual attention**: the strength of initial attraction and early processing. The analysis demonstrated that highlighted elements were not only noticed more quickly but also retained longer during first fixations. **Cognitive load**: locally, when a longer FFD was linked to more intensive initial processing.
DAF	Duration of All Fixations	Average duration of all fixations in the AOI (ms)	**Cognitive load**: in the analysis used to infer depth of processing and cognitive effort; longer fixations were interpreted as reflecting more engaging content processing.
DSAF	Dispersion of Fixations	Degree of spatial dispersion of fixations in the AOI	**Visual attention dispersion**: a key indicator of scattered or chaotic scanning. **Cognitive load**: in the analysis, when combined with REV/SC, indicates increased difficulty in content integration.
REV	Revisits / Returns	Number of gaze returns to the AOI	**Visual attention dispersion**: frequent revisits suggest uncertainty and fragmented processing. **Cognitive load**: in the analysis used to infer the need for context refreshing and additional working memory demands.
SC	Saccade Count	Number of saccades within the AOI/screen	**Visual attention dispersion**: a higher number of saccades indicates more fragmented scanning. **Cognitive load**: discussed in two ways; under high load, the number of saccades may decrease (a "gaze freezing" effect), which is why SC was interpreted alongside DAF/TFD/REV.

Source: own elaboration.

The use of the above eye tracking metrics enabled not only a quantitative assessment of how educational content is perceived but also the development of practical guidelines for the effective design of educational materials and the support of teaching management systems.

Sample screen layouts (2 out of 112 developed) for three versions of the teaching material presentation, with additionally marked AOIs, are shown in Fig. 2.

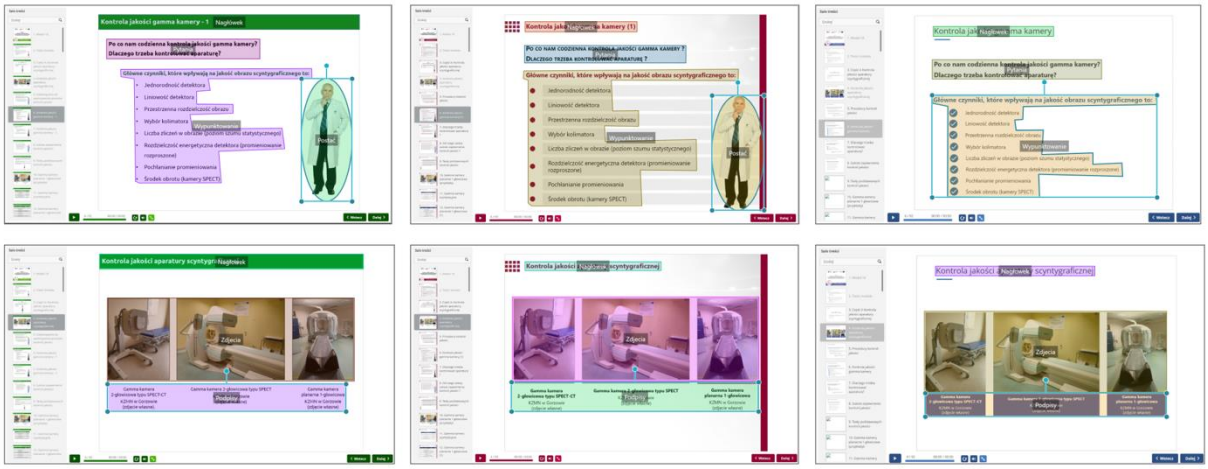


Figure 2. Sample screens for three versions of the module
(from left: version 1, version 2, version 3)
Source: own elaboration.

4. RESULTS

The results of the eye-tracking studies were analysed based on three aspects of the perception process of teaching materials: visual attention, distraction, and cognitive load. Three versions of the same module content were examined, considering different types of screen structures. For each structure type, suitable eye-tracking metrics were determined for each version (Table 1). The metric values were calculated for specific AOIs (screen components) and combined for individual structures.

4.1 Focusing Visual Attention

Eye tracking analysis showed that how content is presented- even with minor changes- significantly influences attention focus. In this context, versions 2 and 3 outperformed version 1. For example, on screens containing only text, the average time to first fixation (TTFF) for the initial paragraph was about 1357 ms in version 1, approximately 1296 ms in version 2, and around 1264 ms in version 3. Analysing the average first fixation duration (FFD) for these paragraphs revealed slightly longer fixations in versions 3 and 3 compared to version 1. The combination of shorter TTFF and longer FFD indicates that the element attracts more attention. This reflects a positive result of the designed text block's format- such as font choice, colours, text area size, and layout on the screen. Participants quickly noticed the text block and looked at it longer, suggesting greater focus during the initial processing of information.

The analysis of structures with bulleted, numbered, and mixed lists confirmed that appropriate formatting helps with content tracking. Versions 2 and 3, thanks to the use of graphic markers highlighting the text and increased spacing, encouraged eye focus and smooth tracking of successive points. Overall, the most orderly scanning pattern was observed in version 3. The average number of fixations (FC) for the bullet point block in version 3 was about 141, in version 2 around 137, while in the classic version 1 approximately 118. The absence of clear graphic markers in the classic version caused uneven attention, more frequent skipping of certain points, and longer TTFF for subsequent items on the list (additional AOIs were created for each text highlight in lists). More revisits (REV) to the AOI of individual list items were also noted. In version 3, appropriately chosen graphic highlights (except for numbering in the form of: 01, 02, ...) attracted attention more effectively, reducing TTFF and supporting smooth eye movement between successive items.

Interesting results were obtained for structures containing graphic elements serving an informative purpose (e.g., photos of equipment). Such objects proved to be strong visual stimuli and immediately attracted attention. The TTFF for each version was low and amounted to: version 1 – 224 ms, version 2 – 245 ms, version 3 – 252 ms. The larger differences concerned the way captions were processed. In versions 2 and 3, minor formatting changes were introduced (e.g., bold text, a line separating the caption from the graphic, a change in colour scheme). This led to a slight increase in reading time (more careful reading), as confirmed by the higher TFD and FC metrics. When analysing the proportion of time spent looking at the graphic and the caption, the best result was in version 2. Another key observation was the

impact of the caption's location on the scanning of the entire message. It was shown that placing the caption on the right side of the graphic hinders smooth scanning, which was confirmed by both eye-tracking analyses and increased REV and FC values. This observation aligns with the principle of spatial contiguity in the design of teaching materials, which emphasises the importance of properly grouping related elements (e.g., image and description) (Mayer, 2009).

In the case of structures containing complex tables, perceptual issues arose, initially causing the gaze to focus on the central area. Later, scanning of the table content became more dispersed in many cases. The table formatting used in versions 2 and 3 (e.g., centring, bold headings, simplified layout) facilitated systematic reading from top to bottom. The TTFF metrics for key sections of the tables, including headings (defined AOIs), were lower in these versions, and the TFD values were higher than in version 1. This suggests greater engagement in data analysis. The minimalist design of the tables reduced distractions, and the visually enriched version organised attention through clear headings.

On screens with videos, participants' attention initially focused on the player and only later on the header. All versions had a similar layout (header, video playback area), so the patterns of attention were also comparable. The main difference was the visual form of the header. The longest viewing time for the title was recorded in version 1 of the materials (TFD approx. 1326 ms), and the shortest in version 2 (TFD approx. 1205 ms). The presence of a film thumbnail in version 3 (first frame) encouraged quicker attention focus, while the black initial screens in versions 1 and 2 caused distraction. This demonstrates that even minor variations in the visual content of the player (image vs. blank screen) influence how the screen content is scanned.

The screens with test questions (quizzes) had a similar layout across all versions: the question at the top and the answers below. Additionally, in versions 1 and 2, a decorative graphic element appeared on the side. In all versions, participants first carefully read the question before moving on to the answers. The TTFF for the question content in version 3, without graphics, was the lowest at approximately 193 ms; in version 2, around 348 ms; and in version 1, about 437 ms. There were slight differences in the decorative elements – in version 1, they were larger and more contrasting, resulting in more glances and longer fixation times compared to version 2 (for version 1, FC was approximately 19 and TFD about 976 ms; for version 2, FC was roughly 14 and TFD approximately 704 ms). Interestingly, an analysis of the impact of decorative graphics on subsequent quiz screens showed a habituation effect – the brain filtered out the decorations as irrelevant stimuli.

A summary of the key AOI metrics relevant to visual attention analysis is shown in Table 2.

Table 2. Summary of key eye-tracking metrics for visual attention concerning different structure types and versions of teaching materials

Structure type	Metrics	Ver. 1	Ver. 2	Ver. 3	Key observation
Text	TTFF	longer	shorter	shortest	Shorter TTFF in V2 & V3 → faster detection of core content
	FFD	shorter	longer	equally longer	Longer FFD in V2 & V3 → stronger initial attention
Bullet/numbered/mixed lists	FC	smaller	larger	largest	Most orderly scanning in V3
	TTFF	longer	shorter	equally short	V2 & V3 support smooth item-to-item tracking
	REV	more frequent	less frequent	least frequent	Visual cues reduce the need for revisits
Graphics with caption	TTFF	short	short	short	All low → image strongly attracts attention
	TFD	lower	higher	higher	V2 & V3 → more attentive caption reading
	REV	lower - caption below image	higher - caption to the right	higher - caption to the right	Caption location is critical for scan fluency
Tables	TTFF	longer	shorter	equally short	V2 & V3 facilitate quick start of reading

Structure type	Metrics	Ver. 1	Ver. 2	Ver. 3	Key observation
	TFD	shorter	longer	longer	V2 & V3 → greater engagement with table content
Video	TFD	longer	shorter	shorter	Header captures most attention in V1
	TTFF	similar	similar	shorter	Thumbnail in V3 → quicker focus on the player
Quiz	TTFF	longer	shorter	shortest	Fastest focus on the question in V3
	FC	larger	smaller	n/a	Decorative graphic attracts attention (habituation across items)
	TFD	larger	smaller	n/a	Strongest pull in V1

Source: own elaboration.

4.2 Visual Attention Dispersion

Another aspect analysed was visual distraction, defined as diverting the gaze away from key content in teaching materials and chaotic screen scanning. This phenomenon is well reflected in eye tracking metrics such as DSAF and REV. High DSAF values indicate disordered scanning, while high REV values may indicate difficulties in processing information. Analysis of both indicators, supplemented by an examination of gaze paths, showed that the greatest distraction occurred in version 1 of the materials, while the least occurred in version 2.

In the text structures, version 1 was characterised by more frequent returns to the screen header. The average REV metric value slightly exceeded 2, while in versions 2 and 3 it was just over 1. The DSAF indicator for text paragraphs was also higher in version 1 than in the others. Eye tracking showed that in version 1, jumps occurred more often both within longer paragraphs and between them. In version 3, shorter, clearly separated paragraphs made reading more organised. Text scanning was more focused on subsequent paragraphs, with fewer returns to earlier ones. Version 2 was intermediate in this respect, mainly due to the use of a different font and coloured highlighting of key passages.

For screens with bulleted or numbered items, the distraction analysis highlighted how bullets, symbols, and list organisation affect content reading. In version 1, there were more instances of zigzag scanning (reading down and then up again). This suggests the need to combine separated information. Weaker highlighting of list items led to increased DSAF and more frequent gaze returns (REV). Using more distinctive symbols or numbers and greater spacing between items organised the scanning flow. This was especially clear in version 2, which had the lowest DSAF value and fewest saccades (SC). The exception was when numbering symbols like 01, 02, ... were used in some screens in version 3, which caused increased distraction.

Graphic elements that are not closely related to the screen content can be highly distracting. Analyses indicated that graphics used as decoration (e.g., a person's figure) did not cause significant distraction when the rest of the screen was well designed and balanced. For instance, on screens with lists (bulleted, numbered, or mixed), decorative graphics placed beside the content did not substantially interfere with understanding the educational material. They were observed, but usually after some time. An analysis of the TTFF metric, such as for the AOI of a person, showed a value of approximately 3826 ms for version 1 and around 5319 ms for version 2 (with no decoration in version 3). Additionally, for version 1, REV = 3.01, and for version 2, REV = 1.98. The repeated appearance of the same graphics led to habituation, further reducing their impact.

In the case of screens with films, distraction was mainly noticeable before playback began. The black player screen without a thumbnail caused uncertainty, leading to looking around the screen and a temporary increase in DSAF (fixations scattered across icons, text, and thumbnails of subsequent screens) and the number of saccades (SC). After the film started, attention stabilised on the video material. In version 1, some people still glanced at the screen header (increase in REV), which may indicate a certain lack of integration. In versions 2 and 3, such behaviour was observed less frequently.

On the quiz screens, alongside the graphic embellishments, the non-linear nature of the answering process could have been a potential distraction. Such distraction occurred in the case of long or unclear questions and longer answer options. Some participants, after reading the answer, returned to the question, probably to ensure they understood it correctly. This created a movement pattern: question –

answers – question. This phenomenon was observed across all versions, although it was slightly more frequent in version 1 than in the others. Versions 2 and 3, thanks to the formatting of the content, reduced the need for such returns, and the DSAF values between the question and the answers were lower. Conversely, the graphic embellishments used in versions 1 and 2 had a similar distracting effect as observed in other structures.

The analysis of visual distraction enabled us to identify differences between types of structures and individual versions of the teaching materials. A summary of the most important conclusions, derived from the analysed eye-tracking metrics, is presented in Table 3.

Table 3. Summary of the distraction analysis results concerning the types of structures and versions of teaching materials

Structure type	Version 1	Version 2	Version 3
Text	Higher DSAF and REV; frequent regressions → less coherent reading	Moderate distraction; font and highlighting improved scanning	Lower DSAF and REV; shorter paragraphs supported focus
Bullet/numbered/mixed lists	More zig-zag scanning; weak markers raised DSAF and REV → fragmented processing	Clearer symbols and spacing lowered DSAF and SC → smoother reading	Mostly ordered; numbering „01, 02…" increased distraction
Graphics	Informative graphics integrated well; decorative ones shifted attention → distraction risk	Informative graphics stable; decorative ones caused minor distraction	No decorative graphics; informative ones supported focus
Tables	Dense layout increased DSAF and regressions → harder to extract info	Borders and highlighted headers reduced REV; moderate DSAF → clearer structure	Simplified layout lowered DSAF → easiest comprehension
Video	Pre-playback dispersion; raised DSAF and REV → momentary loss of focus	Initial dispersion around icons; lower than V1 → quicker stabilisation	Similar to V2; attention stabilised after playback
Quiz	Frequent regressions Q–A; higher DSAF → difficulty integrating question with answers	Formatting reduced regressions; lower DSAF → smoother processing	Similar to V2; decorative graphics still distracting

Source: own elaboration.

4.3 Cognitive Load

The next part of the analysis focused on cognitive load. According to cognitive load theory, this refers to the total mental effort required for the learner to process and remember information (Boere et al., 2024). Since the content was identical across all versions of the materials, differences should be looked for in the way information is communicated, which relates to external load (Sweller, 2023). Eye tracking studies do not directly measure cognitive load, but some metrics (DAF, DSAF, TFD, REV, SC) enable inferences about its relative level under specific conditions.

A general assessment of the analysis results indicates that the different variants of teaching materials caused varying cognitive loads. The highest cognitive load was observed with version 1 (classic), while the lowest was seen in version 2. The minimalist version 3 reduced some perceptual stimuli, but its economical design may have limited support in organising the content in certain parts.

Version 1 of the materials was characterised by the highest number of overload signals, such as long, undivided blocks of text, lack of a clear hierarchy, scattered information, and unnecessary embellishments. These features required more effort to organise and process the information. The DAF for key content was lower than in the other versions, which may indicate superficial processing. For example, regarding text structures, these values were: in version 1 DAF = 181, in version 2 DAF = 213, and in version 3 DAF = 198. Shorter fixations with more frequent saccades suggest superficial tracking

of content and difficulties in immediate understanding. This increased external load, limiting the cognitive resources available for deeper analysis of the content.

The situation changed in version 2 of the materials, where unnecessary load was reduced. For example, choosing relevant distinguishing features and visual elements – aligned with the signalling principle – helped organise the information and made it easier to understand. This was shown in several metrics. Longer average fixations (DAF) on the main content suggest that learners could analyse the material more thoroughly (e.g., bullet points, infographics, test questions) rather than just focusing on the layout. Fewer revisits (REV) to previously seen parts might mean there was no need to replay the context because the content was understood, easing the load on working memory. Lower fixation dispersion values (DSAF) indicated that attention was more focused and that too many stimuli did not overload attention.

In the minimalist version 3, the number of elements distracting visual attention was reduced, which should lead to lower cognitive load. In many cases, this was true, but the lack of distinguishing features increased the effort needed to organise the structure and process information by the recipients. This was evident, for example, in complex tables, which were simplified. This is confirmed by the slightly higher number of saccades (SC) compared to version 2 on screens requiring information search (including tables and graphics with captions on the right-hand side). Version 3 reduced the external load, but in some situations, there was a lack of support in reducing the internal load (e.g., hints or distinguishing features indicating the importance of content and reducing complexity). Version 2 performed much better in this regard, as it both reduced unnecessary elements and retained helpful hints.

A summary of the results related to cognitive load, covering various types of screen structures and three versions of teaching materials, is presented in Table 4.

Table 4. Summary of the distraction analysis results regarding types of structures and versions of teaching materials.

Table 4. Summary of the distraction analysis results regarding types of structures and versions of teaching materials

Structure type	Version 1	Version 2	Version 3
Text	Lower DAF, higher SC → high load (superficial processing)	Higher DAF, fewer REV → low load (deeper analysis)	Medium DAF, more SC → moderate load (structuring difficulties)
Bullet/numbered/mixed lists	Lack of markers, higher DSAF → high load	Clear layout, lower DSAF → low load	Missing cues, limited support → moderate load
Graphics	Decorative images increased SC → higher load	Informative graphics reduced DSAF → lower load	Minimalist, no distraction but less support → moderate load
Tables	Complex layouts, higher SC and REV → high load	Clear markers reduced SC → low load	Simplified, lack of cues raised SC → moderate load
Video	Initial interface uncertainty slightly raised extraneous cognitive load; stabilised after playback	Clearer design reduced extraneous load; processing resources remained for content	Similar to V2; minimal design prevented additional load
Quiz	Poorly structured Q–A pairs increased cognitive load → harder integration of information	Clear formatting lowered extraneous load; cognitive resources freed for task	Minimal layout without distractors reduced load, though less support than in V2

Source: own elaboration.

4.3 Discussion of the Results

The study's results confirm that how digital teaching materials are formatted (visualised) affects the visual behaviour of learners. Screen elements that are properly highlighted draw more attention and keep the gaze on the intended areas. This minimises distraction and allows for smoother navigation between content elements. These findings align with research showing that a well-designed visual structure guides eye movements and reduces chaotic searching of educational content (Gatcho et al., 2024; Liu

& Cui, 2025). They also build on research about creating effective interfaces for training materials (Piwowarski et al., 2024).

Analysis of eye tracking metrics showed that both the number and duration of fixations, as well as dispersion and gaze returns, can be considered indicators of attention and cognitive load processes. Longer fixations were seen as a sign of deeper cognitive engagement. Conversely, a higher number of returns and broader spatial dispersion of gaze indicated difficulties in integrating content components and increased working memory effort (Chytry et al., 2025; Rayner, 2009). Using multiple indicators provided a more comprehensive picture of the changes occurring in cognitive processes, which enhances the reliability of the conclusions drawn.

The aim of the analyses was not only to identify differences in visual behaviour but also to present a methodological approach that enables the study of attention, distraction, and cognitive load in the context of receiving teaching materials. In this respect, the results obtained demonstrate that a set of selected eye-tracking metrics can provide a framework for assessing the quality of designed educational content. This approach is more objective as it relates to human psychophysiological reactions.

The methodological framework developed can be utilised to enhance teaching, both during the design and evaluation of educational materials. This enables predicting which solutions will boost concentration and which may distract attention or increase cognitive load even in the early stages of content development. Incorporating this type of research and analysis into teaching practices helps minimise the element of chance in designing materials.

The research findings can also serve as a foundation for creating a database of models or refining existing ones, which can then be employed to compare different teaching contexts. Such patterns, based on established attention-focusing and cognitive load frameworks, could act as reference points for educational material developers, aid in optimising these materials, and, over the longer term, facilitate the development of data repositories. These repositories could help diagnose issues related to the reception of teaching content and highlight the most effective design solutions.

The proposed methodological approach to designing teaching materials aligns well with the concept of intelligent management of the education process. It facilitates planning and monitoring the teaching process, where materials and strategies can be adapted dynamically to meet the audience's needs. Research using eye tracking and visual metrics helps to identify moments of higher or lower engagement, as well as the risk of cognitive overload, at early stages of design.

Smart management of the teaching process, understood this way, lays the foundation for more personalised education. This concern both the content, the way it is visualised, and how it is received. Consequently, organising the preparation of teaching resources in this manner encourages the development of educational environments that facilitate more effective learning.

5. CONCLUSION

The research showed that using selected eye-tracking metrics (TTFF, FC, TFD, FFD, DAF, DSAF, REV, SC) effectively captures cognitive states crucial for processing teaching materials, such as attention focus, distraction, and cognitive load. Analyses indicated that indicators based on time and the number of fixations particularly reflect changes in concentration, while metrics related to gaze dispersion and returns reveal difficulties in integrating content and the effort involved in processing it. It is important to note that some of these indicators can serve different cognitive functions, and their meaning varies depending on the context. Therefore, the most reliable conclusions are drawn by combining several metrics, providing a more comprehensive view of attention and cognitive load processes.

The results show that the proposed methodological approach offers a valuable framework for evaluating how different visualisations of teaching materials influence their perception. Data from eye tracking can be turned into practical design recommendations that help reduce overload and encourage more effective content understanding.

Another key finding is the possibility of developing a database of visual behaviour patterns from the results obtained. Such a resource could serve as a foundation for creating intelligent, adaptive systems that support the management of the education process.

The limitation of the study remains the small sample size and its specific demographic profile, which may restrict the ability to generalise the results. In future research, it would be beneficial to expand the participant group and incorporate additional psychophysiological indicators, such as electroencephalography, electrodermal activity measurement, or facial expression analysis, to gain a more accurate understanding of the mechanisms of reception and processing of educational information.

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AI-POWERED TAX ATTORNEYS: USING GENERATIVE AI TO ANALYZE TAX LAW TEXTS

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ABSTRACT

Purpose: *The study analyses the potential of Generative Artificial Intelligence (GenAI) in the field of tax law by assessing the ability of Large Language Models (LLMs) to analyse legal texts. The aim is to determine whether LLMs can perform correct and practically useful analyses of tax law.*

Need for the study: *The increasing complexity of legal regulations and the demand for effective legal research require the implementation of AI tools to support lawyers. Tax law, due to partial harmonisation in European Union countries, is an ideal case for evaluating the effectiveness of LLMs in legal analysis.*

Methodology: *The study used an experimental method to test three LLMs: GPT o1-preview (OpenAI), Gemini 2.0 Flash Thinking Experimental 01-21 (GoogleAI Studio) and DeepSeek. The models analysed 54 rulings of Polish administrative courts. Three hypotheses were verified regarding the ability of LLMs to: (1) correctly identify legal provisions and rulings, (2) recognise key legislation and legal institutions, and (3) extract legal arguments from rulings. The results were compared with expert assessments.*

Findings: *The study showed that LLMs can effectively support lawyers in the analysis of tax law. The models achieved high precision in the identification of legal provisions and rulings, with the Gemini 2.0 model achieving the best results. In the more complex analysis of legal theses, the GPT o1-preview model showed the best performance. Overall, the use of LLMs reduced the time needed for legal analysis by up to 90% compared to the work of experts.*

Practical Implications: *The study emphasises the potential of LLMs in increasing the efficiency of tax law analysis and legal cases research. Lawyers can use these models to automate document review, improve legal argumentation and reduce costs. Future research should focus on integrating LLMs into the preparation of pleadings, court justifications and administrative decisions.*

Keywords: Generative AI, Large Language Models (LLMs), Generative Pre-trained Transformers (GPT), law, tax, legal datasets, judicial data, Natural Language Processing (NLP).

JEL Codes: A1, C45, C99, D21, K10, K34.

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1. INTRODUCTION

This study aims to demonstrate the potential for a radical transformation in large law firms' organizational structure and workflows through the application of Generative Artificial Intelligence (GenAI) in document analysis and knowledge management. Tasks delegated to large language models (LLMs) in this research have traditionally been performed by legal professionals, often at significant financial and time costs. The article contributes to the ongoing scholarly discourse on the emergence of hybrid legal organizations – structures in which workflows are shared between human expertise and AI systems. Such a shift holds the promise of fundamentally reshaping legal service delivery, enhancing operational efficiency, and redefining the role of legal practitioners in the post-digital era.

With the emergence of generative artificial intelligence, the legal profession is undergoing gradual change. The use of generative AI (GenAI) (see McKinsey Explainers) in legal practice significantly changes the way the law is analysed and interpreted. GenAI relies on Large Language Models (LLMs), a subset of Artificial Narrow Intelligence (ANI), that uses Machine Learning techniques, including its advanced form – deep learning. The most significant breakthrough in the development of LLM turned out to be GPT (Generative Pre-trained Transformers) networks. These are artificial intelligence models based on transformer architecture, created to analyse, understand and generate text in natural language. The research and implementation work on the use of generative artificial intelligence (GenAI) in the work of lawyers and tax consultants focuses on two main areas. Firstly, the impact of GenAI on the work of lawyers is analysed, including the extent to which GenAI tools support the work of lawyers (Roberts, 2024; Brodeur, Hall & Tynch, 2023). Secondly, the possibility of replacing some of the services provided by lawyers with e-services provided by virtual legal intelligent assistants (GenAI – Paralegal) or virtual lawyers (GenAI – Lawyer) is being considered, which raises both enthusiasm as well as concerns about the accuracy and ethics of these solutions (Ioannidis et al., 2023; Aslett et al., 2024). In particular, the challenges of ensuring generative AI's compliance with legal requirements and its impact on the professional responsibility of lawyers are emphasised (Dashe & Asada, 2023; Alarie, 2024).

In this paper, we present the results of research on the first area, namely the possibility of using GenAI to analyse legal and tax texts. The basic research problem is to answer the question: are LLMs able to make a useful practical and substantively correct analysis of legal and tax texts?

The aim of the presented research, in the context of the research problem posed, is to analyse whether the most developed universal LLM models currently have the ability to conduct correct analyses of tax law texts. The choice of tax law was dictated by the universality of its application (easily accessible large body of tests) and the fact that in the case of European Union member states (such as Poland) this law is partially harmonised. The following LLM were used in the research: 1) GPT o1 – preview by OpenAI; 2) GoogleAI Studio Gemini 2.0 Flash Thinking Experimental 01 – 21; 3) DeepSeek.

In realising the research objective outlined above, the following research hypotheses were verified in the presented research:

- **Hypothesis 1.** LLMs can correctly perform simple analyses of legal and tax texts concerning the identification of the provisions and rulings used.
- **Hypothesis 2.** LLMs have the ability to identify key provisions and legal institutions for a given legal text.
- **Hypothesis 3.** LLMs can perform correctly complex analyses of legal and tax texts concerning the identification of relevant law theses (legal thesis) for the legal text under analysis.

It should be emphasised that GenAI models, in order to be able to perform legal text analysis in a corrected manner, must have the ability to understand legal language and the ability of legal reasoning (law interpretation). In the field of Polish tax law, research on these problems was conducted by T. Strak (Strak, 2024), who positively verified the hypothesis regarding the ability to understand legal language and the ability of legal reasoning.

2. LITERATURE REVIEW

The dynamic development of generative artificial intelligence (GenAI) in combination with techniques such as Retrieval-Augmented Generation (RAG) is significantly changing the field of legal analysis and interpretation. These systems not only improve the process of retrieving legal sources, but also reduce

errors resulting from so-called ‘hallucinatory’ language models, which is crucial in the context of legal fairness. Contemporary research on AI in law focuses on evaluating the effectiveness of these tools in legal practice, their impact on the efficiency of lawyers' work, and the potential for integrating different reasoning methods to increase the precision of analysis. The following section reviews recent developments in the field, covering the application of RAG in legal analysis, legislation and decision-making processes, the effectiveness of different AI models and the challenges of their implementation, including the problem of hallucination and the need for further development of neuro-symbolic systems. Retrieval-Augmented Generation (RAG) techniques enable AI systems to dynamically retrieve and analyse up-to-date legal sources, minimising the risk of ‘hallucinating’ language models and increasing the accuracy of the generated content (Kalra et al., 2024; Pipitone & Alami, 2024). RAG models allow for precise retrieval and citation of legal material, which is becoming crucial in the context of increasing demands for reliability and accuracy in legal analysis. Legal Bench-RAG (Pipitone & Alami, 2024), as one of the first tools to evaluate the effectiveness of RAG systems in the legal field, demonstrates that a structured text extraction approach significantly improves the quality of the generated legal answers (Pipitone & Alami, 2024). RAG is not only applied in legal analysis, but also in the legislative process. The SAVIA tool, based on RAG, enables the analysis of legal acts and their implementation in the context of regional legislation, which shows how AI can support both lawyers and legislators (Visciarelli et al., 2024). In addition, new approaches, such as Case-Based Reasoning (CBR) in RAG models, point to the growing role of a structured approach to legal reasoning in AI systems, which allows for the contextual use of previous rulings and precedents (Wiratunga et al., 2024).

One of the most recent studies on AI in law is the work of Schwarcz et al. (2025), who conducted the first randomised controlled trial evaluating the impact of both RAG and AI reasoning models on the quality of legal work. In the experiment, participants used the Vincent AI tool (RAG system) and the OpenAI o1-preview (AI reasoning model), and their results were compared with a control group without access to AI. The study showed that both tools significantly improved the quality of legal work, with Vincent AI increasing efficiency from 38% to 115% and o1-preview from 34% to 140% (Schwarcz et al., 2025). The AI reasoning model improved depth of analysis, but also introduced more ‘hallucinations’ than the RAG system, which reduced the number of hallucinations to a level comparable to lawyer work without AI. The results suggest that combining RAG capabilities with reasoning models may lead to synergistic improvements in AI for lawyers.In addition, studies confirm that Generative AI can significantly increase the productivity of lawyers. For example, Nielsen et al. (2024) have shown that the use of AI in law firm work can reduce document analysis time by up to 60%. However, the risk of hallucination remains a significant problem – as a study by Magesh et al. (2024) has shown, even RAG systems used in legal tools such as Westlaw AI or Lexis+ AI can generate incorrect information in 17-33% of cases.

In the context of AI reasoning models, neuro-symbolic systems are gaining in importance, combining LLM techniques with formal logical reasoning (Jayakumar et al., 2023, Shui, et al., 2023). This approach improves the quality of legal analyses by better structuring the argumentation and drawing conclusions based on multi-stage reasoning.

Generative artificial intelligence (GenAI) is also finding increasing application in tax law, particularly in automating legal reasoning, retrieving relevant documents and assisting tax lawyers in analysing complex cases. Tax law is a complex field characterised by a high degree of structuring and frequent regulatory changes. AI models such as GPT-4 and its more recent versions have demonstrated the ability to process tax texts, extract key legal principles and formulate legal arguments (Nay et al., 2024). However, while these models excel at analysing patterns in legal documents and generating coherent answers, they often lack the interpretive depth required for complex legal argumentation. Strak (2024) conducted a series of experiments assessing the ability of large language models (LLMs) to understand tax law. The study showed that, while AI can support tax lawyers in formulating answers to legal questions, it has difficulties in analysing legal cases and interpreting individual tax interpretations (PTRs). In particular, the experiment revealed a strong hallucination effect (50% of the cases studied) in the analysis of court rulings. This highlights the need to integrate legal databases with AI models through methods such as RAG.

3. RESEARCH METHODOLOGY

An experimental design was employed to verify the research hypotheses, in which selected GPT models simulated the work of a tax law expert.

Three GPT models with advanced reasoning capabilities were employed in the study. in the study: 1) the GPT o1-preview model from OpenAI, 2) the Gemini 2.0 Flash Thinking Experimental 01 – 21 model from Google, and 3) DeepSeek.

During the experiments, 54 judgments of Polish administrative courts (judgments of Voivodship Administrative Courts -VAC) in tax cases were analysed. The judgments were randomly selected from the Central Database of Judgments of Administrative Courts (https://orzeczenia.nsa.gov.pl/cbo/query).

Table 1 summarizes the VAC judgments analyzed in the experiments.

Table 1. VAC judgments that were used in the experiments

No.	Reference Date	No.	No.	Reference Date	No.
1	I SA/Kr 245/24	19.04.2024	28	SA/Bd 679/19	18.12.2019
2	III SA/Wa 597/24	8.05.2024	29	I SA/Bd 71/23	28.03.2023
3	I SA/Łd 51/24	18.04.2024	30	II SA/Wa 2381/24	16.01.2025
4	I SA/Łd 114/24	9.04.2024	31	I SA/Ol 442/24	15.01.2025
5	II SA/Po 152/24	4.04.2024	32	I SA/Wr 505/24	10.12.2024
6	II SA/Rz 1857/21	24.01.2022	33	I SA/Gd 653/24	19.11.2024
7	I SA/Lu 639/21	4.03.2022	34	I SA/Ol 355/24	13.11.2024
8	III SA/Wa 415/23	20.06.2023	35	I SA/Op 451/24	4.09.2024
9	I SA/Gd 1042/22	7.02.2023	36	I SA/Sz 182/22	12.05.2022
10	III SA/Po 867/14	28.05.2015	37	III SA/Wa 2714/21	12.05.2022
11	III SA/Wa 1575/22	7.02.2023	38	I SA/Go 551/18	6.02.2019
12	III SA/Wa 347/23	15.05.2023	39	I SA/Bd 51/19	7.05.2019
13	I SA/Wr 952/23	19.06.2024	40	III SA/Gl 951/16	5.09.2017
14	I SA/Po 42/22	15.06.2022	41	III SA/Wa 2374/24	29.01.2025
15	I SA/Lu 164/24	7.06.2024	42	I SA/Gl 86/24	27.08.2024
16	I SA/Rz 919/19	13.02.2020	43	I SA/Wr 548/23	13.03.2024
17	III SA/Łd 214/22	6.07.2022	44	I SA/Wr 297/17	13.07.2017
18	VIII SA/Wa 256/24	8.05.2024	45	I SA/Op 299/11	30.11.2011
19	I SA/Ke 219/24	27.06.2024	46	I SA/Bk 421/24	29.01.2025
20	I SA/Wr 104/24	25.06.2024	47	I SA/Gl 93/24	16.09.2024
21	I SA/Lu 734/12	11.12.2013	48	III SA/Wa 1609/23	10.11.2023
22	I SA/Po 198/23	30.01.2024	49	I SA/Gd 805/22	29.11.2022
23	I SA/Wr 106/23	25.01.2024	50	I SA/Po 44/22	31.08.2022
24	I SA/Kr 1692/14	10.03.2015	51	I SA/Ol 602/21	10.11.2021
25	III SA/Wa 3222/14	15.04.2015	52	I SA/Po 679/24	14.01.2025
26	I SA/Wr 392/20	3.02.2021	53	I SA/Gd 991/23	13.02.2024
27	III SA/Wa 374/23	25.05.2023	54	I SA/Bd 146/19	24.04.2019

Source: own elaboration.

The judgments analysed concerned cases concerning the following taxes: VAT (Value Added Tax), CIT **(Corporate Income Tax**), PIT **(Personal Income Tax),** excise duty and inheritance and gift tax. The research experiments were conducted between 20.01.2025 and 28.02.2025. The results of the experiments were verified by three experts in the field of tax law. Each expert analysed 18 rulings of the VAC.

Three research experiments were conducted. Experiment I aimed to verify hypothesis I and proceeded as follows:

1. For 54 judgments, three LLM models were issued to identify the regulations used in the rulings (indicating the normative act and the editorial unit of the legal text) and court decisions (judgments of the Supreme Administrative Court (SAC), judgments of Voivodship Administrative Courts (VAC), judgments of the Court of Justice of the European Union (CJEU)) and tax interpretations (individual tax interpretations and general tax interpretations);
2. Calculating separately, for regulations and judgments, the rates of convergence for each judgment under consideration according to the following formula:

$$Wz_{ij} = \frac{LLM_{ij}}{WSA_{ij}} \quad (1)$$

where:

- Wz – convergence index;
- i – i - this court decision;
- j – value 1 for regulations, 2 for court decisions; 3 for tax interpretations;
- LLM – number of regulations or judicial decision or tax interpretations identified by the model;
- VAC - the number of regulations or judicial decision or tax interpretations used in a given verdict of the VAC;

1. Determination of the average value of the convergence index for the three language models.
2. Evaluation of the obtained results.

Experiment II aimed to verify hypothesis II and included the following steps:

1. Identification by the experts, using metadata in the LEX legal information system, of the three key regulations and the three key legal institutions for each of the 54 judgments analysed.
2. Instructing the three LLMs to identify, for the 54 judgments, the three key regulations and the three legal institutions most relevant to the case.
3. Calculating separately for the key regulations and legal institutions the convergence indices.
4. Determining the average value of the convergence indices for the three language models.
5. Evaluation of the obtained results.

Experiment III aimed to verify research hypothesis III and proceeded as follows:

1. Identifying for 54 rulings the legal cases theses using the theses defined by Wolter Kluwer experts and presented in the Lex legal information system.
2. For 54 rulings, issuing a command to three LLM to identify the jurisprudential theses on the basis of an example made by the expert to identify the jurisprudential theses, which were formulated in an exemplary verdict of the VAC.
3. Assessing the accuracy of the identified theses using the following criteria: relevance and completeness, correctness, precision.
4. Determination of indicators of the effectiveness of the identification of theses using the following formula

$$QLT = \frac{C_1+C_2+C_3}{3} \quad (2)$$

where:

- QLT – Quality of Identification of Law Theses;
- C_1 – a measure to assess the relevance and completeness of the LLM's formulated theses; where: 1 – all relevant theses were identified in the judgment; 0.5 - at least one relevant thesis was identified; 0 - no relevant theses were identified;
- C_2 – a measure to assess the correctness of the LLM's identified theses; where: 1 – all identified theses are factually correct; 0 - at least one identified thesis is factually incorrect;
- C_3 – a measure to assess the precision of the theses formulated by the LLM; where: 1 – all these are formulated in an unambiguous and precise manner; 0.5 – one thesis is imprecise (vague or ambiguous); 0 - at least two theses are imprecise.

5. Determination of the average value of the convergence indexes for the three language models.
6. Evaluation of the obtained results.

4. RESEARCH RESULTS AND DISCUSSION

4.1 Experiment I

The aim of Experiment I was to assess the ability of selected universal LLM models to perform in a corrected manner an analysis of court judgments consisting in the identification of the regulations used in these judgments (indication of the normative act and the editorial unit of the legal text) as well as court decisions (rulings of the SAC, rulings of the VAC, rulings of the CJEU) and tax interpretations.

This analysis is carried out in order to build a database of court rulings and, for the purposes of training junior lawyers at the firm. It allowed the identification of particular regulations for the analysed rulings, which is important for preparing pleadings and forming justifications for rulings.

Table 2 presents the results obtained for each LLM.

Table 2. Average value of convergence indexes for each LLM

No.	Model	Wz1	Wz2	Wz3
1	GPT o1-preview	0.98	0.99	0.99
2	Gemini 2.0 Flash Thinking Experimental 01-21	0.99	1.00	1.00
3	DeepSeek	0.95	0.94	0.95

Source: own elaboration based on conducted experiment.

Where:

- Wz1 – convergence index of identified regulations;
- Wz2 – convergence index of quoted rulings of the VAC, SAC and CJEU;
- Wz3 – convergence index of quoted tax interpretations.

The result obtained from Experiment I indicates the high utility of using the LLM to carry out this type of analysis. The best results were obtained for the Gemini 2.0 model. This model for each of the 54 judgments analysed identified all judgments and tax interpretations quoted in the legal justification. In addition, in 50 judgments, the model identified all the provisions quoted in the legal reasoning. The model performed a fully accurate analysis for 25 cases. The worst results were obtained for the DeepSeek model. This model gave the correct legislation, decisions and interpretation. However, it did not indicate all regulations and all quoted rulings or interpretation. The model for 25 cases performed a fully accurate analysis. In the case of GPT o1-preview, for 40 cases it performed a fully accurate analysis. To summarise the results of Experiment I, it should be stated that hypothesis 1 was positively verified, i.e. LLMs are useful in supporting lawyers when analysing legal and tax texts regarding the identification of the legislation and judgements used.

Furthermore, it should be added that on average, an expert needed about 15 minutes to perform this type of analysis. On average, LLM models performed such an analysis in about 10 seconds.

4.2 Experiment II

The aim of Experiment II was to assess the ability of the selected universal LLM models to assess the relevance of the provisions used in the legal reasoning of the analysed judgments, and to correctly identify, the key legal institutions for the legal classification of the analysed cases.

The first stage of this experiment was for the experts to identify, using metadata from the LEX legal information system, three key regulations and three key legal institutions for each of the 54 rulings analysed. On average, the time required for the expert to carry out such an analysis on his/her own was approximately 25 minutes for one court verdict.

The analysis performed in Experiment II required language models to have the ability to assess the relevance of the provisions used and knowledge of the legal institutions for tax law and the ability to identify them. This was a much more complex analysis than in Experiment I.

Table 3 presents the results obtained for Experiment II for each LLM.

Table 3. Average value of convergence indexes of key legislation (Wz4) and legal institutions (Wz5) for each LLM

No.	Model	Wz4	Wz5
1	GPT o1-preview	0,85	0,88
2	Gemini 2.0 Flash Thinking Experimental 01 – 21	0,96	0,94
3	DeepSeek	0,80	0,78

Source: own elaboration based on conducted experiment.

The result obtained from Experiment II indicates the usefulness of using the LLM to carry out this type of analysis. The best results were obtained for the Gemini 2.0 model. This model correctly identified:

1. All three key legal provisions were correctly identified for 47 rulings; 2 key legislation was correctly identified for 7 rulings.
2. Identified all three key legal institutions correctly for 44 rulings; for 10 rulings it identified 2 legal institutions correctly.

The worst results were obtained for the DeepSeek model. This model correctly identified:

1. Identified all three key legal provisions correctly for 36 rulings; identified 2 key legislation correctly for 8 rulings; identified one key legislation correctly for 6 rulings; identified no key legislation correctly for 4 rulings.
2. All three key legal institutions were correctly identified for 37 rulings; for 5 rulings, 2 legal institutions were correctly identified; for 6 rulings, one legal institution was correctly identified; for 6 rulings, no legal institutions were correctly identified.

For GPT o1-preview, the following results were obtained:

1. All three key legal provisions were correctly identified for 39 rulings; for 9 rulings, 2 key legislation was correctly identified; for 3 rulings, one key legislation was correctly identified; for 3 rulings, no key legislation was correctly identified.
2. All three key legal institutions were correctly identified for 39 rulings; 2 legal institutions were correctly identified for 11 rulings; 1 legal institution was correctly identified for 4 rulings.

Summarising the results of Experiment II, it should be stated that hypothesis 2 was positively verified, i.e. LLMs are useful in supporting lawyers in the analysis of legal and tax texts concerning the identification of key legislation and legal institutions. Furthermore, it should be added that on average an expert needed about 25 minutes to perform this type of analysis. On average, LLM models performed such an analysis in about 10 seconds.

4.3 Experiment III

The aim of Experiment III was to assess the ability of selected universal LLM models to conduct an analysis of court decisions, the purpose of which is to define the legal cases theses contained in the analysed judgments. The identification of legal cases theses (often referred to as 'judgment theses' or 'decision theses') is of great importance in the practice of the Polish justice system, despite the fact that the principle of precedent is not formally binding in Poland.

Legal cases theses help to clearly and quickly read the most important conclusions from the ruling, which brings several practical benefits: facilitating the work of legal practitioners, improving trial arguments, organising and standardising legal cases, facilitating access to legal knowledge and strengthening legal certainty. Publications (e.g. in LEX, Legalis or other legal information systems) usually present rulings together with theses - this significantly reduces the time needed to familiarise oneself with the essence of the judgement. Students and researchers also use theses for educational and research purposes.

The analysis of a tax verdict by the VAC, which results in the identification of legal theses, takes a specialist about 30 minutes.

Table 4 presents the results obtained for experiment III.

Table 4. Results of experiment III

No.	Model	C1	C2	C3	QLT
1	GPT o1-preview	0.98	0.98	0.93	0.96
2	Gemini 2.0 Flash Thinking Experimental 01 – 21	0.83	0.98	0.83	0.88
3	DeepSeek	0.80	1.00	0.75	0.85

Source: own study based on the experiment conducted.

where:

- C1 – a measure of the assessment of the significance and completeness of the theses formulated by the LLM;

- C2 – a measure of the assessment of the correctness of the theses formulated by the LLM;
- C3 – a measure of the assessment of the precision of the theses formulated by the LLM;
- QLT – Quality of Identification of Law Theses.

The weakest results were obtained for the C3 indicator (thesis accuracy). The following number of cases involved too generally formulated theses:

1. GPT o1-preview – 8 cases;
2. Gemini 2.0 Flash Thinking Experimental 01-21 – 18 cases;
3. DeepSeek – 27 cases.

For all analysed models, results were obtained indicating the usefulness of LLM for identifying legal theses. In the case of the GPT 01 - preview models, very good results were obtained, which are comparable to the results obtained in the case of identification of legal theses by experts in the field of tax law. The average time needed for an expert to identify the legal thesis in a verdict of the VAC (Regional Administrative Court) concerning tax law is about 30 minutes. In the case of LLM, the time needed for such an analysis was 20 seconds. Experiment III was also extended to include an analysis of the time needed for an expert to identify legal theses when supported by the LLM model. Only the GPT o1-preview model was used for this analysis. In this case, the average time needed for an expert to formulate legal theses for one verdict was approximately 10 minutes.

It should be emphasised that the results obtained for experiment III allowed for a positive verification of hypothesis 3. Moreover, they potentially indicate significant financial savings. For example, the cost of an analysis aimed at identifying legal theses for 100 VAC rulings is approximately PLN 15,000 (at an hourly rate of PLN 300). In the case of using LLM, taking into account the work of an expert concerning only the verification of LLM results, it is approximately PLN 3,000.

5. CONCLUSION

The results obtained from the tests conducted in relation to the LLM models allow the following main conclusions to be drawn for Polish tax law:

1. LLMs are useful tools to support experts in the analysis of legal and tax texts.
2. LLM models are useful for both simple and complex legal analyses.
3. The quality of the results obtained and the time taken to generate them indicate that their use can lead to a real reduction in the cost of legal services.
4. The usefulness of the test LLM models is similar, however:
   a) for analyses aimed at identifying regulations, rulings and legal institutions, the best results were obtained for the Gemini 2.0 Flash Thinking Experimental 01-21 model;
   b) in the case of complex legal analyses aimed at identifying judicial theses, the best results were obtained for the GPT o1-preview model.
5. The time needed to perform legal analyses, which was the subject of experiments carried out without the support of LLM models, is about three times longer than the time needed for such analyses to be performed by an expert with the support of LLM. In the case of such analyses being performed automatically by LLM, the analysis time was reduced by a factor of ninety compared to manual expert evaluation, then in the case of such an analysis being performed by an expert.

Further research on the usefulness of LLM models for analysing legal and tax texts should focus on assessing the usefulness of LLM models to support lawyers in preparing pleadings and justifications for rulings or tax decisions.

Future studies should continue to explore the integration of LLMs into the preparation of pleadings, court rulings, and administrative decisions, emphasizing both practical benefits and ethical considerations.

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AI TOOLS IN THE EVALUATION OF CONTENT MANAGEMENT SYSTEM DATABASES

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ABSTRACT

Purpose: *The study evaluated the effectiveness of AI tools in automatically assessing student database projects in content management systems (CMS). It focused on evaluation criteria covering data structure, performance, integrity, scalability, and business context.*

Need for the Study: *Assessing CMS database projects is complex, combining technical and business considerations. With increased reliance on data, efficient and objective evaluation methods are needed. AI offers potential for automation, but its reliability and alignment with expert judgment were unclear, motivating the study.*

Methodology: *Several AI models (e.g., ChatGPT, Google Gemini, Microsoft Copilot, DeepSeek, and Grok3) were used to grade a set of student CMS database projects. Their scores on the five criteria were compared to expert reference evaluations to gauge accuracy and consistency.*

Findings: *DeepSeek and Microsoft Copilot showed the smallest deviations from expert grades but struggled to distinguish the highest- and lowest-quality projects (indicating score smoothing). Grok3 was the most balanced, closely aligning with experts while preserving some variability. In contrast, ChatGPT and Google Gemini had larger deviations and tended to misjudge project quality (over- and under-scoring respectively).*

Practical Implications: *AI tools show promise for streamlining database project evaluation in educational and business contexts by speeding up grading and providing initial feedback. However, limitations like averaged-out scoring and difficulty capturing context mean they cannot replace human experts. Further refinement—such as better handling of outlier cases and integration with analytical tools—is recommended to improve reliability. With improvements, AI evaluators could become valuable support tools in academia and industry.*

Keywords: AI Tools, AI Evaluation, AI Accuracy, Database Evaluation, CMS, Education, Social Sciences

Jel codes: M15, C88, I23

1. INTRODUCTION

The evaluation of databases in Content Management Systems (CMS) represents a complex research challenge, integrating technical aspects such as data structure normalization and query performance with their implications for business processes in social sciences, including economics, finance, and management. In the digital era, marked by the increasing importance of data as a cornerstone for

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decision-making, ensuring database integrity, scalability, and efficiency becomes crucial and necessitates precise analytical methods (Zhou et al., 2023). The introduction of artificial intelligence tools, particularly generative language models, provides new avenues for automating this process, potentially supporting the analysis of data structures and optimizing database designs (Bychkov et al., 2018). However, their application raises questions regarding reliability, the capability to grasp business context, and alignment with expert evaluations (Hamilton et al., 2024).

This article attempts to identify the most effective AI tool for evaluating CMS databases by comparing popular models such as ChatGPT, Google Gemini, and Grok3 in terms of their effectiveness in analyzing key criteria: structure, performance, integrity, scalability, and business adequacy (Sukhija et al., 2017). The research outcomes aim to provide recommendations for educational and business practices, highlighting the potential and limitations of contemporary AI technologies in this domain (Mohapatra & Mishra, 2023).

The research hypothesis formulated in this study is as follows: Artificial Intelligence (AI) tools can effectively evaluate database designs in the context of Content Management Systems (CMS); however, their ability to reflect expert assessments and differentiate projects of markedly varying quality remains limited, necessitating further development and adaptation to specific evaluation criteria.

The primary objective of this research is to assess the effectiveness of widely available AI tools in automatically evaluating student database projects by comparing their outputs with expert reference assessments, thereby identifying the most reliable tool and understanding its limitations within educational and professional contexts. The following specific objectives have been defined:

- Analyzing the consistency between evaluations generated by AI tools (such as ChatGPT, Google Gemini, Microsoft Copilot, Perplexity AI, DeepSeek, and Grok3) and expert assessments for database projects.
- Determining which AI tool produces evaluations closest to reference assessments, considering the sum of absolute deviations and standard deviation.
- Investigating the degree to which AI tools can differentiate between projects of varying quality, with particular emphasis on projects receiving extremely high or low evaluations.
- Identifying weaknesses of AI tools in evaluating critical criteria such as data structure, performance, integrity, scalability, and business context.
- Proposing specific improvements or further research directions to enhance the precision and usability of AI tools in automatically assessing database projects.

2. ASSESSMENT OF DATABASE SYSTEMS: AN INTERDISCIPLINARY PERSPECTIVE

The evaluation of database systems, particularly within the context of Content Management Systems (CMS), represents a complex research challenge necessitating consideration of both technical aspects and their impact on business processes. Literature emphasizes that, in the era of digitalization and the growing significance of data in social sciences – particularly in economics, finance, and management – databases have become a critical infrastructure component for decision-making support, efficiency analysis, and the optimization of organizational processes (Porter, 1985). This complexity stems from the simultaneous requirement to meet technical criteria, such as data structure normalization and query performance, and to tailor solutions to specific business needs, thereby making database evaluation an interdisciplinary challenge (Laudon & Laudon, 2019). The introduction of artificial intelligence (AI) tools, including generative language models, further complicates this issue, creating new opportunities but also raising questions about the credibility and precision of analyses (Goodfellow et al., 2016).

Literature indicates that databases within CMS systems serve as the foundation for information storage, processing, and dissemination, directly influencing organizational effectiveness in economic and managerial areas (Drucker, 1999). Studies suggest that a properly designed database should exhibit a high level of normalization, reducing data redundancy and facilitating updates (Codd, 1970). However, Date (2003) observes that excessive normalization can diminish query performance, particularly problematic when handling large data volumes—a scenario increasingly common in enterprises managing digital content (Elmasri & Navathe, 2015). In social sciences, particularly finance, ensuring data integrity is crucial for maintaining real-time consistency of financial information (Gray & Reuter, 1992).

Database performance is another critical aspect addressed in literature. In CMS systems, where users expect rapid content access, database structures must enable efficient select and update queries (Garcia-Molina et al., 2008). Research indicates that optimizing indexes and appropriately selecting data types can significantly enhance system response times, essential in business-oriented content management (Ramakrishnan & Gehrke, 2002). Nevertheless, Silberschatz et al. (2019) stress that designing efficient databases requires balancing speed with scalability, complicating quality assessments under dynamic market conditions (O'Neil & O'Neil, 2000).

Scalability – the capability of systems to manage increasing data volumes without performance degradation – is especially important in economics and management, where big data analysis has become a standard practice (Chen et al., 2012). Literature notes that systems like PostgreSQL, due to their flexibility and advanced feature support, are frequently chosen for business applications (Stonebraker & Cetintemel, 2005). However, Connolly and Begg (2014) highlight that inadequate relationships between tables or incorrect application of constraints can negatively impact integrity and scalability, complicating database design evaluation.

In a business context, literature underscores the necessity for database structures to reflect industry-specific requirements—for example, finance demands precise transaction tracking, while management requires flexible structures for process analysis (Mintzberg, 1979). Failure to adapt database designs to these needs may result in inefficient resource use, especially significant in economics, where cost optimization remains a priority (Kaplan & Norton, 1996).

Introducing artificial intelligence, particularly generative language models, to database evaluation opens new avenues yet poses challenges related to reliability and understanding of complex data structures (Russell & Norvig, 2020). Literature suggests AI can analyze data structure correctness, detect normalization anomalies, and evaluate SQL query performance (Mitchell, 1997). For instance, Vaswani et al. (2017) demonstrate models like ChatGPT or Grok effectively support evaluation processes by generating reports and optimization guidance. However, Russell (2019) warns that models' incomplete comprehension of technical contexts might lead to superficial or erroneous evaluations.

Recent years have seen increased use of generative AI to automate student work assessments, including database projects (Zawacki-Richter et al., 2019). Tools such as ChatGPT (Brown et al., 2020) and Google Gemini (Google, 2023) are tested for their capabilities to analyze SQL scripts and evaluate compliance with normalization standards (Zhang et al., 2022). However, literature highlights that AI effectiveness depends on training data quality (Marcus, 2018), the interpretation of business contexts (Brynjolfsson & McAfee, 2017), and avoiding errors from excessive generalization (Floridi, 2023).

For example, research by Lodge et al. (2023) indicates language models can identify errors in foreign keys effectively but struggle with assessing structural adequacy to industry specifics (e.g., CMS for the financial sector). In this context, interdisciplinary studies integrating technology with social sciences, such as the analysis of data structure impact on corporate content management efficiency, are crucial (Davenport & Harris, 2017).

In social sciences, generative AI applies not only to database analysis but also to student assessment. Studies reveal AI tools increasingly facilitate automated evaluation of programming assignments, including database projects, reducing expert workload and delivering rapid results (Finnie-Ansley et al., 2022). Brown et al.'s (2020) experiment evaluating ChatGPT's capability in SQL code analysis found AI assessments aligned with human evaluations in 70% of cases. Similar conclusions emerge from studies on AI application in content management, where language models supported database designs tailored to business requirements (Davenport & Ronanki, 2018).

However, literature emphasizes generative AI limitations. Brynjolfsson and McAfee (2017) note these models may struggle evaluating nuanced aspects such as business context or long-term scalability, necessitating expert intervention. In finance, where data precision is paramount, AI tools must be calibrated with specific criteria to mitigate errors (Froot & Stein, 1998). Additionally, Chollet (2017) highlights discrepancies between models – such as ChatGPT versus Perplexity AI – that can influence evaluation consistency, complicating tool selection.

In conclusion, literature underscores that the evaluation of database systems within CMS is multidimensional, incorporating technical aspects and their significance for social sciences. Generative AI offers promising prospects, especially in education and business optimization; however, its limitations suggest further research is necessary to enhance contextual and scalability analysis capabilities.

3. METHODOLOGY

The selection of tools was based on their prevalence, accessibility, and potential capability for analyzing database projects. Each tool was examined regarding its core functionalities and their relevance in the evaluation context. This process involved reviewing literature, official documentation, and user reports, enabling the identification of each tool's key characteristics. For instance, ChatGPT was examined using studies by Xinyi et al. (2024), which highlight the effectiveness of language models in code analysis, whereas Google Gemini relied upon Google's official announcement from 2023. For less familiar tools, such as DeepSeek, potential capabilities were assumed based on available information, warranting further investigation.

ChatGPT: Developed by OpenAI, ChatGPT is a language model built on the GPT architecture capable of generating natural language-like text. Its primary applications include content generation, programming assistance, and text analysis. In assessing database projects, ChatGPT can analyze SQL scripts and database structure descriptions. Potential assessment capabilities include data structure (normalization level, data type selection, primary and foreign keys, inter-table relationships, and constraints), performance (suggesting query optimizations, evaluating whether structures support efficient updates and selects, and enabling easy optimization for large data volumes), integrity (verifying data consistency and correctness through analysis of constraints and relationships), scalability (evaluating structure capability for handling extensive data with minimal performance degradation), and business context (assessing project suitability for CMS domains by verifying the inclusion of essential tables and relationships). Studies such as Xinyi et al. (2024) indicate that language models like ChatGPT effectively analyze code and database structures, rendering them suitable for this task.

Google Gemini: Announced by Google in 2023, Google Gemini is a multimodal AI model capable of processing text, images, audio, and other data types. Its objective is to facilitate more natural interactions with AI, suggesting potential application in analyzing various database project representations, including ER diagrams or SQL scripts. In the evaluation context, Gemini can analyze textual descriptions or diagrams to assess normalization and relationships, potentially simulate queries, or predict performance based on structure; however, capabilities in these areas require further research. It can also check data consistency through constraints and relationships, evaluate scalability based on project structure (though literature remains limited), and assess the project's alignment with business requirements, particularly in CMS systems requiring integration of diverse data types. Due to its novelty, detailed research on Gemini's capabilities is limited, but Google's official announcement suggests considerable versatility (Gemini, 2023).

Microsoft Copilot: Introduced in 2021, Microsoft Copilot is an AI assistant integrated into platforms like Visual Studio and GitHub, designed to support programmers in code writing, including SQL. Its primary features include suggesting code completions, correcting errors, and optimization. For database project evaluations, Copilot can analyze SQL scripts, suggesting improvements related to normalization, data types, keys, and relationships, propose query and structural optimizations for enhanced performance (especially with large datasets), verify and recommend constraints such as foreign keys or uniqueness for data consistency, evaluate the design's capacity to manage increasing data volumes, and, although not directly focused on the business context, assist in adapting code to CMS system requirements if previously defined. GitHub documentation highlights Copilot's utility in code analysis, making it suitable for project evaluation.

Perplexity AI: Perplexity AI is an AI-powered search engine that provides precise answers to queries with citations, functioning as an advanced research tool. While not directly designed for database project evaluations, it supports this process by locating recent practices and standards in database design for specific domains, such as finance or management, essential for CMS systems. It finds information on best practices regarding normalization, data types, and relationships useful for project assessments and identifies effective design methodologies for handling large data volumes, supporting the evaluation of these aspects. Although its role is more indirect, it provides context and knowledge on which experts or other AI tools can base assessments. The official Perplexity AI website emphasizes its research capabilities (Perplexity, 2025).

DeepSeek: Assuming DeepSeek is an AI tool focused on deep data analysis, it might employ machine learning techniques for advanced database project evaluations. Potential applications include forecasting project performance with large datasets by analyzing historical patterns, statistical or pattern-

based structural analyses for evaluating quality, such as normalization levels and relationships, and consistency checks based on patterns and constraints. However, DeepSeek's precise functionalities in this domain are not entirely clear, indicating lower popularity or specialized applications. The DeepSeek AI website emphasizes its data analysis focus, warranting further database-related research (DeepSeek, 2025).

Grok3: Created by xAI, Grok3 is a language model aiming to be helpful and curious, resembling ChatGPT. It can analyze SQL scripts and project descriptions, providing feedback on normalization, data types, keys, relationships, query optimization suggestions based on its knowledge, constraint and relationship validation for data consistency, scalability assessment regarding large data volumes, and understanding the CMS system's thematic context to evaluate project suitability. Grok3's unique features, such as its inquisitiveness and information-seeking capabilities, may enable it to conduct deeper analyses. xAI's official announcement underscores its versatility (Grok, 2025).

The aim of the research experiment was to evaluate ten database projects prepared by second-year Computer Science students. Each project pertained to a different business context for a content management system and was implemented as an SQL script intended for deployment in the PostgreSQL database management system. Projects varied significantly in quality, as reflected in the final evaluations provided by an expert assessor. Nevertheless, among all the projects, three were selected which had received identical final scores. Project evaluations were based on five key criteria.

Data Structure – This criterion assessed the level of normalization to ensure databases achieved an appropriate normal form (e.g., Third Normal Form – 3NF), thus minimizing redundancy and avoiding anomalies during data operations such as insertion and updates. The correctness of chosen data types was evaluated to ensure they were suitable for stored values (e.g., INT for integers, VARCHAR of appropriate length), affecting memory efficiency and query performance. Additionally, primary and foreign keys were reviewed for uniqueness, correctness of table relations, and referential integrity maintenance. Relations between tables (one-to-one, one-to-many, many-to-many) were analyzed for correct implementation, such as the use of junction tables in many-to-many relationships, and the application of constraints (e.g., NOT NULL, UNIQUE, CHECK) was reviewed to ensure data consistency and adherence to business requirements.

Performance – Databases were assessed for their ability to rapidly and efficiently execute update queries (UPDATE operations), including evaluations of the impact of indexes, normalization, and potential locks on operation duration, especially during extensive data modifications. The efficiency of executing select queries (SELECT operations) was also analyzed, paying close attention to optimal index usage, minimization of JOIN operations, and query selectivity to ensure rapid data retrieval even under complex filtering conditions. Furthermore, performance optimization potential was evaluated for handling large data volumes, including table partitioning, composite indexing, and sharding, facilitating scalability and performance maintenance with growing record numbers. Tests were conducted on both small and large datasets to verify structural robustness under various workloads, accounting for system resource utilization, such as CPU and I/O.

Integrity – Projects were evaluated regarding data consistency and correctness throughout system operations, fundamental for stability and reliability in delivering accurate information. The analysis involved verifying mechanisms such as foreign keys with cascading rules (CASCADE) or restrictions (RESTRICT) to prevent scenarios where parent data is deleted without updating associated records. Constraints enforcing data integrity, such as NOT NULL and CHECK, were examined to ensure only valid data entry, eliminating risks such as empty fields in critical columns or inconsistent data entries. Additionally, the robustness of the system against anomalies resulting from concurrent operations (e.g., via transactions and locks) was assessed, ensuring consistency during intensive multi-user scenarios.

Scalability – Analysis focused on the database structures' capability to efficiently store and manage large datasets without significant operational performance degradation. Evaluation criteria included verifying that index structures and table relationships were optimized for maintaining query and update speeds, even with millions of records, thus avoiding bottlenecks such as excessive table scans. Schema flexibility was also assessed, specifically its adaptability for future expansions, such as adding new columns or tables, without requiring extensive database restructuring.

Business Context – The adequacy of the solutions was assessed based on alignment with specific business requirements, considering organizational goals and domain-specific needs. Evaluations examined whether the proposed solution effectively supported business processes and was appropriately

tailored to industry specifics. Particular attention was paid to table completeness, ensuring the data structure contained all essential information necessary for correct system functionality. Moreover, data relationships were scrutinized to confirm effective storage, processing, and retrieval, ensuring consistency and alignment with user expectations.

Each project was evaluated both by an expert and by six widely accessible AI tools: ChatGPT, Google Gemini, Microsoft Copilot, Perplexity AI, DeepSeek, and Grok3. These AI tools were selected due to their popularity, extensive application in data analysis, and their capability to generate evaluations closely resembling human assessments. The previously mentioned database evaluation criteria were provided to each AI tool. Evaluation scores were assigned on a scale from 2 to 5, consistent with the expert's grading approach. The final project score for each AI tool was calculated as the arithmetic mean of ratings across individual criteria.

A variance analysis was performed to find the AI tool with standard deviations closest to expert evaluations. This analysis aimed to ascertain the consistency level between the variability in AI-generated scores and expert evaluations, serving as a critical indicator of the stability and reliability of AI tools in the context of database project assessments. Finally, AI-generated results were compared to the expert's reference evaluations to identify the tool best replicating the expert approach in database project evaluations. This comparison involved calculating the cumulative distance from reference scores assigned by AI tools, with the tool yielding the lowest cumulative distance and a standard deviation closest to the expert reference considered as best approximating expert judgment.

4. RESULTS

The Fig. 1 illustrates the reference ratings for ten projects, labeled consecutively from 1 to 10. These ratings, assigned by experts, range between 3.00 and 4.50, suggesting a varying quality among the evaluated projects.

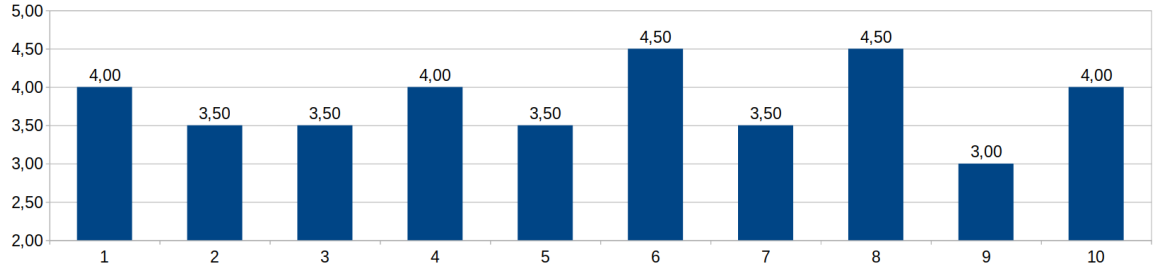


Figure 1. CMS database projects reference ratings
Source: own elaboration.

Most projects (positions 2, 3, 5, and 7) scored 3.50, showing consistent quality. Two projects (positions 6 and 8) stand out with the highest rating of 4.50, potentially reflecting their exceptional quality compared to others. Conversely, project number 9 received the lowest score of 3.00, suggesting it was considered the least valuable in the series. Projects numbered 1, 4, and 10 received ratings of 4.00, placing them in an intermediate quality range, slightly above average. The distribution of scores highlights that AI tools should be tested for their ability to reflect both extreme values (e.g., 3.00 and 4.50) and recurring ratings (e.g., 3.50) to evaluate their precision and consistency against expert assessments. The histogram clearly emphasizes the diversity in project quality, providing a suitable foundation for verifying the effectiveness of AI algorithms in analysis and classification tasks.

Fig. 2 and Fig. 3 presents comparisons between project evaluations conducted by various AI tools and the expert-established reference values. The reference values (green line) reflect expert ratings, while the bars represent scores assigned by individual AI models.

It can be observed that ChatGPT consistently overrates projects relative to the reference scores. For most projects (1, 3, 4, 5, 7, 8, and 9), ChatGPT ratings are 4.30 or higher, reaching up to 4.80 for projects 7, 8, and 9. The most significant discrepancies occurred in projects 7 (4.80 vs. 3.50) and 9 (4.80 vs. 3.00), indicating substantial difficulties in accurately assessing these projects. Grok3 presents more diverse evaluations, often closer to the reference values. For example, in projects 1 (4.10 vs. 4.00), 2

(3.60 vs. 3.50), and 8 (4.60 vs. 4.50), the differences are minor. However, in project 9 (4.00 vs. 3.00), Grok3 also overrates the assessment, although to a lesser extent than ChatGPT. The greatest deviation occurs in project 6 (3.80 vs. 4.50), where Grok3 underrates the project.

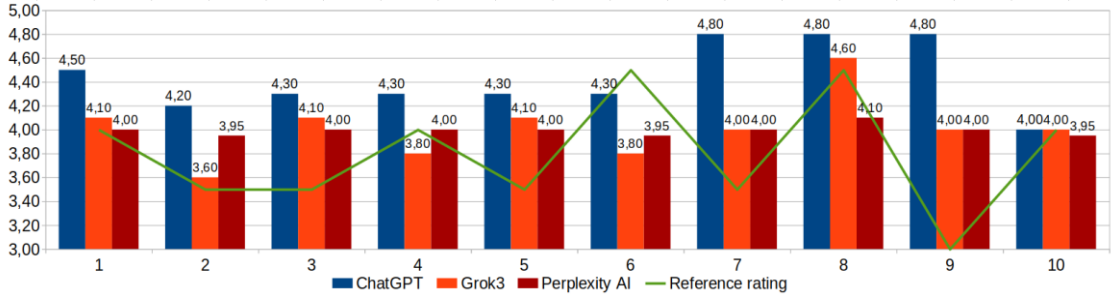


Figure 2. AI tool ratings of projects compared to reference ratings – ChatGPT, Grok3, Perplexity AI
Source: own elaboration.

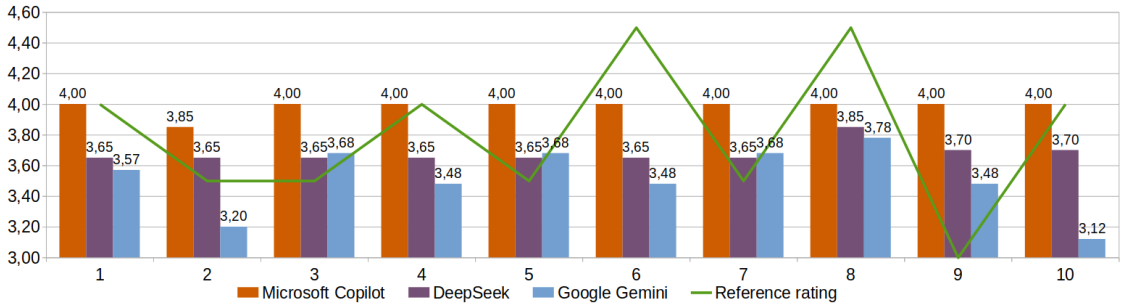


Figure 3. AI tool ratings of projects compared to reference ratings – Microsoft Copilot, DeepSeek, Google Gemini
Source: own elaboration.

Perplexity AI precisely matches reference values for projects 1 and 4 (both rated 4.00). Moderate deviations are observed in projects 2 (3.95 vs. 3.50) and 6 (3.95 vs. 4.50). A tendency to smooth evaluations across projects of varying reference ratings negatively impacts the usefulness of this tool. Microsoft Copilot demonstrates a similar trend, assigning a rating of 4.00 to nearly every project, with only a slight deviation toward the reference value for project 2. The most significant deviation is in project 6 (4.00 vs. 4.50), where Copilot underrates the value.

DeepSeek, like Perplexity AI and Copilot, is characterized by relatively uniform ratings but at a lower level, ranging around 3.65–3.85. In projects 2 (3.65 vs. 3.50), 3 (3.65 vs. 3.50), and 7 (3.65 vs. 3.50), its ratings closely align with reference values. However, for higher-rated projects such as 6 (3.65 vs. 4.50) and 8 (3.85 vs. 4.50), DeepSeek clearly underrates the scores. Conversely, in project 9 (3.70 vs. 3.00), it overrates the value.

Google Gemini exhibits some of the largest discrepancies among the evaluated projects. Its scores are frequently too low compared to reference ratings, notably in projects 2 (3.20 vs. 3.50), 6 (3.48 vs. 4.50), and 10 (3.12 vs. 4.00). The most significant deviation occurs in project 10, with a difference of 0.88. For projects 3 (3.68 vs. 3.50) and 7 (3.68 vs. 3.50), Gemini slightly overrates the evaluations. For Copilot, DeepSeek, and Perplexity AI, the uniformity of ratings across projects with significant variability in reference scores is problematic.

Fig. 4 displays average ratings of six AI models compared to the average of the reference values. Microsoft Copilot (3.99) and DeepSeek (3.68) show the greatest alignment with reference values, whereas ChatGPT (4.43) and Google Gemini (3.52) exhibit the least consistency.

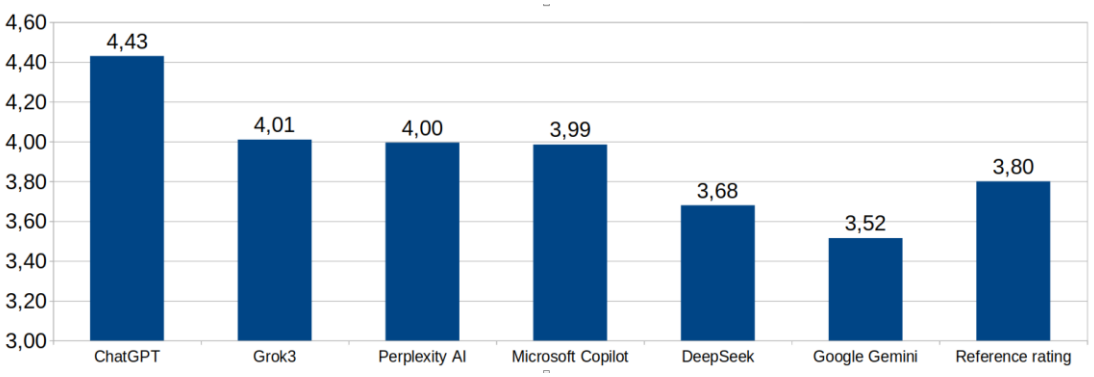


Figure 4. Average ratings of AI models and average of the reference ratings
Source: own elaboration.

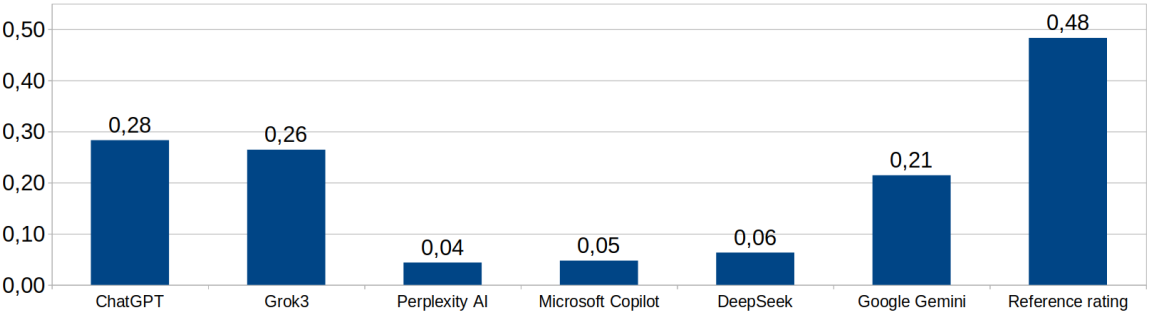


Figure 5. Standard deviations of AI-generated and reference ratings
Source: own elaboration.

According to the established criteria, the standard deviation was also analyzed and shown in Fig. 5. The standard deviation of reference values indicates considerable variability among project ratings, suggesting significant differences in project quality. The standard deviation for ratings generated by each AI tool was substantially lower. Perplexity AI, Microsoft Copilot, and DeepSeek notably deviate from the reference standard, suggesting these tools struggle with accurately assessing projects of varying quality levels.

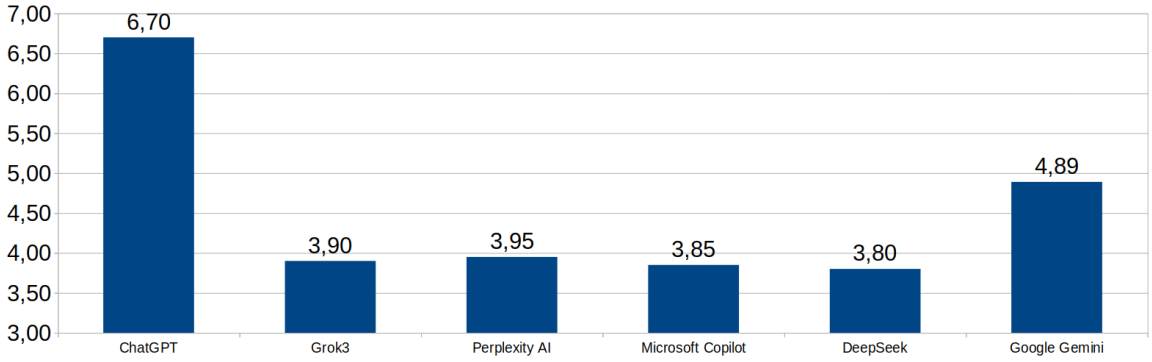


Figure 6. Standard deviations of AI-generated and reference ratings
Source: own elaboration.

Fig. 6 illustrates the sum of absolute deviations between ratings given by AI models and the reference ratings established by experts. The lowest sum indicates the model whose ratings most closely align with expert ratings. DeepSeek (3.80) and Microsoft Copilot (3.85) exhibit the smallest sums of deviations, making them the most consistent with the reference ratings. Google Gemini (4.89) and ChatGPT (6.70) have the highest deviations, indicating lower consistency – Google Gemini primarily

due to underrating, and ChatGPT due to overrating. Grok3 (3.90) and Perplexity AI (3.95) fall within a mid-range, offering acceptable but not ideal alignment.

5. DISCUSSION

The results highlight significant differences in AI tools' ability to replicate expert evaluations. DeepSeek and Microsoft Copilot demonstrated the closest alignment with reference scores, suggesting their potential for preliminary assessments. However, their low standard deviations – indicative of score smoothing – reveal a critical limitation: an inability to distinguish between high- and low-quality projects. This undermines their utility in educational contexts, where nuanced feedback is essential for student development.

ChatGPT's tendency to overrate projects, particularly those with major flaws (e.g., Project 9), suggests a bias toward leniency, possibly due to training on idealized examples. Conversely, Google Gemini's underestimation of quality may stem from overly conservative evaluation heuristics. These discrepancies underscore the challenges of aligning AI outputs with human judgment, especially when contextual or industry-specific nuances (e.g., financial sector requirements) influence assessments.

The smoothing effect observed in Perplexity AI, Copilot, and DeepSeek raises concerns about their ability to detect subtle technical or business context distinctions. For instance, while Copilot excels at identifying structural errors, its uniform scoring fails to reflect scalability or business adequacy differences critical in professional CMS environments. Grok3, despite its balanced performance, still struggled with extreme cases (e.g., Project 6), highlighting a broader issue: current AI models lack the depth to fully replicate expert reasoning.

These findings align with literature emphasizing AI's limitations in contextual interpretation (Brynjolfsson & McAfee, 2017) and overgeneralization (Floridi, 2023). For example, tools like ChatGPT may misinterpret normalization trade-offs, prioritizing theoretical correctness over practical business needs—a gap noted by Lodge et al. (2023). Hybrid approaches are essential, with AI for initial screenings and human experts for final evaluations, especially in finance and management where accuracy is crucial.

6. CONCLUSIONS

The study aimed to evaluate the effectiveness of publicly available artificial intelligence (AI) tools in the automatic assessment of database projects created by second-year Computer Science students. These projects, developed for content management systems (CMS), were analyzed according to five criteria: data structure, performance, integrity, scalability, and business context. Ratings generated by six popular AI tools – ChatGPT, Google Gemini, Microsoft Copilot, Perplexity AI, DeepSeek, and Grok3 – were compared to expert-established reference assessments, enabling an evaluation of their precision and usability in educational and potentially professional contexts.

Analysis revealed significant variability in the quality of student projects, reflected by reference ratings ranging from 3.00 to 4.50. AI tools generated scores between 2 and 5, but their consistency with expert evaluations varied. DeepSeek (3.80) and Microsoft Copilot (3.85) achieved the best results in terms of the minimal sum of absolute deviations from reference values, suggesting relatively high alignment with expert judgments. However, both tools displayed low standard deviations compared to the reference (0.26 versus 0.55), indicating a tendency to smooth out evaluations and a potential loss of differentiation capacity among projects of extremely varying quality. Grok3, with a deviation sum of 3.90 and standard deviation of 0.26, emerged as the tool offering the best balance between conformity with reference scores and reflecting quality variability across projects. ChatGPT and Google Gemini exhibited the greatest discrepancies – the former with a tendency to inflate scores (sum of deviations 6.70) and the latter to underestimate them (4.89) – thus limiting their usefulness for precise evaluation. Perplexity AI had 3.95 deviations but, like DeepSeek and Copilot, it struggled to capture the full range of variability.

These findings have significant implications for education in database design. Automated assessment through AI tools like Grok3 can considerably streamline the educational process, enabling educators to deliver detailed feedback to students more promptly. In educational contexts, where

distinguishing the quality of student work is crucial for instructional purposes and motivation, Grok3 appears most promising due to its capacity to closely mirror expert evaluations while maintaining some degree of variability. Conversely, the tendency of other tools, such as ChatGPT or Microsoft Copilot, to flatten scores might lead to insufficient identification of project strengths and weaknesses, thus limiting their educational value. Introducing AI into education could also reduce the workload of academic staff, allowing them to focus on more advanced teaching aspects, such as mentoring or designing complex practical tasks. However, for these tools to be fully effective, further adaptation to specific educational assessment criteria is necessary, requiring collaboration between AI developers and educational specialists.

In professional contexts, the study results suggest that AI tools could support database design and evaluation processes, particularly in environments where rapid analysis is prioritized, such as small businesses managing CMS systems. DeepSeek and Microsoft Copilot, due to their high conformity with expert evaluations, may be useful for preliminary assessments before detailed verification by specialists. Nevertheless, their limitations in reflecting extreme values indicate they will not fully replace human expertise in scenarios demanding precise quality assessment, such as database design for the financial or management sectors, where integrity and scalability are critical. Grok3, with its balanced approach, may find applications across a wider range of scenarios, providing support both in education and professional practice, particularly where business context consideration is essential.

The research identified several critical limitations of AI tools in database project evaluation. First, the tendency to smooth evaluations, particularly evident in Perplexity AI, Microsoft Copilot, and DeepSeek, suggests these models may struggle to detect subtle quality differences, which is problematic in education and practice where assessment precision is crucial. Second, the AI tools demonstrated limited capability to fully grasp the business context of CMS systems. For instance, ChatGPT and Google Gemini struggled to assess data structure suitability for specific industry requirements, possibly due to insufficient specialization within their training data. Third, variance analysis showed that none of the models reached a standard deviation comparable to the reference assessments, highlighting a general challenge in reflecting project quality diversity. These limitations underscore that current AI tools serve more as supplementary support rather than replacements for human experts, especially in tasks requiring profound technical and business understanding.

To enhance AI tools' usefulness in database evaluation, future research should focus on several key areas:

- **Improved consideration of business context:** Developing methodologies to train AI models on industry-specific data (e.g., finance, content management) could enhance their ability to evaluate project adequacy for practical demands.
- **Better reflection of extreme values:** Adjusting algorithms to more effectively identify exceptionally high or low-quality projects, critical both in education and business.
- **Increased rating diversity:** Experimenting with modifying cost functions or supervised learning techniques could help AI-generated ratings better reflect genuine project differences.
- **Integration with analytical tools:** Combining generative AI models with dedicated database analysis software (e.g., PostgreSQL EXPLAIN) might improve performance and scalability assessment precision.
- **Comparative research:** Evaluating newer or less-known AI tools could identify alternative solutions with greater potential in automated database project evaluation.

One key conclusion drawn from the study is the significance of business context in database project evaluation. Experts assessed projects not only on technical correctness but also on applicability to specific CMS use-cases, a challenge for AI tools. For example, a highly normalized project might score lower if it failed to meet specific business needs, such as rapid reporting in the financial sector. AI tools like ChatGPT or Google Gemini often missed these nuances, highlighting the need for further development toward greater contextualization. Grok3, due to its ability to query and seek additional information, demonstrated some advantage in this regard, though even it did not fully match expert assessments. Future integration of AI with industry-specific training data could substantially enhance their effectiveness.

In conclusion, AI tools show significant potential for automating database project assessment, offering time savings and enhanced efficiency in both educational and professional practices. Grok3 stands out as the most balanced tool, combining high alignment with expert assessments with moderate

representation of project quality variability. However, limitations shared by all tested models – including smoothing tendencies and difficulties in fully comprehending business context – indicate their current form serves more as support than as substitutes for human expertise. Continued technological development, including training data specialization and algorithmic adjustments to specific assessment criteria, could make these tools more reliable and versatile. In education, their implementation could improve teaching quality, provided they are properly calibrated and integrated with traditional assessment methods.

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ANALYSIS OF THE EFFECTS OF APPLYING CLOUD COMPUTING IN ENTERPRISES USING ROUGH SET THEORY

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ABSTRACT

Purpose: *This article explores the impact of cloud computing on enterprise operations using rough set theory. It identifies key factors influencing implementation success and business growth. By addressing uncertainty and subjectivity, the method enables intelligent, experience-driven decisions and supports dynamic, flexible optimization in evolving markets.*

Need for the study: *As rapid technological change and increasing competition push companies to adapt, cloud computing introduces uncertainty and incomplete data that complicate analysis. Traditional methods cannot fully capture this complexity, highlighting the need for advanced, multi-criteria tools like rough set theory to better assess its impact on efficiency and enterprise development.*

Methodology: *The study analyzes data from over 400 Polish SMEs using rough set theory to identify decision rules connecting cloud strategies with their outcomes. This method captures data ambiguity and subjectivity, revealing complex factor relationships. It supports formal knowledge representation and cyclical, multi-criteria decision-making for adapting strategies to market changes.*

Findings: *Data from over 400 enterprises revealed decision rules linking cloud strategies to business outcomes, shaped by ambiguity and subjective factors. Cloud computing effectiveness depends on market and organizational context, requiring flexible approaches. Rough set theory effectively addresses uncertainty and supports multi-criteria decision-making, with ongoing updates essential for adapting to change.*

Practical Implications: *To manage uncertainty and incomplete data, businesses should adopt tools like rough set theory, fuzzy logic, or expert systems. Integrating them into existing systems enhances decision-making, while developing data skills and regularly updating rules ensures adaptability to change.*

Keywords: Cloud Computing; Rough Set Theory; Benefits of Cloud Computing; Threats of Cloud Computing

Jel codes: L86; L23; D83

1. INTRODUCTION

In the face of dynamic technological changes, increasing competition, and the complexity of business processes, companies are taking various actions to modify their structure and operating rules to adapt their business model to the changing market. One of the essential measures to adapt the enterprise to the

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changing environment, providing opportunities for development and the potential to create competitive advantage, is the extensive implementation of various information and communication technologies and the dynamic implementation of the digital transformation process. A vital role in enterprises is played by implementing solutions based on Cloud Computing (CC), using various IT resources (hardware, platform, software) in the form of services via the network. The cloud computing model generally facilitates flexible and scalable management of IT resources, access to modern and technologically advanced IT systems, and enterprise cost optimisation. In addition, IT solutions in cloud computing can facilitate an enterprise's implementation of its digital strategy by influencing the agility, efficiency, and effectiveness of business processes (including decision-making processes) and enabling the generation and implementation of new business models and innovations. However, the analysis of the impact of cloud computing implementation on business operations is not straightforward, as it depends on many factors of a vague and variable nature. As a result, classic methods of analysing the effects of cloud computing, based on precise and unambiguous figures, may not always reflect actual business conditions. It should be emphasised that, in practice, cloud computing adoption decisions are often made under uncertainty and incomplete information, making objective analysis difficult. An interesting direction could, therefore, be the application of rough set theory which is considered as an artificial intelligence tool enabling effective decision-making support under conditions of limited availability of complete and precise information. This approach was used to model the uncertainty and subjective evaluation of various aspects of cloud computing applications (e.g. technological, organisational, economic).

For discovering knowledge from a dataset. Knowledge in the form of decision rules. This paper applies a rough set theory to analyse the effects of Cloud Computing on businesses. This approach allows a better account of the fuzziness of the data and the ambiguous relationships between factors. It will enable a multifaceted characterisation of the effects of using cloud computing in enterprises. The study presented here aims to identify the key factors influencing the effectiveness of cloud computing implementation and assess their importance in enterprise development. The proposed approach can be considered a manifestation of intelligent management, based on creating a pattern of behaviour in the reality under discussion based on real experiences and the resulting results. Applying this multi-criteria decision-making procedure cyclically will make it dynamic. In addition, it will make it possible to follow the changes taking place and flexibly optimise behaviour given changing conditions.

2. LITERATURE REVIEW

In a rapidly changing business environment, companies are extensively implementing modern IT solutions to improve their processes' efficiency, effectiveness and agility. The significant popularity and development of Cloud Computing provide companies with new opportunities to acquire, operate, and develop information and communication technologies. CC, by offering access via a network to a set of flexible, scalable and professional IT services (e.g. ICT infrastructure, computing power, software platforms, software and databases), enables companies to replace or supplement their own and locally used IT solutions, which in turn leads to a change in the current IT resource management model. CC, by offering investment-free and almost unlimited on-demand access to technologically and functionally advanced IT solutions offered by external (or in-house) providers, occupies an increasingly important role in the digital transformation strategy of modern companies.

CC is now not only an important trend in the IT market, but it is also a very fast-growing technology and a dominant model for delivering IT resources that offers significant potential for transforming small and medium-sized enterprises (Jain, 2024; Alam, 2021; Shakeel, 2020; Sunyaev, 2020). Overall, CC is a concept in outsourcing IT operations as an adopted paradigm for delivering IT services over the Internet by organisations. (Moghadasi, 2018). More broadly, CC refers to the paradigm of delivering computational resources, including storage, processing power, and applications, as on-demand services over the Internet (Putzier, 2024). Similarly, a synthetic definition specifies that CC is the on-demand delivery of networking, computing power, database, storage, applications, and other IT resources via the Internet with pay-as-you-go pricing (Kaur, 2019). In another view, CC is defined as a kind of parallel and distributed system which involves groups of remote servers that are networked to allow the sharing of centralised data storage, data processing tasks, and online access to Information Technology (IT)

services or resources (Saraswathi et al, 2015]). The main characteristics of CC (as indicated by NIST from the US) include (Mell, Grance 2011; Dziembek, 2019):

- the possibility for recipients to self-manage their IT resources without the need to involve the service provider,
- high availability of the services offered, which are used by recipients via various computer devices with access to the network,
- high flexibility of services and dynamic allocation of IT resources offered by the provider in the form of services (computing power, memory resources, applications, databases) depending on the changing needs of the recipient,
- sharing of IT resources, which enables services to be used in parallel by multiple users,
- automated measurability of services, facilitating control and accounting of the IT resources actually used by the recipient.

The most important IT services available in CC are: IaaS (Infrastructure as a Service) offering hardware resources e.g. servers, virtual machines and computing power, and disk space, PaaS (Platform as a Service) providing development environments for IT professionals developing and testing software and SaaS (Software as a Service) offering various types of applications including ERP, CRM, BI systems. The above services are made available in several main cloud types, i.e.: public cloud (generally available), private cloud (available only to one organisation), hybrid cloud (which is a combination of public and private cloud) and partner cloud (for a strictly defined group of organisations).

As CC is a form of IT e-outsourcing, companies using IT solutions available through CC transfer responsibility for accessing, operating and developing services to the provider. The use of CC services is location-independent, requiring users to have a suitable electronic device with network access. Charges for CC services are based on declared or actual usage, reducing the need for significant hardware, software and network costs for businesses and simplifying IT resource management. The CC provider has a specialised Data Centre with the necessary IT infrastructure and qualified human resources through the application of various techniques, methods and tools, e.g. virtualisation, aggregation, self-service tools, Parallel and Distributed Systems (PDS), data deduplication, WEB 2.0, web services, Utility and Grid Computing and Service-Oriented Architecture (SOA), can guarantee efficient access for multiple audiences and ensure flexibility, versatility, performance, reliability, security, pay-per-use and distribution dynamics of IT services (Dziembek 2024, Aldahwan, Ramzan 2022).

The distinguished features and properties of CC services make it possible for them to fit in and coexist with existing local IT solutions of enterprises. The enterprise's needs, specifics, human potential, and financial capabilities will determine the analysis and application of a particular model and type of CC. It is also necessary to thoroughly analyse the benefits and risks associated with implementing a given model and type of CC. A presentation of the main benefits and risks of Cloud Computing is shown in Table 1.

CC generates many benefits for businesses that can improve flexibility to adapt to changing market situations, reduce operational costs, or enable faster and cheaper generation of innovations (e.g., e-services) (Islam, 2023). Today's cloud solutions provide businesses with not only flexibility but also the ability to instantly adapt IT resources to changing needs, which, combined with the absence of IT investments, contributes to increased operational efficiency and faster business growth. Furthermore, the ease of access to advanced IT solutions in the cloud can support the optimization of business processes, support the creation of new products (e.g., e-services), and reach new customers, as well as enable a change to the existing business model. Increasingly, CC enables access to and the ability to use solutions based on artificial intelligence (AI) and machine learning. With these technologies, companies can analyse huge amounts of data in real time, enabling faster and better business decisions.

The cloud thus becomes a tool for obtaining valuable information to support strategic decisions. The ability to realise flexible forms of working and collaboration in distributed teams and the security of data and documents improves the quality of cooperation between company personnel. As a result, using CC services can increase a company's competitiveness and market position. Dynamic technological development, progressive computerisation and automation of processes, the ever-increasing amount of data resources, the growing demand for computing power, and the growing importance of cloud computing have made CC the cornerstone of digital transformation in many modern companies. The decision to implement a particular model and type of CC is not easy and - given the many benefits but

also problems and risks - should be conducted on the basis of an accepted method and decision rules (e.g., rough sets).

Table 1. Benefits and threats of Cloud Computing services

Benefits	Threats
• to purchase expensive hardware and software (low entry costs) and no need to maintain and develop specialized rooms with equipment (allocating the saved funds for other business purposes), • relatively lower costs of acquiring, maintaining and developing IT resources (fees only for the resources used), • greater predictability of IT costs, • quick access to the necessary IT resources from anywhere and at any time, • lower demand for IT staff, • reduction of investment risk in the field of information and communication technologies, • high scalability and efficiency of shared IT resources, • transferring responsibility for the functioning and development of IT resources to the supplier, • high level of IT resources security (including negligible failure rate, high availability and reliability, various data backup locations, systematic and automatic updates, comprehensiveness and systematic protection measures, certifications, data protection standards, redundancy of power supply, internet connections and other components), • professional technical support and service provided by the supplier, • simplicity of use of IT resources (the interface is a web browser), • the possibility of using functional IT solutions that allow you to compete with larger entities and create innovation	• certain problems related to security of collected and processed data (concerning e.g. data storage place, separation of client data, access control, data encryption and confidentiality, disaster recovery, etc.), • Internet network failures limiting or preventing the use of IT resources, • partial or complete dependence on the provider (lack of control over the provider's actions), • risk of cooperation with an unprofessional provider, • vulnerability of solutions offered in a cloud to cyberterrorism or intelligence activities, • possibility of sudden termination of activity and provision of services by the provider, • some difficulties in adaptation of the offered IT services to the client's needs, • difficulties associated with data migration in the event of a change of provider, • relatively high costs of broadband Internet connections enabling use of services, • limited possibilities to integrate local and external IT resources, • complexity of managing IT services across multiple vendors, • possible legal problems (different regulations in different countries, unfavorable contractual provisions, unsatisfactory provisions in the case of a serious breakdown or a provider's bankruptcy, lack of best practices, etc.)

Source: Turek et al. 2021.

3. METHODOLOGY

3.1. Rough Set Theory

The study employs the theory of rough sets, published by Z. Pawlak in 1982 (1982a; 1982b) as a response to the problem of 'imperfect' knowledge, which was on the minds of philosophers, logicians and mathematicians alike in the past for. "Many science and technology problems involve uncertainties; hence, uncertainty optimization problems are the topic of great interest among researchers." (Shende et al., 2023).

Moreover, in line with the development of computer techniques, including artificial intelligence, this issue has also been agitating the minds of computer scientists. Many AI-related problems involve decision-making under uncertainty; optimization under uncertainty is imperative for expert systems (Sinha, Shende, 2022).

The growing complexity of the world and the need to operate with rapidly growing sets of empirical data, which are by nature imprecise and incomplete, as well as the development of computational technologies, favour the continuous growth of the popularity of this theory and the tools in which it is implemented. Moreover, this development has resulted in it being widely considered to be one of the

fastest-developing artificial intelligence methods, and R. Tadeusiewicz (2015) calls it a Polish island in the artificial intelligence archipelago.

From a logical point of view, rough set theory is a mathematical approach to fuzzy concepts, while from a practical perspective, it is a new method of data analysis that helps to search for relationships among data, reduce data redundancy, determine the weights of individual data components, or to derive decision rules from data (Greco et al., 2016). Simultaneously, Pawlak (1981) pointed out that data analysis should be treated as a special instance of inductive inference which, starting from certain partially known facts about the reality and by way of generalizations, strives to create knowledge about a world broader than the one being the starting point for the considerations. Such efforts are aimed at drawing probable (possible) conclusions, while the validation of hypotheses is performed by way of experiments.

Based on the accuracy of reality measurement, the objects in question can be considered either different or indistinguishable from each other. Yet, the measurements often do not need to be too precise, and instead of differences the similarity of the elements is more interesting. “The elements about which we have received identical information are similar and compose the so-called elementary sets. They provide grounds for reasoning in the rough set theory. The sum of any elementary sets is called a definable set. Sets that are not definable are called rough sets. Obviously, the definable sets can be explicitly described by the properties of their elements, while the rough sets cannot be described in this way. That is why the rough set theory introduces the terms of lower and upper rough sets that enable any non-definable (rough) set to be characterized by two definable sets, i.e. its lower and upper roughness (...) the very essence of the method lies in the introduction of two membership functions $\in$ and $\bar{\in}$ that respectively denote ‘certainly belongs’ and ‘possibly belongs’.” (Pawlak, 1981).

Let $IS = (U,A,V,f)$ be an information system, where U is a nonempty finite set of objects; A is a nonempty finite set of attributes; $V = \bigcup a \in A Va$ and Va is the domain of the attribute a; $f:U \times A \rightarrow V$ is an information function, and $f(x,a) \in Va$, where f(x, a) denotes the attribute value of object $x \in U$ with respect to attribute $a \in A$.

For an attribute subset $B \subseteq A$, B determines a binary indiscernible relation denoted by I(B) as follows: $I(B) = \{(x,y) \in U \times U : \forall a \in B\ f(x,a)=f(y,a)\}$.

The I(B) is an equivalence relation on U, and the derived partition is $U/I(B) = \{[x]A : x \in U\}$, where $[x]A$ is the equivalence class containing x.

This leads to lower and upper approximations of $X \subseteq U$ which are denoted by $B_(X)$ and $B^{-}(X)$ and defined as:

$B_(X) = \{x \in U : B(x) \subseteq X\}$,

$B^{-}(X) = \{x \in U : B(x) \cap X \neq \emptyset\}$.

The set theory terminology is used to describe “rough operations on sets, as well as exact operations on rough sets. (...) The proposed method is based on an imperceptible relation that glues together all the objects that one could not distinguish by available means of observation (measurement) or expression (language).” (Pawlak, 1982b).

As a result of the rough set theory application, we obtain decision rules with their far better fit with the human mind than it is the case of black box type techniques such as discriminant functions or neural networks. The decision rules provide an explicit representation of knowledge, which adds to better understanding and explanation of the decision problems under consideration. The significance of this issue is illustrated by the fact that the juxtaposition of these two approaches has earned its own name: data fit versus mental fit (Weihs, Sondhauss, 2002).

Both Pawlak's classic theory and its emerging extensions have been successfully used in many areas to deal with vague and uncertain data.

We can perceive growing interest in a wide range of applications, among other, in the field of knowledge discovery (An et al., 2023), knowledge acquisition (Qian et al., 2022), data mining (An et al., 2023), attribute reduction (Xie et al., 2022), medical diagnosis (Jiang et al., 2020), conflict analysis (Hu, 2023), and of course decision making (Jiang et al., 2021), and so forth and so on. We also refer readers to Wang at al. who mean that “the achievements of rough sets in application fields are low-hanging fruit in many domains (...) They show that the demands of practical use in many real-life fields are one of the driving forces promoting the development of rough set theory.”(Wang, 2023). They give a lot of examples.

3.2 Research description

The proposed procedure is based on the search for knowledge in data. It attempts to find repetition in the data. The rules discovered are representations of knowledge about behaviour and phenomena occurring. The patterns discovered in views, behaviours and phenomena form the basis for decision-making about future phenomena under similar conditions. A dataset derived from our own survey research was used for inference. The study was conducted under the title Multifaceted Analysis of Applied Cloud Computing Solutions and Their Impact on the Formation of Business Processes and Strategies in Business Organisations.

The research was conducted among small and medium-sized enterprises in Poland that declared using CC. The distribution of enterprises in terms of their size was fairly proportional: 56% of small and 44% of medium-sized enterprises operating in various sectors of the economy took part in the survey (micro-enterprises were not taken into account). Of the enterprises invited to the survey, it was possible to obtain correct answers from 409 enterprises classified as small and medium-sized enterprises. The questionnaire included questions with single and multiple-choice answers and used a 5-point Likert scale. The scale used in the survey consisted of 5 response categories (e.g. from number 5, meaning 'definitely yes' to number 1, meaning 'definitely no') ordered correctly. The research was conducted using the CAWI (Computer Assisted Web Interview) method, in which the respondent filled in a questionnaire posted on a website. MS Excel was used to process and analyse the data. The data obtained focused, on the one hand, on the reasons for implementing CC in business, the types, models and services of CC used and the recognition of this technology as more or less important in business. On the other hand, the impact of the choices made on the business was analysed, including the increase in innovation and changes in business management.

In accordance with the requirements of the rough sets theory and the assumption for research and the adopted goal, the primary data set was prepared. It contains 30 conditional and 9 decision variables. The conditional attributes (q1-q30) describe the reasons for using CC solutions, the models, types and importance of CC in the activities of the surveyed companies. The decision attributes (d1-d9) represent the conclusions that were tested during the study. Answers were sought to questions of what combinations of q1-q30 influence d1-d9. Which company behaviours result in identifying which consequences. Table 2 shows all considered variables.

Table 2. Conditional attributes included in the decision table

Symbols for conditional variables	**Names of conditional variables - which of the following sources influenced the decision to implement CC in the enterprise**
q1	Recommendation from another operator
q2	Own analysis of documented projects carried out
q3	Offers from CC service providers
q4	Expert opinions
q5	Standards and regulations
q6	Articles, industry publications
q7	Recommendations from own IT staff
q8	IT solutions only available in a cloud environment
q9	Pandemic and related impacts
q10	Number of years of using CC solutions
	Which type of CC is used?
q11	Private cloud (internal)
q12	Public cloud (external)
q13	Hybrid cloud
q14	Partner cloud

	Which CC model is used?
q15	IaaS (Infrastructure as a Service)
q16	PaaS (Platform as a Service)
q17	SaaS (Software as a Service)
	What CC services are used?
q18	e-Mail
q19	Websites, hosted company portal, content management systems
q20	File sharing
q21	Archiving and storage of data, documents and databases (backup)
q22	Anti-virus tools and security systems
q23	Communication support applications (e.g. fax, instant messaging, videoconferencing)
q24	Office applications (e.g. Office365) and workflow support applications
q25	Project management applications
q26	Applications supporting information and knowledge management (e.g. e-learning, corporate portals)
q27	Applications supporting management of a selected area of activity
q28	Applications supporting management of all processes in an enterprise (ERP).
q29	Applications supporting business analytics
q30	CC is: insignificant, minor, key, important part of business strategy
	To what extent did the use of CC solutions influence the company's innovativeness in the following areas?
d1	Product
d2	Process/technology
d3	Organisational
d4	Marketing
	To what extent did CC solutions influence management in the following areas?
d5	Improved management of existing resources
d6	Improved management of business processes within the company
d7	Structural changes and remodelling of existing management processes within the company
d8	Changes to the operating model on the market
d9	Overall impact of CC solutions on business operations

Source: own elaboration.

Taking into account that some of the attributes are discrete (i.e. the importance of CC solutions), some binary (i.e. use of services), some continuous (i.e. time using CC), and the scales are various, the primary decision table was discretized by replacing measurement scales used in the source data with scales operating with two values, where 0 means no, 1 means yes, or three values, where 1 represents a low, 2 – medium, and 3 – high value of a given characteristic. Only the scale of the q30 attribute was not changed, the 4 values that appeared in the survey questionnaire were left. This procedure, which reduces the level of detail in the source data, is expected to increase the likelihood of discovering repeatability in the data, i.e. the induction of decision rules. In this way, a secondary decision table was created.

The rough set theory makes it possible to identify data redundancy in information tables and eliminate it, i.e. create attribute reduces. Hence, the next step was an attempt to reduce the number of conditional attributes. Potential reduces still allow for the identification of condition attribute combinations that lead to the selected conclusions. Unfortunately, no reduces could be created, which means that all the assumed conditional attributes are relevant, and none can be omitted without a lack of classification quality. Further inference will be made using the full set of 30 conditional attributes.

An attempt was then made to discover decision rules taking into account the levels of satisfaction, including rule firmness and strength of support – backed up by as many examples as possible from the dataset corresponding to both the conditional (premise) and decision (conclusion) sections of the rule. The resulting set of rules was subjected to interpretation and discussion.

The attempt to discover knowledge in data using rough set theory can be realised using various rule induction algorithms. Most existing solutions are based on the algorithm for generating successive coverages developed by R. Michalski. The procedure consists in learning a single rule and then eliminating from the input data set the examples covered by it and repeating the process for the remaining examples in the universe. This way, a set of rules covering the considered examples is obtained. This action is often referred to as Basic Minimal Covering. One of the classical algorithms that implement this procedure is LEM2. (Michalski, 1983). A popular approach is also to use Extended Minimal Covering with modified ModLEM algorithms.

Both approaches often generate many rules, among which one searches for value rules by filtering out interesting rules in terms of the criteria indicated. In this study, the procedure was decided to be implemented with the indication of minimum requirements for rules. For this purpose, the Explore algorithm was used and fed with requirements. In this case, the tuning parameters were defined as Maximum length = 4, Minimum strength (support factor) = 30% relative and Minimum discrimination level (certainty factor) = 70%. This step allowed a limited number of satisfactory rules to be obtained, which are readable and easy to interpret, giving an interesting picture of the fragment of reality under study. The indicated procedure is in line with the proposals put forward in the literature (Stefanowski, 2001).

The research was performed using ROSE2 (Predki et al., 1998; 1999) software developed by the Laboratory of Intelligent Decision Support Systems of the Poznan University of Technology.

4. RESULTS

The search for decision rules was conducted in three stages. The first concerned the overall impact of the use of CC solutions on the activities of the surveyed companies, the second the impact on innovation, and the third on changes in the management of companies.

Attempts made in the first stage to link the conditional variables to the decision variable describing the overall impact of CC solutions on company operations (d9) did not yield results. Satisfactory rules could not be discovered. There were no certain rules, while possible rules had a small support factor with values below 20%.

In the next step, rules with conclusions on the impact of CC solutions on business innovation were sought. The effect on four dimensions of innovation was tested here:

- Product-related (CC solutions enabled the creation of a new product/service or influenced the improvement or differentiation of existing products/services) (d1).
- Process/technological (CC solutions changed existing manufacturing or logistical processes or introduced new production methods, service provision or distribution methods) (d2).
- Organisational (CC solutions enabled the implementation of a new organisational method both within the company and in its relations with the environment, resulting in greater flexibility, flattening of the structure, introduction of outsourcing, etc.) (d3).
- Marketing (CC solutions influenced introducing a completely new marketing method, e.g., product and packaging design changes, product promotion, pricing strategy, etc.) (d4).

At this stage, clear repetitions in the data on organisational innovation became apparent. The analysis of qualitative parameters highlighted 4 rules. All indicate a strong influence of CC on organisational change. These are possible rules i.e. rules in which not all examples covered by the rule (consistent with the premise) support the rule (are consistent with the conclusion). For pragmatic

reasons, rules were sought that have the highest possible certainty factor, high strength (relation of support to the size of the entire set of examples) and, at the same time, a small number of conditional attributes. This is an attempt to identify factors and their combinations that clearly impact conclusions defined in the rules.

The rules' certainty factors were 70-71%, and support factors were above 30%. The rules have a small number of conditional attributes, which contributes to their readability and ease of interpretation. The first rule takes the form of:

If (q23 = 1) & (q30 = 1), then (d3 = 3); [104, 73, 31.47%, 70.19%] [6, 25, 73] (1)

Given the names of the metrics denoted by the symbols of the rule conditional attributes (Table 2) and taking into account the employed discretization of their values, as well as the decision attribute (d3), the rule can be read as:

If we use a CC service such as applications to support communication (e.g. fax, instant messaging, videoconferencing) (q23 = 1) and CC is a minor element of our business strategy (q30 = 1), then CC has a significant impact on the company's innovativeness in the organisational area (d3 = 3).

The advantage of the rule is its length. The conditional section consists of only two attributes, making it readable and easy to interpret. It's a possible, not certain, rule. From the analysis of the quality of the rule, it can be read (first square bracket) that the rule covers 104 examples in the decision table, 104 (out of 409 – total number of examples in the data table) companies are characterized by (q23 = 1) and (q30 = 1). The rule is supported by 73 of them, so its certainty factor equals 70.19%. In other words, 70% (73 of 104) of companies that use a CC service such as applications to support communication (e.g. fax, instant messaging, videoconferencing) (q23 = 1) and see CC as a minor element of our business strategy (q30 = 1), declare that CC has had a significant impact on the company's innovativeness in the organizational area (d3 = 3). It can also be seen (second square bracket) that 6 firms characterized by the conditional part of the rule see a small impact, and 25 firms see a medium impact. This bracket shows the distribution of firms into decision classes.

At the same time, the rule support factor says that 31.47% of companies (73 out of 232) that declare that CC has had a significant impact on their innovativeness in the organizational area (d3 = 3) are described by (q23 = 1) and (q30 = 1) indicated by the rule.

The second rule worthwhile pointing out is:

If (q2 = 3) & (q15 = 1) & (q29 = 0), then (d3 = 3); [121, 86, 37.07%, 71.07%] [11, 24, 86] (2)

It can be decoded to:

If the decision to implement CC was significantly influenced by the in-house analysis of documented projects (q2 = 3) and we use the CC Infrastructure-as-a-Service (IaaS) model (q15 = 1) and we do not use CC services such as Business Analytics Support Applications (q29 = 0), then CC has a significant impact on the company's innovativeness in the organisational area (d3 = 3).

It's a certain rule, with a certain factor of 71.07%, covering 121 examples and supported by 86 of them. The rule describes the behaviour of 37% (86 out of 232) of firms that declare that CC has a big impact on the company's innovativeness in the organizational area (d3 = 3). It's worthwhile to point out that the behaviour of those companies is strongly based on their conscious analysis of projects (q2 = 3).

The next rule is similar to the previous one:

If (q2 = 3) & (q15 = 1) & (q17 = 1) & (q20 = 1), then (d3 = 3); [100, 70, 30.17%, 70.00%] [11, 19, 70] (3)

It can be read as:

If the decision to implement CC was significantly influenced by the in-house analysis of documented projects (q2 = 3) and we use the CC Infrastructure as a Service (IaaS) model (q15 = 1) and Software as a Service (SaaS) model (q17 = 1) and we use a file sharing service (q20 = 1), then CC has a significant impact on the company's innovativeness in the organisational area (d3 = 3).

The conditional section of the rule covers 100 firms, and 70 of those support the rule, so the certainty factor is 70%. 19 firms declare medium impact (d3=2), and 11 declare small impact (d3=1) on the company's innovativeness in the organizational area. The support factor reveals that 30% of companies with significant impact are described by these four attributes included in the premise part of the rule. This is a more detailed description than rule (2), showing more information on using cloud computing. What's more, rules (2) and (3) are supported by as many as 67 of the same companies.

The last satisfactory rule in this group is a rule of the form:

If (q17 = 1) & (q20 = 1) & (q23 = 1) & (q26 = 0), then (d3 = 3); [107, 75, 32.33%, 70.09%] [8, 24, 75] (4)

It has 3 conditional attributes already present in previous rules (q17, q20, and q23), and they have the same values. This suggests their importance in the decision-making process. However, the argument q26=0 appears, indicating that companies do not use services such as applications that support information and knowledge management (e.g., e-learning, corporate portals).

Thus, the rule can be understood as:

If we use the CC Software as a Service (SaaS) model (q17 = 1) and we use a file sharing service (q20 = 1) and we use CC services such as applications supporting communication (e.g. fax, instant messaging, videoconferencing) (q23 = 1) and we do not use services such as applications supporting information and knowledge management (e.g. e-learning, corporate portals), then CC has a significant impact on the company's innovativeness in the organisational area (d3 = 3).

As in the previous cases, this is a possible rule with 70% certainty and a support factor of more than 30%. The rule, however, is supported by mainly different actors than those who supported rules (2) and (3).

The third stage of the study was an attempt to discover rules regarding the impact of the use of CC solutions on the management of the companies surveyed. Four conclusions were tested here:

- Improvement in the management of owned resources (e.g., improving the use of human, tangible and intangible resources increased the efficiency of activities undertaken and investments made) (d5).
- Improvement in the management of the company's business processes (e.g. optimisation, automation and acceleration of existing core and support processes in the company – customer service processes, logistics processes, production processes, technological processes, etc., as well as activities involving the design, modelling and improvement of existing processes) (d6).
- Significant structural change and remodelling of the existing management processes in the enterprise (i.e. including not only substantial changes in the organisational structure and business processes but also modifying the principles of cooperation with business partners) (d7).
- A change of the operating model on the market (change of industry, focus on operations in the Internet space, entering new markets, creation of a network or virtual organisation) (d8).

Rules with satisfactory characteristics relating to improving business process management in the company (d6) and structural changes and remodelling existing management processes in the company (d7) did not emerge.

In the case of improving the management of owned resources, 3 interesting regularities were highlighted. Each of them belongs to a different decision-making class (d5 = 1, 2 and 3). Their advantage is their short length. Attention is drawn to the argument q30, which appears in each rule, each time with a different value. Certain rules are visible this time, which were not present in the previous knowledge induction step.

The first rule takes the form:

If (q19 = 0) & (q30 = 1), then (d5 = 1); [59, 59, 40.14%, 100.00%] [59, 0, 0] (5)

It can be decoded as:

If we do not use services such as websites, hosted company portal, content management systems (q19=0) and CC is a minor element of our business strategy (q30 = 1), then CC does not affect better management of existing resources (d5 = 1).

The strength of the rule is its length; the premise consists of only two arguments. The rule covers 59 cases from the database and is supported by all of them. Thus, it is a certain rule. Every case that conforms to the rule's conditional part leads to the rule's conclusion. Support factor equals 40%, showing that 40% (59 out of 147) of companies that do not see the impact of using CC on better management of existing resources are characterized by (q19=0) and (q30=1).

The next certain rule in this set is extremely short and looks like:

If (q30 = 0), then (d5 = 2); [29, 29, 50.00%, 100.00%] [0, 29, 0] (6)

And can be read as:

If CC is an insignificant part of our business strategy (q30 = 0), then CC has a moderate impact on better management of existing resources (d5 = 2).

Among the 58 firms in the data set that see CC's moderate impact on better managing existing resources, 50% (support factor) treat CC as an insignificant part of their business strategy.

The 3rd rule of this set can supplement the situation:
If (q30 = 2), then (d5 = 3); [205, 146, 71.57%, 71.22%] [59, 0, 146] (7)

It also has a premise that includes only one q30 argument, but now, it has a value of 2, meaning that CC is a key part of our business strategy. This leads to the conclusion that CC has a major impact on better managing existing resources (d5 = 3).

The premise is consistent with 205 companies and 146 of them see a major impact – are supported by the rule, so this is a possible rule with 71.22% certainty. It can be seen, looking at the support factory, that 71.57% (146 out of 204) firms declaring a major impact (d5 = 3) treat CC as a key part of their strategy (q30 = 2). But it can also be noticed that 59 firms treating CC as a key part of their strategy do not see the impact of using CC on better management of existing resources – they are in the first decision class (second square bracket).

The search for knowledge regarding the impact of applying CC solutions on management revealed rules with a conclusion regarding a change in the market operating model (d8).
And in this case, they refer to both no, medium and strong impact.
A rule of the form is worth noting:
If (q19 = 0) & (q30 = 1), then (d8 = 1); [59, 59, 40.14%, 100.00%] [59, 0, 0] (8)
It can be decoded into the form:
If we do not use services such as Websites, hosted company portal, content management systems (q19 = 0) and CC is a minor element of our business strategy (q30 = 1), then CC does not affect the management in the area of the market functioning model (d8 = 1).

This is a certain rule that applies to the 59 examples in the decision table. It describes the behaviour of the 40% of actors who do not note the impact of CC on the market operating model. A clear similarity can be seen with rule (5), which described an identical mechanism about the lack of impact on better management of existing resources. What's more, both rules are supported by the same companies. So, the considered premise leads to both conclusions: no better management of existing resources and no change in the market functioning model.
One more similar rule was revealed:
If (q19 = 0) & (q29 = 0), then (d8 = 1); [117, 88, 59.86%, 75.21%] [88, 0, 29] (9)
If we do not use services like websites, hosted company portal, content management systems (q19=0) and services like business analytics support applications (q29 = 0), then CC does not affect the management in the area of the market functioning model (d8 = 1)

This is a possible rule with a certainty factor of 75.21%. The support factor takes a high value, indicating that almost 60% (88 out of 147) of companies that do not see an impact of CC on the market functioning model do not use the services indicated by the rule's premise. In contrast, only 25% of the companies that do not use these services see a strong impact of CC on the market functioning model.
It may be added that the rule covers the same examples as rules (5) and (8) and additional ones.

Another noteworthy rule concerns the average level of influence on the change in the market functioning model:
If (q18 = 0) & (q19 = 1), then (d8 = 2); [58, 58, 50.00%, 100.00%] [0, 58, 0] (10)

Again, this is a certain rule. It is supported by 58 entities and describes the behaviour of half of the companies that perceive an average impact of CC in changing their operating model.
The rule can be read as:
If we do not use CC services such as email (q18 = 0) and we use services such as websites, company portal on a hosted basis, content management systems (q19 = 1), then CC solutions influence management to a medium degree in the area of changing the operating model in the market (d8 = 2).

The last pair of rules discovered relates to conclusion (d8 = 3) and differs by one conditional attribute (q16 vs. q24).
If (q16 = 0) & (q19 = 0) & (q20 = 1) & (q30 = 2), then (d8 = 3); [64, 45, 30.82%, 70.31%] [19, 0, 45] (11)
If we don’t use the CC model of Platform-as-a-Service (PaaS) (q16 = 0) and we don't use services like Websites, hosted company portal, content management systems (q19 = 0) and we use file sharing service (q20 = 1) and CC is a key element of our business strategy (q30 = 2) then CC solutions have a major impact on management in the area of changing the model of operation in the market (d8 = 3).
If. (q19 = 0) & (q20 = 1) & (q24 = 1) & (q30 = 2), then (d8 = 3); [62, 44, 30.14%, 70.97%] [18, 0, 44] (12)

If we use a service like websites, hosted company portal, content management systems (q19 = 0) and we use a file sharing service (q20 = 1) and we use a service like an office and workflow support applications (q24 = 1) and CC is a key element of our business strategy (q30 = 2) then CC solutions have a major impact on management in the area of changing the operating model in the market (d8 = 3). Both rules are possible rules with a certainty factor equal to 70%. They cover 64 and 62 examples of the analysed reality, respectively. Together, they describe the behaviour of 74 companies that see a high impact of CC on business model changes.

A holistic look at all 12 rules allows one to see the limited number of conditional attributes that occurred in the rules, as well as their repetition. This may indicate their greater validity in the relationships sought and, thus, in the decision-making processes for implementing cloud-based solutions. Searching for the right decisions supported by knowledge of the mechanisms governing the reality under study is worth paying special attention to them.

Remember, however, that the rules reveal specific combinations of components. More does not mean better here. This can be observed in the example of argument q19. The lack of use of the service it represents, in the case of rules (8) and (9), leads to the conclusion of a low impact of CC on changes in the business model. In rule (10), the service described by q19 is implemented, and the conclusion indicates a medium impact of CC on changes in the business model. In rules (11) and (12), the service associated with q19 is again not present, while the conclusion states that CC has a high impact on business model change. Each time, however, the argument of q19 is accompanied by other arguments with the right values, which creates a meaningful whole. Thus, specific combinations of features and their values are important. These combinations can be discovered using rough set theory. They take the form of rules representing the discovered knowledge regarding the specific reality under study. Similar conclusions can be drawn from the occurrences in the rules of the argument q30. It occurs in rule (1) on the impact of CC on innovation and in as many as 6 rules out of 8 in the area of management change. It relates, it seems, to a key issue concerning the attitude of the surveyed companies to the CC phenomenon, namely its place in the organization's strategy.

5. CONCLUSION

This paper attempts to analyse the effects of implementing Cloud Computing (CC) solutions in companies using advanced methods based on rough set theory. The choice of this methodology was driven by the need to capture the complexity of the decision-making process, which is characterised by multifaceted, multi-criteria and the presence of uncertainty and incomplete information about the possible effects of the implemented solutions. An important element of consideration was the need to take into account the ambiguity of the data and the subjective judgements of decision-makers, which determined the adoption of tools capable of modelling ‘imperfect’ knowledge. In this context, rough set theory was seen as an adequate artificial intelligence tool to effectively support decision-making processes under the limited availability of complete and precise information (Kuczera, Dziembek, 2024).

The collected empirical data, originating from our own research (over 400 enterprises classified as small and medium-sized enterprises in Poland were surveyed), were subjected to a thorough analysis, which resulted in the extraction of decision rules depicting the interdependencies between CC implementation strategies adopted by enterprises and their operational and strategic consequences. The developed decision rules can be considered as a formal representation of the knowledge discovered in the data set, showing the repetitive patterns of behaviour of the studied business entities. These rules are of a practical nature - they constitute a benchmark that can serve as a reference point for enterprises facing similar decision-making dilemmas, especially in choosing an appropriate cloud model, the scope of services or the degree of integration of CC with the existing IT infrastructure.

However, it is worth emphasising that the effectiveness and usefulness of the proposed approach are highly dependent on the context in which companies operate. The rules developed relate to specific market, technological and organisational conditions, which - by their very nature - are variable and subject to dynamic change. Factors such as technological progress, regulatory changes, evolving customer needs or changing resource availability can affect the validity and relevance of the decision

rules. Thus, an important limitation of the proposed solution is its dependence on the current decision-making context.

It is therefore recommended that a mechanism for cyclically repeating the research be implemented according to the methodology presented. Only systematic monitoring of changes in the market environment and internal conditions of enterprises will allow for intelligent updating of the decision-making rule base. In practice, this means the need to build a flexible system of collecting, processing and analysing data, which will enable not only the ongoing assessment of the effectiveness of the implemented CC solutions but also the adaptation of the enterprise's strategy in response to new challenges and opportunities emerging on the market.

From a practical perspective, companies should consider implementing dedicated tools to support decision-making in implementing and developing cloud services. It is recommended that these tools are based on artificial intelligence methods capable of considering ambiguity and incompleteness of data, such as rough set theory, fuzzy logic or expert systems. Furthermore, they should be integrated with existing business management systems, enabling their use in both strategic IT development planning and day-to-day management of operational processes.

It is also worth emphasising the importance of building organisational competence in interpreting the results of data analysis and implementing recommendations arising from decision rules. The mere presence of analytical tools does not guarantee success. What is crucial is the ability of managers to put the results of the analysis into practice, adapt their strategy of action and respond flexibly to changing conditions.

In conclusion, the analysis that was conducted confirmed the validity and usefulness of the application of rough set theory in assessing the effects of CC implementation in enterprises. The developed decision rules provide essential support for business entities in the decision-making process under conditions of uncertainty and imperfect information, characteristic of the modern business environment. Moreover, the proposed approach can be effectively used in a broader context - to analyse other digital technologies implemented as part of the digital transformation processes of enterprises. Further research in this area should focus on extending the model with additional variables and developing mechanisms for automatic rule learning as new data arrives, further adapting the recommendation system to changing economic realities.

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ASSESSING LLM'S THROUGH SCENARIO-BASED SOFT SKILLS TASKS FOR MANAGERS: EXPLORATORY STUDIES

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ABSTRACT

Purpose: *The aim of this study is to analyze the training potential of large language models (LLMs) in developing managerial soft skills. By potential, we refer to the model's demonstrated understanding of the key elements involved in resolving conflict scenarios.*

Need for the study: *Soft skills remain a critical component of managerial effectiveness, yet traditional training methods often lack scalability and accessibility. With the rise of advanced language models capable of human-like interaction, there is an opportunity to explore their applicability in leadership development. This study addresses a gap in current literature by evaluating the practical use of LLMs for supporting the growth of interpersonal and emotional intelligence among managers.*

Methodology: *The study employed an experimental design based on ten conflict scenarios representing typical managerial challenges. Each scenario consisted of a short background narrative, a description of the employee's personality, and a task for the manager. The scenarios were processed by three large language models—GPT-4o, Gemini 2.0 Flash, and Claude 3.5 Haiku. The model responses were evaluated by the authors and supervisory LLM model across seven categories.*

Findings: *All tested models demonstrated a solid understanding of conflict dynamics and offered appropriate managerial responses. The supervisory distinctly favored Claude 3.5 Haiku, which it rated notably higher than the other models.*

Practical Implications: *The study confirms that large language models can potentially support managerial development by offering interactive, on-demand, and risk-free simulations. A solid understanding of the dynamics underlying conflict scenarios may indicate the validity of using them in simulation-based training.*

Keywords: Soft Skills Development; Managerial Training; Large Language Models; Digital Learning Tools

Jel codes: M12; O33; D83

1. INTRODUCTION

The rapid advancement and widespread availability of large language models (LLMs) have significantly transformed the contemporary landscape of work and education. These models are now accessible to

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the general public, require no specialized technical expertise for operation, and can be utilized virtually anywhere – on various devices, at any time, and across a broad spectrum of professional and personal domains. However, this technological expansion has also introduced a degree of uncertainty, particularly with regard to job security and the evolving role of human labor in knowledge-based and soft skills professions. Many individuals across diverse sectors perceive LLMs as a disruptive force, potentially threatening the stability of employment and altering the traditional value of human experience.

Such anxieties, while understandable, are not new. They represent a recurring social pattern in which the introduction of groundbreaking technologies – regardless of their actual capacity – triggers widespread concern about disintermediation, automation, and redundancy. Historically, these concerns often precede periods of adaptation, during which new tools are eventually integrated into existing professional frameworks, frequently augmenting rather than replacing human capabilities.

In light of this context, we chose to critically examine the potential applications of LLMs in the domain of managerial education and development. Specifically, the authors focused on their capacity to support and enhance the acquisition of soft skills, which are essential to effective leadership. Our central research hypothesis was that language models are capable of accurately identifying key elements necessary for conducting a conflict scenario simulation, taking into account the characteristics of the employee involved. An additional hypothesis assumed that supervision of the simulation by a language model is feasible, which would be reflected in a similar pattern of key point evaluations between human raters and the model.

To explore this question, we designed an experimental study aimed at analyzing the training potential of LLMs in the context of managerial development. The aim of our study was to determine whether language models demonstrate a solid understanding of conflict situations and are able to identify key elements relevant to their resolution.

This inquiry is particularly relevant in today's volatile, uncertain, complex, and ambiguous business environment, where organizations face continuous pressure to innovate, adapt, and maintain a competitive edge through strong and agile leadership. Within such a context, the ability to access intelligent, AI-based tools for managerial development offers a promising complement to traditional training programs. LLMs, by virtue of their conversational and generative capabilities, may serve as platforms for leadership simulation, role-play, reflective practice, and experiential learning – methods long recognized as effective in adult education and executive coaching.

Our preliminary findings suggest that large language models can indeed play a meaningful role in the development of soft managerial skills. Rather than posing an existential threat to human professionals, these models may enhance human potential by offering continuous, scalable, and personalized learning experiences. Furthermore, the integration of LLMs into organizational learning ecosystems may contribute to error reduction, more informed decision-making, and greater alignment between managerial behavior and organizational goals. The researchers also observed that the use of LLMs in simulation-based learning enables a new form of interactive, on-demand mentoring—one that could easier the access to high-quality managerial development resources, especially in organizations with limited budgets for traditional training interventions.

2. LITERATURE REVIEW

Managerial competency training has emerged as a cornerstone of leadership development, ensuring that managers at all levels are equipped with the necessary skills to navigate complex organizational environments. Managers play a crucial role in facilitating knowledge transfer and embedding learning within workplace practices. (Gumuseli & Ergin, 2002) In the subject literature, we can find many definitions of competencies, both detailed and general. Regardless of how we examine and analyze them, when we speak of 'competencies', we refer to the ability to effectively utilize one's own potential or the potential of an organization. This potential lies in knowledge, skills, attitudes, employees, effective leadership, motivation, available resources, psychological assets, environmental conditions, etc. The twenty-first century is a time focused on efficiency. Therefore, we expect competencies to lead to the desired outcomes. All administrative levels in nowadays organizations, need talented, well prepared top managers and this need is constantly increasing, and the effectiveness of management

becomes one of the most crucial conditions for organization's success. (Zakarevičius & Župerkienė, 2008)

Several competency frameworks have been developed to structure training programs. One widely referenced model is the Kirkpatrick Framework, which evaluates training effectiveness through four levels: reaction, learning, behavior, and results. The Kirkpatrick model provides a systematic method for assessing the impact of managerial training interventions. Training is an instrument to expand the knowledge base of the employees and allows them to transfer this on their jobs in the form of improved performance (Sahni, 2020).

The general strengths of the Kirkpatrick model in evaluation theory and practice have been extolled by scholars. They recognize the model for its ability to provide the following: simple system or language in dealing with the different outcomes and how information about these outcomes can be obtained; descriptive or evaluative information about the kind of training that are needed, thus allows organizations to anchor the results of what they do in business points of view; and practical approach for the typically complex evaluation process. With these strengths, it cannot be denied that Kirkpatrick model has offered significant contributions to the evaluation theory and practice (Cahapay, 2021).

Knowing the value of training and its impact on an organization, it is worth considering the possibility of creating an equally effective model using artificial intelligence and large language models (LLMs) available on the market. This is not about preparing training materials per se, but rather about exploring the potential for collaboration with modern technologies, grounded in the structure and strengths of the aforementioned training model. The authors of the article see potential in the use of LLMs for employee training, as well as in the practical application of tools that, at this moment, may appear more as a threat than as a clear opportunity for development.

2.1. Defining Managerial Competencies

Managerial competencies encompass a wide array of knowledge, behaviors, and skills required for effective leadership. Competencies can be grouped into strategic orientation, business management, people management, and self-management. These competencies evolve depending on management levels, emphasizing flexibility, decision-making, communication, and emotional intelligence (Kwaśniewski, 2024).

One of the first definitions of this concept was presented by Boyatzis in 1982. He indicated that competencies constitute a combination of general knowledge, motivation, traits, self-image, social roles, and skills that are essential for properly performing a specific job. Another insightful definition was proposed by Levy-Leboyer in 1996, who emphasized that competencies involve the integrated use of abilities, personality traits, and acquired knowledge and skills in order to successfully carry out complex tasks within an organization (Witaszek, 2011).

Additionally, Boyatzis in 2011 highlighted emotional, social, and cognitive intelligence as foundational for behavioral leadership competencies (Boyatzis, 2011). Their research underlines the importance of experiential learning and receiving feedback in fostering these skills. Experiential learning offers several key advantages in managerial development:

- contextual relevance: managers learn in environments that mirror their actual work contexts, increasing the transferability of skills,
- immediate feedback: learning through action enables the rapid identification of strengths and areas for improvement,
- personalization: experiences are subjective, allowing managers to draw lessons that are uniquely meaningful to their roles and personalities,
- emotional engagement: real-life challenges elicit emotions that strengthen memory retention and deepen understanding.

According to Kolb's experiential learning theory (1992), effective learning is a cyclic process involving four stages: 1. Actions. Specific experience from what we call 'the real life'. 2. Thinking. Empiric observation and analysis of activities. 3. Understanding. Logical analysis of the observations, search for respective patterns in observations, memorising what was taught. 4. Checking. Checking how new expertise relates to 'the real world' and how the behaviour has changed (Zakarevičius & Župerkienė, 2008). Managers who participate in this cycle are better equipped to internalize complex competencies such as strategic thinking, conflict resolution, and adaptive leadership. Integrating experiential learning into competency development initiatives fosters a growth mindset, enhances

resilience, and encourages lifelong learning among managers. It also supports the cultivation of critical metacompetencies, such as self-awareness, systems thinking, and emotional regulation, which are increasingly essential in complex organizational environments.

The authors assume that these elements can be achieved with proper use of LLMs as a training tool. Experiential learning plays a pivotal role in the development of managerial competencies. Unlike traditional training methods focused primarily on the transmission of theoretical knowledge, experiential learning emphasizes the active engagement of managers in real-world problem-solving, decision-making, and leadership challenges. It promotes deep, durable learning by allowing individuals to reflect on their experiences, adapt their behaviors, and continuously refine their skills. AI and large language models can work collaboratively with trainees to analyze real-life situations and evaluate the solutions they have applied. This enables individuals to receive feedback and test their own decisions and approaches in a fast, widely accessible manner – without the need to wait for consultation with a supervisor. In high-pressure situations, modern technologies can support managers and their skillsets by providing analysis of alternative solutions without triggering real-world consequences.

Competencies Managerial training programs significantly contribute to the development of individual and organizational capabilities. Managerial support is essential in ensuring that knowledge gained through training is effectively transferred to the job (Gumuseli & Ergin, 2002). Training initiatives enable managers to better handle strategic tasks, lead teams with confidence, and align departmental goals with broader organizational strategies.

In small business contexts, management training correlates positively with improved organizational performance, especially when the training content is tailored to industry-specific challenges (Panagiotakopoulos, 2020).

The impact of managerial training extends beyond skill acquisition. It directly influences employee satisfaction and retention. Investments in leadership development lead to reduced turnover intentions and higher engagement among staff (Malek et al., 2018). Managers who undergo structured training are more likely to foster positive work cultures, provide effective feedback, and support employee development. Of course, this perspective applies to training in its traditional sense. While the benefits are substantial, organizations must also consider the design and delivery of training programs. Context, duration, follow-up, and managerial involvement are key success factors. Lack of strategic alignment or insufficient post-training support can undermine program effectiveness. All these reasons present a perspective to explore the topic of modern tools that can provide managers with the necessary skills training at almost any time. The use of AI and large language models (LLMs) can serve as tools to support managers in moments when they are unsure of their competencies in a given situation. This kind of support is likely to enhance a sense of stability and confidence among employees.

Furthermore, transforming managerial competencies becomes critical in ensuring resilience, innovation, and sustainability. That is a global challenge that can reshape business practices (Kwaśniewski, 2024).

2.2. LLMs in manager's soft skills development

In recent years, we have observed rapid advancements in language models (Zhao et al., 2023). This process was undoubtedly influenced by two key events. From a technical perspective, it was the introduction of the attention mechanism proposed by Vaswani (Vaswani et al. 2017), which enabled the creation of modern language model architectures. From a societal perspective, a significant milestone was OpenAI's release of the ChatGPT chatbot in 2022 (OpenAI, 2022), based on the GPT-3.5 model (OpenAI, 2022), allowing a broad audience to experiment with the technology and seek practical applications. Since then, many competing models have emerged, such as Gemini (Anil et al., 2023), Grok (xAI, 2024), Claude (Anthropic, 2024), DeepSeek (Bi et al., 2024), and LLama (Touvron et al., 2023), which also achieve excellent evaluation results (Rangapur & Rangapur, 2024).

It did not take long before attempts were made to apply language models to management (Nihal et al., 2023), particularly in the area relevant to this publication: the development of managerial soft skills (Sun, 2024).

We can distinguish two main directions in utilizing language models in this context. The first is an advisory approach, where the language model acts as a virtual assistant for management staff. AI-based systems supporting business decision-making are not new (Huang, 2024); however, only recent advances in language models have enabled their use in a 'conversation with an expert' format. In this

arrangement, the model analyzes the situation, offers advice, identifies potential risks, and generates possible solutions. Additionally, these systems can be fed large amounts of internal company data, recognizing subtle patterns and relationships that might otherwise escape human notice. This allows for data-driven decision-making and minimizes the impact of personal biases and political factors on decision-making processes. Nevertheless, it is crucial to emphasize that these systems are intended solely as advisory tools, with ultimate decisions and responsibility resting on the manager, who must also consider immeasurable or hard to measure factors such as team morale or organizational culture.

In addition to complex advisory systems, language model-based chatbots can be used less formally by managers, for instance, in brainstorming sessions. Interestingly, research suggests that advice generated by language models is perceived as highly substantive (Howe et al., 2023). Naturally, this also carries certain risks. Biases present in language models' training datasets can influence managers' management styles. Studies have shown (Geleilate & Humberd, 2024) that managers who used ChatGPT to solve case studies tended to prefer more rigid and controlling solutions. Another study (Kirshner et al., 2025) demonstrated that ChatGPT exhibits typical human cognitive biases in decision-making. This highlights the necessity of providing the model with comprehensive context and considering the softer aspects of decisions. Despite this, recommendations generated by language models should always be critically evaluated and combined with the manager's own perspective.

The second direction involves using language models as simulators, enabling managers to practice skills such as conflict resolution, team management, coaching, or providing feedback. This leverages the ability of language models to simulate the personalities of team members (Wang et al., 2025). Chatbots assume the roles of subordinates, customers, or collaborators interacting with each other. Virtual dialogues allow managers to gain practical experience, which proves more effective than purely theoretical learning (Dai & Ke, 2022). Simulators enable testing various management styles without fearing real-world consequences of incorrect decisions. An additional advantage of this approach is the ability to generate a simulation report for the participating manager, highlighting areas needing improvement.

Market needs, given possibilities, a review of the literature and curiosity encouraged the authors to conduct tests on large language models in order to verify and analyze their capabilities in the area of training, developing, and supporting managerial competencies, recognizing their potential for practical application. Competency training is an indispensable element of workforce development. It strengthens leadership capacity, enhances strategic alignment, and fosters a culture of continuous improvement. As organizations embrace technological innovations like LLMs, there is a growing opportunity to simulate experiential learning digitally. Artificial Intelligence-powered simulations, virtual coaching, and scenario-based training modules can replicate real-world managerial challenges, providing managers with rich experiential learning opportunities in a scalable and flexible manner.

The primary aim of this study is to explore the potential of modern language models in the second of the two previously described roles – simulation agents. By potential, we refer to the model's demonstrated understanding of the key elements involved in resolving conflict scenarios. Given the pilot nature of this research, we will evaluate the model-generated outputs ourselves, and we will not assess the simulated conversations per se, but rather the model's ability to identify the key elements that must be included in such a simulation. Here, the model's self-awareness becomes critical and resembles reasoning processes used in prompting strategies such as chain-of-thought (Wei et al., 2022). Evaluating the capacity of language models to perform this function will allow us to determine whether this is a research direction worth pursuing with the current generation of models, or whether it would be more prudent to wait for future, more advanced iterations.

An additional goal of this study is to investigate how well language models perform in the evaluation of other language models, and how their assessments compare to those made by human. The potential of such an approach – where an LLM oversees the performance of another LLM during simulation – is important to examine, given the emerging interest in self-supervising multi-agent systems. In such a configuration, an evaluator model could generate guidelines and feedback for simulation agents (those emulating employees) based on ongoing analysis or even intervene in real time during a simulation. For this to be feasible, the evaluator model must perceive and interpret the behavior of other models in a manner comparable to human evaluators.

3. METHODOLOGY

To conduct an evaluation of the potential of large language models in managerial soft skills development, we have prepared a dataset containing 10 tasks (conflict situations) designed for managers to solve. Each task consists of three key components:

1. Scenario – a description of a problematic situation,
2. Employee Personality – a description of the role that the language model should play,
3. Manager's Task – instructions outlining the objectives that the participant in the simulation must achieve.

Examples of these tasks are presented in Table 1.

Table 1. Example tasks used to test the usefulness of language models for developing soft skills

Scenario	Employee Personality	Manager's Task
Emily Taylor recently requested a salary increase based on her past achievements. However, her recent interactions with clients have been marred by sarcastic remarks and a noticeable lack of professionalism, which has raised questions about her current performance levels.	Emily is confident and knowledgeable, with a proven track record. Nevertheless, she becomes notably defensive when faced with criticism and her current approach has begun to erode trust among clients and colleagues alike.	Conduct a performance review meeting with Emily. Present specific examples of her recent behavior, discuss the discrepancies between her achievements and current performance, and collaboratively create a development plan aimed at addressing these issues.
Your employee John Doe has been repeatedly late to work and missing scheduled virtual meetings. This inconsistency has disrupted project timelines and frustrated team members, especially during critical phases of projects.	John is highly capable and creative but struggles with organization and time management. While he has shown great potential in his work, personal challenges seem to affect his punctuality. He is usually receptive to feedback but can become defensive when he feels singled out.	Conduct a candid disciplinary conversation with John. Explain the impact his tardiness and lack of communication have on the team, and work together to develop a clear plan to improve his punctuality and participation in meetings.
Michael Brown has recently submitted a vacation request during a critical project period. Compounding this issue, there are reports that he has been neglecting essential safety procedures at work, which is concerning for both team productivity and overall workplace safety.	Michael is generally dedicated and conscientious, but recent personal stress may have led to lapses in attention and an increasing tendency to take shortcuts. This shift in behavior is uncharacteristic of his usual performance.	Discuss the timing of his vacation in the context of the current project demands. Emphasize the importance of following safety protocols, and collaboratively devise a plan to ensure that his absence does not adversely affect team operations.

Source: own elaboration.

To assess the usefulness of language models as simulators, we evaluated the prepared tasks using large language models. The prompt used in our assessment can be found in Appendix A. As part of the task evaluation, we requested responses addressing the following aspects:

1. What key discussion points must be included for the task to be considered successfully completed?
2. What key discussion points must be included for the task to be considered unsuccessfully completed?

3. What are the critical aspects of problem-solving that the participant must achieve to complete the task?

The responses generated by the models were compared and analyzed. For this comparison, we selected the following large language models (LLMs) available as of today: GPT-4o, Gemini 2.0 Flash, and Claude 3.5 Haiku.

3.1 Evaluation of model-generated responses by human

Given the pilot nature of the study, the initial evaluation of model-generated responses was conducted by the authors themselves. To ensure consistency and depth in the analysis, we proposed seven evaluation categories, detailed in Table 2 along with their definitions. In addition to standard aspects such as clarity of expression and relevance of the response, we introduced criteria focused on the model's capacity for personalization, and its sensitivity to contextual dimensions such as empathy, collaboration, and the importance of feedback in interpersonal scenarios. In their evaluations, the authors strictly followed the definitions introduced in Table 2, drawing on both their theoretical and practical knowledge in the field of management.

The evaluation categories were as follows:

Table 2. Example tasks used to test the usefulness of language models for developing soft skills

Category	Description
Success Points	Did the model correctly identify the key elements that should be present for the managerial conversation to be considered successful?
Failure Points	Did the model sensibly highlight the main risk factors that may lead to failure in the given scenario? Did it overlook critical threats?
Empathy	Did the model demonstrate an understanding of the emotional dynamics of the situation? Did it acknowledge the need for empathy toward the employee?
Cooperation	Did the model reflect an awareness of the collaborative nature of the problem? Did it emphasize joint responsibility, active listening, or team engagement?
Feedback	Did the model understand the importance of feedback in the scenario? Did it include concrete and constructive feedback strategies?
Structure	Was the response logically structured, clearly articulated, and easy to follow? Or was it vague, inconsistent, or overly general?
Context	Did the model refer specifically to the scenario context (e.g., employee traits, situation-specific details), or did it rely solely on generic statements?

Source: own elaboration.

All model responses were evaluated in random order using a five-point Likert-type scale (see Table 3):

Table 3. Rating scale used to evaluate model responses in soft skills assessment tasks

Score	Description
1 – very poor	The model failed to recognize key elements, provided random or irrelevant answers, and showed no connection to the scenario.
2 – poor	The model captured some relevant points but omitted or misinterpreted key elements. The response was either vague or inaccurate.

3 – fair	The main aspects were correctly identified, but the response lacked depth or full alignment with the scenario.
4 – good	Most key points were correctly recognized, context was considered, and the response was logically structured.
5 – very good	The response was accurate, deep, and highly adapted to the scenario, incorporating subtle elements appropriately.

Source: own elaboration.

In the context of the evaluation scale for model responses proposed above, we assume that a score of 3 or higher indicates the potential for using a language model in training managerial soft skills. This is based on the premise that if the model is capable of correctly understanding the scenario's assumptions, it is also capable of incorporating them appropriately within a simulated interaction.

The statistical analysis was based on the null hypothesis assuming no significant performance differences among the evaluated LLMs. To compare model performance across the defined categories (see Table 2), we conducted the non-parametric Friedman test, which is appropriate for repeated-measures comparisons across multiple conditions. The significance threshold was set at $\alpha = 0.05$. For categories where significant differences were detected, we performed post-hoc pairwise Wilcoxon tests, corrected for multiple comparisons using the Holm-Bonferroni method. The decision to use non-parametric methods was driven by the limited number of observations (10 scenarios per category) and the potential violation of normality assumptions, which are required for classical ANOVA.

3.2. Evaluation of model-generated responses by LLM

In the next stage of the study, we employed the Gemini 2.5 Pro model as a reviewer to assess the same responses generated by the three LLMs. The model was prompted to assign scores using the same scale and categories as the human evaluators (the exact prompt is included in Appendix B). The scores generated by Gemini 2.5 Pro were then analyzed in the same way as the human ratings - via Friedman tests and Wilcoxon comparisons with Bonferroni correction, maintaining the $\alpha = 0.05$ significance threshold. The choice of the model was due to the fact that it is currently one of the most powerful models available on the market. The model received the category definitions and rating definitions mentioned in Table 2 and Table 3 as part of the prompt.

Finally, we compared the evaluations assigned by the human raters with those produced by the Gemini 2.5 Pro model. To do so, we used the Spearman rank correlation test to assess the alignment between the two sources of ratings. To detect any systematic bias, we additionally conducted a paired Wilcoxon signed-rank test.

4. RESULTS

The evaluation results for each model across all categories are presented in Figure 1, along with standard deviations to illustrate the variability in scoring. Most ratings across all models fell within the 2 – 4 point range. As shown in the Figure 1, Claude 3.5 Haiku achieved the highest scores across all categories, except for Cooperation, where it ranked second. GPT-4o in most categories occupied the second position overall, while Gemini 2.0 Flash ranked lowest in most categories.

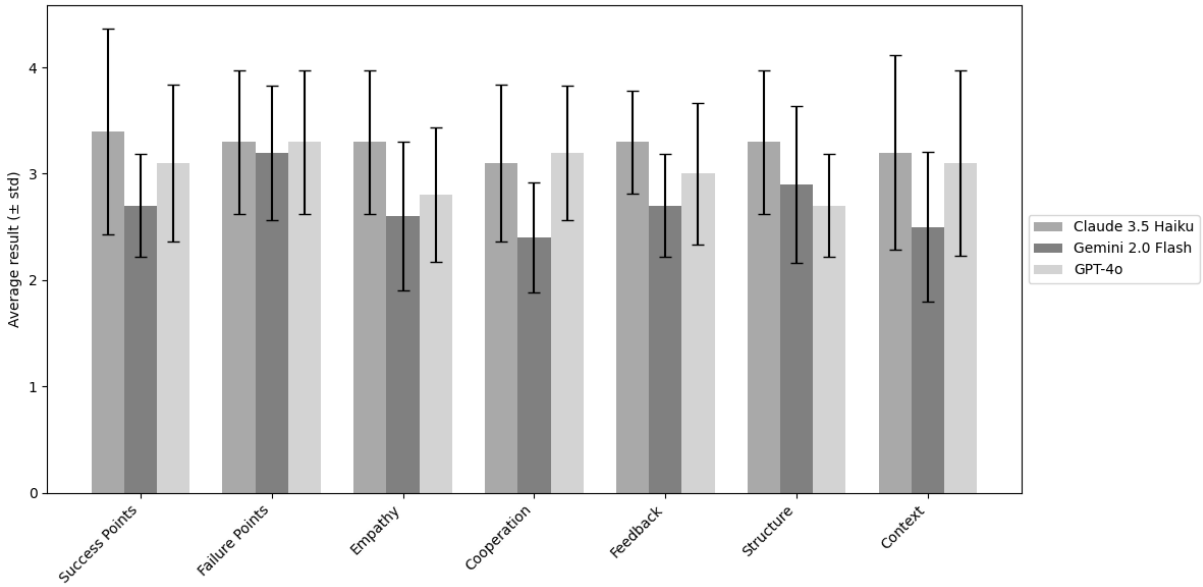


Figure 1. Average results of evaluation in all categories for all three tested models
Source: own elaboration.

The greatest divergence in model scores was observed in the Cooperation category, while the Failure Points category exhibited the smallest variation. Regarding standard deviation, it did not exceed the value of 1 in any category. The Feedback category had the lowest score dispersion, whereas Context exhibited the highest. In terms of average score variability per model, Gemini 2.0 Flash showed the most consistent performance, while Claude 3.5 Haiku had the highest variation.

To statistically assess the significance of differences between the models across all categories, we applied the Friedman test for three models and ten scenarios per category. The test statistics are summarized in Table 4:

Table 4. Results of the Friedman test for significance level at $\alpha = 0.05$. Statistically important results are bolded

Category	χ^2 (df=2)	p
Success Points	4.522	0.104
Failure Points	0.080	0.961
Empathy	7.000	**0.030**
Cooperation	8.960	**0.011**
Feedback	4.526	0.104
Structure	4.323	0.115
Context	4.200	0.122

Source: own elaboration.

Based on these results, we identified two categories (Empathy and Cooperation) where the differences between models were statistically significant. From a managerial practice perspective, it is important not only that language models accurately identify elements of conflict, but also that their understanding and responses can genuinely support managers in making interpersonal decisions. For example, higher scores in the 'Empathy' category may suggest that model is more capable of recognizing the emotional aspects of a situation and adjusting its communication to the needs of the employee – an essential factor for effective conflict resolution and building trust within a team. For categories with statistical significance, we conducted post-hoc pairwise Wilcoxon tests with Bonferroni correction. The results are summarized in Table 5:

Table 5. Post-hoc pairwise comparisons between models in categories with significant group-level differences (Wilcoxon tests with Holm-Bonferroni correction). Statistically important results are bolded

Category	Model comparison	p Bonferroni
Empathy	Claude 3.5 Haiku vs Gemini 2.0 Flash	0.244
	Claude 3.5 Haiku vs GPT 4o	0.573
	Gemini 2.0 Flash vs GPT 4o	0.629
Cooperation	Claude 3.5 Haiku vs Gemini 2.0 Flash	0.319
	Claude 3.5 Haiku vs GPT 4o	1.000
	Gemini 2.0 Flash vs GPT 4o	0.080

Source: own elaboration.

In the next part of research, we employed the Gemini 2.5 Pro model to evaluate the same responses from the three models across seven categories. The results are presented in Figure 2. What can be immediately observed is that, overall, the LLM model assigned higher scores, as indicated by the ratings ranging between 3 and 5. Another noticeable feature is the lower variability in the scores assigned by human raters. In extreme cases - such as the Structure category across all models and the Failure Points category for Gemini 2.0 Flash and GPT-4o – the standard deviation is zero, which means the model assigned identical scores to all scenarios within these models and categories. Similar to the ratings provided by the authors, Claude 3.5 Haiku achieved the highest scores. The other two models obtained nearly identical results in most categories.

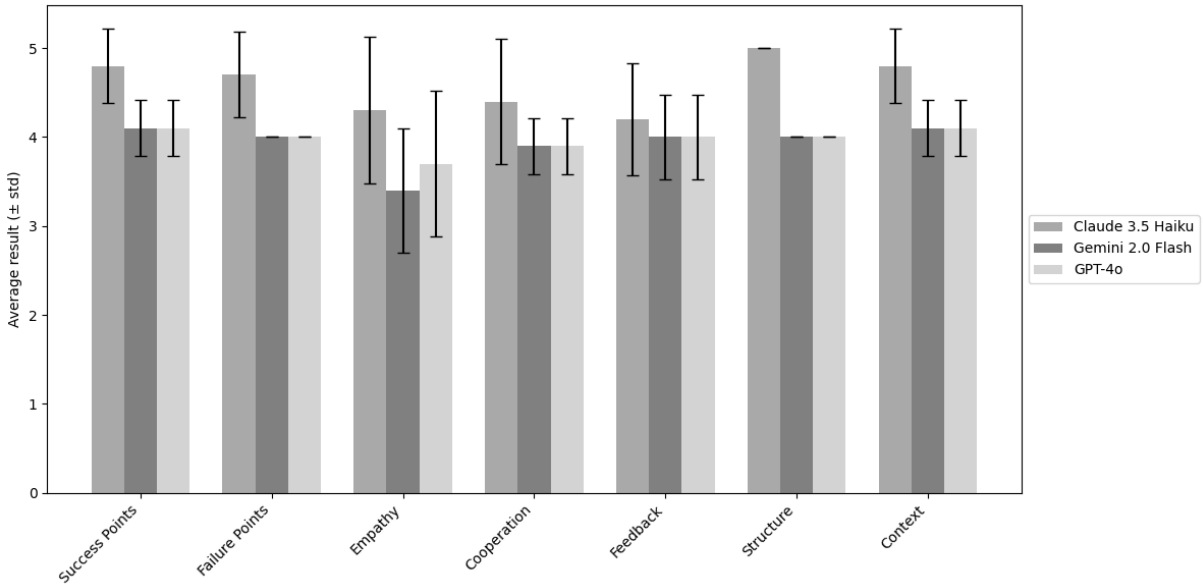


Figure 2. Average results of evaluation by Gemini 2.5 Pro model in all categories for all three tested models
Source: own elaboration

To statistically assess the significance of differences between the models across all categories, we applied again the Friedman test for three models and ten scenarios per category. The test statistics are summarized in Table 6. In this case, we see statistically significant differences for all categories except for Feedback. For Structure, we obtained an extremely low p-value, which results from the zero scatter of estimates for all three models in this category.

Table 6. Results of the Friedman test for rating created by Gemini 2.5 Pro, significance level at α = 0.05. Statistically important results are bolded

Category	χ^2 (df=2)	p
Success Points	14.000	**0.001**
Failure Points	14.000	**0.001**
Empathy	12.087	**0.002**
Cooperation	10.000	**0.007**
Feedback	4.000	0.135
Structure	20.000	**0.000**
Context	14.000	**0.001**

Source: own elaboration.

For all categories except Feedback, we conducted post-hoc pairwise Wilcoxon tests with Bonferroni correction. The results are summarized in Table 7:

Table 7. Post-hoc pairwise comparisons between models in categories with significant group-level differences (Wilcoxon tests with Holm-Bonferroni correction) for rating created by Gemini 2.5 Pro. Statistically important results are bolded

Category	Model comparison	p Bonferroni
Success Points	Claude 3.5 Haiku vs Gemini 2.0 Flash	**0.049**
	Claude 3.5 Haiku vs GPT 4o	**0.049**
Failure Points	Claude 3.5 Haiku vs Gemini 2.0 Flash	**0.049**
	Claude 3.5 Haiku vs GPT 4o	**0.049**
Empathy	Claude 3.5 Haiku vs Gemini 2.0 Flash	**0.049**
	Claude 3.5 Haiku vs GPT 4o	**0.049**
Cooperation	Claude 3.5 Haiku vs Gemini 2.0 Flash	0.051
	Claude 3.5 Haiku vs GPT 4o	0.051
Structure	Claude 3.5 Haiku vs Gemini 2.0 Flash	**0.014**
	Claude 3.5 Haiku vs GPT 4o	**0.014**
Context	Claude 3.5 Haiku vs Gemini 2.0 Flash	**0.049**
	Claude 3.5 Haiku vs GPT 4o	**0.049**

Source: own elaboration.

The obtained results indicate that in all evaluated categories – except for Cooperation – we observed statistically significant differences in favor of the Claude 3.5 Haiku model, which outperformed the other two models in a statistically meaningful way. It is worth noting here that outside the Structure category, statistical significance value is on the border and must be treated with caution. In the automated evaluation conducted by Gemini 2.5 Pro, Claude 3.5 Haiku obtained the highest scores in all categories except for Cooperation. This may indicate its stronger capacity to identify emotionally and contextually relevant elements of conflict scenarios, which is particularly important in training soft managerial skills. The lack of a clear advantage in the Cooperation category suggests that current models may still face limitations in reflecting the interactive and reciprocal nature of collaborative workplace situations.

Finally, we turn to the comparison between human evaluations and those provided by the automated evaluator, in this case represented by the Gemini 2.5 Pro model. The model's ratings were discussed in the preceding section. To examine the consistency in rank ordering, we used Spearman's rank correlation analysis, with the results presented in Table 8.

Table 8. Spearman rank correlation coefficients between human and LLM-based evaluations across categories. Significance level at $\alpha = 0.05$. Statistically important results are bolded

Category	Spearman ρ	p
Success Points	0.283	0.129
Failure Points	0.168	0.375
Empathy	0.538	**0.002**
Cooperation	0.111	0.560
Feedback	0.224	0.235
Structure	0.357	0.053
Context	0.305	0.102

Source: own elaboration.

Statistically significant Spearman coefficients were observed only for Empathy catgory. The coefficient suggests a moderate positive correlation.

In the next step, we examined whether one of the evaluation systems (human vs. LLM-based) consistently rated model responses higher or lower than the other. For this purpose, we used the Wilcoxon signed-rank test, and the results are presented in Table 9.

Table 6. Wilcoxon signed-rank test results comparing the level of ratings between human and LLM-based evaluations

Category	Wilcoxon p
Success Points	**0.0001**
Failure Points	**0.0001**
Empathy	**0.0001**
Cooperation	**0.0001**
Feedback	**0.0001**
Structure	**0.0001**
Context	**0.0001**

Source: own elaboration.

As shown in the table above, statistically significant results were obtained across all categories, indicating that the LLM systematically assigns higher scores to the evaluated model responses than the human raters. The discrepancies between human evaluations and those generated by the Gemini 2.5 Pro model indicate a possible lack of rigor in automated assessment or a different prioritization of communicative aspects. In practice, this means that using LLMs to supervise simulations (e.g., as coaching agents) requires further research into their independence and their capacity for reliable evaluation.

5. DISCUSSION

The results obtained in our study indicate that all evaluated models performed well in identifying the core challenges associated with the development of soft skills among managerial staff. Model ratings, which mostly ranged between 2 and 4 on the applied scale, suggest that LLMs are indeed useful tools for addressing the problem space described in this study. Particularly noteworthy are the results related to the inclusion of empathy, cooperation, and feedback in simulated managerial conversations. All three models appear to recognize the relevance of these interpersonal dimensions in effective leadership.

Despite apparent differences in mean scores – and the seemingly dominant performance of Claude 3.5 Haiku – statistical analysis revealed significant differences only in two categories: Empathy and Cooperation. However, these differences were not confirmed by the post-hoc analysis with Holm correction, which identified only a single statistically significant pairwise difference: Gemini 2.0 Flash vs GPT-4o in the Cooperation category, where Gemini exhibited the weakest performance.

The lack of sufficient evidence to reject the null hypothesis – stating that all models demonstrate comparable levels of understanding the conflict scenarios – may serve as an indication that these LLMs are, in practice, similarly applicable for supporting the development of managerial soft skills.

The situation differs in the case of evaluations conducted by the Gemini 2.5 Pro model. Compared to human raters, the model consistently assigned higher scores to the responses of the other models and exhibited lower variance across scenarios, suggesting it applied a narrower scoring range. Under this evaluation scheme, Gemini 2.0 Flash and GPT-4o achieved very similar results – a finding that was also confirmed by statistical analysis. The case of Claude 3.5 Haiku, however, presents a different picture. Pairwise comparisons with the other two models revealed that Claude outperformed them in five out of seven evaluated categories, indicating a more decisive advantage under the automated review. One particularly noteworthy finding is the consistency of statistically significant distinctions identified by the Gemini 2.5 Pro model when evaluating outputs generated by other LLMs. This suggests a promising direction for systems aiming to leverage agent-based architectures for soft skills training in managerial contexts.

In the final stage of the study presented in this paper, we compared the evaluation of model responses conducted by the authors with that of an automated scoring system implemented via the Gemini 2.5 Pro model. Preliminary analysis based on score distribution plots suggested a potential systematic overestimation of responses by the LLM compared to the human raters which was later confirmed with statistical analysis. Rank correlation analysis showed only moderate correlation for Empathy category.

Our study indicate that all evaluated models performed adequately in identifying interpersonal and procedural elements central to conflict resolution. From a managerial perspective, the ability of Claude 3.5 Haiku to more effectively address categories such as empathy or contextualization may enhance the quality of feedback during employee conversations and signal its greater utility for leadership development tools.

However, it is essential to highlight the potential biases in LLM-generated evaluations. As shown in our results, the automated model (Gemini 2.5 Pro) consistently rated responses higher than human experts. This may stem from shared architectural features or alignment strategies during training that prioritize politeness or generic completion over critical analysis. Such tendencies raise concerns about overestimating the effectiveness of peer LLMs, especially if used for evaluative purposes in multi-agent systems.

Naturally, several improvements should be considered for future iterations. Most notably, the model evaluation was conducted solely by the authors, resulting in a limited sample size and potential evaluator bias. Replicating the study with a larger and more diverse group of raters would undoubtedly strengthen the robustness and generalizability of the results. In particular, involving experienced managers as evaluators could enable deeper insights into the behavioral validity of the model responses and provide more credible assessments of their practical utility.

6. CONCLUSIONS

In this publication, we reviewed the issue of developing soft skills among managers and the role of large This study demonstrated that large language models are capable of recognizing key elements in managerial conflict scenarios and that they differ in the quality and depth of such recognition. Claude 3.5 Haiku achieved the highest scores in multiple categories, particularly in emotional and contextual understanding, suggesting that it may offer greater utility in developing soft skills related to empathy and communication.

At the same time, we identified that LLM-based evaluations tend to be more lenient and less differentiated than human evaluations. This finding underscores the importance of human oversight in simulation-based training and highlights potential risks in fully automating evaluation processes.

While the study supports the use of LLMs as simulation agents, the application of multi-agent systems or fully autonomous supervisors was not tested. As such, any recommendations in that direction remain hypothetical and should be treated cautiously.

Claude 3.5 Haiku showed higher effectiveness in the evaluation of soft managerial skills scenarios, which may suggest its potential applicability in personalized leadership training programs. While human raters did not observe statistically significant differences between the models – indicating that all performed satisfactorily – the automated evaluation suggests that certain models may better capture specific interpersonal competencies. This may point to subtle but meaningful differences in their suitability for particular training contexts.

Future research should explore whether these results hold in real-time simulations, involve diverse managerial participants, and test the longitudinal effectiveness of LLM-based training programs in real organizational settings.

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APPENDIX A

PROMPT:
You are an expert in training managerial staff in soft skills through conflict situation simulations. After each simulation, you can assess its strengths and weaknesses and prepare a report for the user.
Below, you will find a task scenario enclosed within triple backticks (```), where you will take on the role of a problematic employee. Example:
```
Scenario:
{A scenario outlining a problematic situation}
Employee Personality:
{The personality traits of the employee you need to embody during the simulation}
Task:
{The objective that the participant engaging with you must achieve}
```

Your task is to respond to the following questions for each scenario:

1. What key discussion points must be included for the task to be considered successfully completed?
2. What key discussion points must be included for the task to be considered unsuccessfully completed?
3. What are the critical aspects of problem-solving that the participant must achieve to complete the task?

Be precise and limit your response to a maximum of 10 sentences.

APPENDIX B

PROMPT:
You are an expert in training managerial staff in soft skills through conflict situation simulations. After each simulation, you can assess its strengths and weaknesses and prepare a report for the user.
Below, you will find a task scenario and model response about most important things to include during the simulation. They are enclosed within triple backticks (```). Example:

```
Scenario:
{A scenario outlining a problematic situation}
Employee Personality:
{The personality traits of the employee you need to embody during the simulation}
Task:
{The objective that the participant engaging with you must achieve}
Critical aspects:
{Model response – What are the critical aspects of problem-solving that the participant must achieve to complete the task?}
Success Points:
{Model response – What key discussion points must be included for the task to be considered successfully completed?}
Failure Points:
{Model response – What are the critical aspects of problem-solving that the participant must achieve to complete the task?}
```

Your goal is to evaluate the model's response in the 7 categories defined below:

1. Success Points – Did the model correctly identify the key elements that should be present for the managerial conversation to be considered successful?
2. Failure Points – Did the model sensibly highlight the main risk factors that may lead to failure in the given scenario? Did it overlook critical threats?
3. Empathy – Did the model demonstrate an understanding of the emotional dynamics of the situation? Did it acknowledge the need for empathy toward the employee?
4. Cooperation – Did the model reflect an awareness of the collaborative nature of the problem? Did it emphasize joint responsibility, active listening, or team engagement?
5. Feedback – Did the model understand the importance of feedback in the scenario? Did it include concrete and constructive feedback strategies?
6. Structure – Was the response logically structured, clearly articulated, and easy to follow? Or was it vague, inconsistent, or overly general?
7. Context – Did the model refer specifically to the scenario context (e.g., employee traits, situation-specific details), or did it rely solely on generic statements?

Use the 5-point scale defined below:

1 – very poor – The model failed to recognize key elements, provided random or irrelevant answers, and showed no connection to the scenario.
2 – poor – The model captured some relevant points but omitted or misinterpreted key elements. The response was either vague or inaccurate.
3 – fair – The main aspects were correctly identified, but the response lacked depth or full alignment with the scenario.
4 – good – Most key points were correctly recognized, context was considered, and the response was logically structured.
5 – very good – The response was accurate, deep, and highly adapted to the scenario, incorporating subtle elements appropriately.

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AI AND AUTOMATION IN IT: SHAPING FUTURE JOBS AND SKILLS

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ABSTRACT

Purpose: *Amid the new developments in AI and Automation across the globe, it is noteworthy that the IT industry in Poland also shows growing trends in the applications of AI and automation technologies in the IT sector. It has shown that these trends have impacted on the labor market conditions in the IT industry in Poland.*

Need for the study: *Hence, this paper aimed at resolving the research problem of what are the impacts of artificial intelligence (AI) and automation on employment structures, job roles, and new skill requirements in the IT industry in Poland? In resolving this problem, the authors questioned the emerging new competencies and workforce perceptions in the IT industry, while assessing how education and HR strategies to be adapted to prepare for such future labor market trends in the IT industry in Poland.*

Methodology*: This research employed a mixed-methods approach that combined a review of scientific literature and global reports that present research results on the phenomenon in question as well as analyzed data, gathered qualitatively using in-depth interviews, held with the experts in the IT industry in Poland. This approach allowed the authors to obtain a greater understanding of context-specific trends and events around the phenomenon in question. The results revealed that AI and automation have impacted on the employment structures, new skills, and reskilling, changing job roles and organizational priorities, and redefining workforce expectations.*

Findings*: Further, the study presented the importance of proactive adaptation, redesigning education systems, and shaping hybrid skill sets that integrate technological proficiency with human-centric competencies. Last, the authors argued that fostering a synergistic partnership between human talents and AI technologies is essential to building a resilient, inclusive, and future-ready labor market.*

Practical Implications: *This will implicate in demanding continuous learning and digital fluency to equip the workforce with AI-driven competences and job structures, ensuring sustainable and inclusive employment growth. Importantly, this will create a critical need from the state for appropriate changes in relevant Acts and legal regulations.*

Keywords: Artificial Intelligence, Automation, Labor market trends, IT industry in Poland, Employment structures and reskilling, and Digital literacy.

JEL classifications: M15

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1. INTRODUCTION

The integration of artificial intelligence (AI) and automation continues to accelerate in a way to profoundly changing the scope and way of working while redefining employment structures and transforming the skills required in the labor market (Sreerangapuri, 2024). Such technologies increase operational efficiency and new ways of creating value, however, they also pose significant challenges for individuals, organizations, and societies. Yet, the adoption of such modern technologies is inevitable as success depends on the ability to be adaptive to use future-proof strategies, based on lifelong learning, ethical responsibility and collaboration between people and intelligent systems. As a result of shifting towards AI-driven solutions, the IT industry is experiencing a dual shift: a rapid obsolescence of routine and automatable roles – such as junior IT support and data processing, and a growing demand for new interdisciplinary profiles. This has demanded AI strategists, cybersecurity specialists, cloud architects, and consultants capable of bridging technical expertise with the business acumen. According to recent industry reports, organizations are increasingly reallocating budgets toward AI development, workforce training, and digital infrastructure, reflecting the critical need to align human capital with evolving technological capabilities.

Fundamental human attributes – such as interpersonal communication, creativity, empathy, and visionary leadership remain essential. AI systems can outperform humans in performing repetitive or procedural tasks, but they lack the nuance to build trust, navigate complex social contexts, and inspire transformative change. As such, individuals with strategic foresight, emotional intelligence, and the ability to drive innovation will become increasingly important in shaping the future of work.

2. LITERATURE REVIEW

The employment structures are shifting jobs are evolving to include more and more AI in coordination, interpretation, and oversight processes rather than purely execution. Fteimi & Hopf (2021) outline how AI affects current working processes. Presenting Artificial Intelligence as a new actor and component of traditional knowledge management strategies and pointing out the growing role of AI as it reshapes knowledge work by introducing new forms of knowledge (e.g., machine-generated, pattern-based insights) and changing the human role from being sole knowledge creators to collaborators with AI systems. There is a need to redefine the strategy for managing processes within the organization, including knowledge management, and include Artificial Intelligence as an active participant. The authors point out the impact of AI on current jobs and task division while at the same time pointing out a huge need for the role of AI in the organizational context needs to be better understood, especially how people can train AI to support them in their work.

Yadav (2024) also emphasizes the need for tight collaboration between humans and AI. He states that automation also gives rise to new job roles focused on managing and developing AI systems, necessitating upskilling. Industries like transportation and manufacturing may experience immediate displacement, while those innovating with AI, such as healthcare and technology, may witness the creation of specialized roles.

The OECD's AI Expert Group AIGO defines an AI system in a broad sense as a “machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations or decisions influencing real or virtual environments” (OECD, 2019).

According to the Future of Jobs Report 2025 (World Economic Forum 2025), AI is one of the most transformative technological trends shaping the future of work. Alongside automation and digitalization, AI is expected to:

- reshape industries, altering workflows and job functions,
- serve as a dual force—creating and displacing jobs depending on sector and function.

It is estimated that, by 2030, new job creation and job displacement due to macro trends will represent 22% of today’s total jobs. Macrotrend-driven creation of new jobs is estimated to amount to 170 million jobs, and this growth is expected to be offset by the displacement of 92 million current jobs, resulting in a net growth of 78 million jobs. The report highlights that on average, workers can expect that two-fifths (39%) of their existing skill sets will be transformed or outdated over the 2025-2030 period.

Manuti & Monachino (2020) present a philosophy of AI that focuses on creating workflows where an AI learns from the human operator while intuitively making the human's work more efficient and the approach according to which machine and human being coexist within the system (p. 183).

The transformative impact of AI on the future of work creates both significant opportunities and complex challenges for emerging professionals. As AI continues to transform industries through automation, data-driven decision-making, and new ways for humans to collaborate with machines, it becomes imperative for young professionals to adapt to this changing landscape. From Zebulon's (2024) perspective, staying competitive in this context requires a commitment to continuous learning, developing interdisciplinary competencies, and cultivating fundamental human-centric skills, including creativity, effective communication, and ethical judgment.

Masood (2024) emphasizes that AI impact on labor markets is markedly different between developed and emerging economies. In developed economies (United State study), AI tends to disrupt high-skilled jobs, leading to both opportunities and challenges. In contrast, in emerging economies (India study), AI's influence is less pronounced due to varying levels of technological adoption and economic structures (p.3). This suggests that building human capacity and preparing for labor market transformation and the growing need to integrate AI in curricula are crucial. Update educational programs to include AI literacy, preparing the workforce for future job markets (following the Council on OECD Legal Instruments Artificial Intelligence Recommendation, OECD 2019).

The alarmingly fast pace of changes that AI will bring to the job market also highlights Yang (2025). An increasing number of industries will be impacted by artificial intelligence, with jobs in these sectors facing the challenge of being entirely replaced by AI. Workers from those industries will encounter the same predicament as taxi drivers. Yang gives the example of the launch of Tesla's autonomous taxi, which Tesla also introduced, with its humanoid robots capable of communicating with humans and performing various actions. It is imaginable that jobs such as waiters, bartenders, and butlers are likely to be carried out by humanoid robots, traditionally belonging to middle-class occupations (p.364). It's not just lower-level positions that AI will replace. Yang (2025) states that the rapid development of AI and its potential for application in various fields have placed middle-class jobs and high-paying positions at risk of being replaced.

The swift integration of AI into the IT sector has introduced a double-edged shift in the job market, as tasks once reliant on manual effort – like data entry, routine network upkeep, and basic coding – are increasingly being automated by AI systems that perform them with higher speed and precision (Chhatre, 2024, p. 404).

Based on the Future of Jobs Report 2025 by the World Economic Forum (2025), the fastest-growing professions stand out as big Data Specialists, AI/ML Specialists, FinTech Engineers, Software Developers, and Green energy roles (e.g., Renewable Energy Engineers). The Most Declining Roles are data Entry Clerks, Administrative Assistants, Cashiers, postal clerks, and Bank Tellers.

The shift to AI-driven IT operations has made a significant skills transformation imperative for many companies. Recent studies by KPMG (2024) highlight that the majority of business representatives believe that AI will fundamentally change the nature of their business over the one-to-two-year horizon.

The Future of Jobs Report 2025 by the World Economic Forum (2025) highlights how AI is influencing organizations' structures and workforces. It states that by 2030, tasks are expected to be evenly distributed between humans alone (33%), machines (33%), and human-AI collaboration (34%).

McKinsey&Company global report (2025) shows how GenAI tools are rapidly changing workflows, with 92% of companies planning to invest more in AI, yet only 1% feel they've reached maturity in AI deployment. The report also identifies a readiness gap among leadership. It argues that the real barrier to AI adoption is lack of strategic vision from executives. Employees are already using AI regularly, and they are three times more likely than leaders realize to believe that AI will replace 30 percent of their work in the next year, and are eager to gain AI skills. Yet employees are not getting the training and support they need.

Studies by PwC (2024) highlight that the Polish market shows strong awareness and interest in AI among both consumers and businesses. However, full potential will only be realized with clear business strategies and skilled workforces. The support from the government is also welcome.

The emerging skills critical for future employment are: data literacy, AI awareness, and hybrid human-AI collaboration abilities. This is also supported by the research results described in the Future of Jobs Report 2025. The following skills were presented as core ones:

- AI and big data,
- networks and cybersecurity,
- technological literacy,
- creative thinking,
- resilience, flexibility and agility,
- curiosity and lifelong learning,
- leadership and social influence,
- talent management,
- analytical thinking.

This has many implications for the education system. A shift towards skill-based models and the inclusion of AI-related content in formal education is necessary.

Emerging Skills and the Future Workforce: The demand for cognitive and technical skills is surging as AI transforms workplace requirements. According to Li (2022), critical thinking, problem-solving, and technological proficiency are the skills of the future. Young professionals must prioritize acquiring hybrid skills that combine technical expertise with human-centric abilities like creativity and empathy (Manyika, 2017).

So, in addition to technical skills, there is an increasing demand for human-centered skills such as resilience, flexibility and agility, and leadership and social influence.

By the Future of Jobs Report (2025, p. 47), by 2030, 59 out of every 100 workers will need reskilling:

- 29 can be trained in current roles,
- 19 reskilled and redeployed,
- 11 risk lacking reskilling opportunities.

Current technological advances will drive more skill change than any other trend over the next five years. For employers, these insights emphasize the need for training and upskilling initiatives focusing on advanced prompt-writing skills and broader AI literacy.

There are also many challenges and limitations that AI brings. The impact of AI on human innovation, the reliability of content produced by AI, the ownership and rights of works produced by AI, and the potential for exploitation or abuse of AI technology are just a few of the moral, social, and artistic concerns raised by Bharathi & Vardhan (2024, p. 34).

On August 1, 2024, the Artificial Intelligence Act came into force in Poland (Regulation (EU) 2024/1689 of the European Parliament and of the Council of June 13, 2024, on establishing harmonized rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139, and (EU) 2019/2144, as well as Directives 2014/90/EU, (EU) 2016/797, and (EU) 2020/1828 (Artificial Intelligence Act, Official Journal of the EU 2024/1689)). This is the first regulation that comprehensively addresses the AI sector.

It is important to emphasize that this regulation conditions the obligations of providers and entities implementing AI models and systems on the potential risk of harming the economy. Considering the labor market, AI is expected to transform the Polish job market while mitigating the negative effects of this process. It aims to simplify or eliminate tasks that previously required excessive time. According to the adopted assumptions, this should increase the productivity of certain workers. It may also serve as an incentive for acquiring new skills and enhancing qualifications (Korgul et al., 2024).

Yadav (2024, p. 7191) points out that it is necessary to take advantage of the opportunities that AI presents in art and creativity, while consciously addressing ethical issues, thus ensuring that AI remains a source of inspiration, innovation and cultural enrichment in the field of creativity. For this to happen, it is important to develop digital skills in society.

In the context of emerging development needs, the literature review made it possible to notice:

- the need for continuous reskilling and professional development, especially in AI-literate decision-making and oversight roles,
- these changes reinforce the need for adaptive learning environments, microlearning modules, and AI-oriented curricula in formal and corporate education,
- future organizations must re-architect workflows, team structures, and leadership styles to integrate AI tools.

3. METHODOLOGY

Data Collection:

- Industry Reports: Recent publications from organizations such as PwC, McKinsey, KPMG, and World Economic Forum form the basis for understanding the broader industry trends related to AI and IT employment.
- Academic Literature: Peer-reviewed journals and papers focusing on workforce automation, AI integration, and the evolution of skill requirements. The literature was classified based on its topic. As such, there are three major categories. The first is about how AI changes Employment Structures and Professional Roles. The second is about employee perceptions and expectations regarding AI. The last one is associated with skill development and education in AI.
- Data Analysis.
- Qualitative Analysis: In-Depth Interview Method: This study employed the in-depth interview method to gain a nuanced understanding of IT experts' perceptions, experiences, and expectations regarding the evolving nature of work in the context of artificial intelligence and automation. This method was chosen for its capacity to elicit rich, detailed insights and uncover underlying attitudes and motivations that may not be accessible through quantitative approaches.

A total of 14 in-depth interviews were conducted with professionals working in the information technology sector. The sample included IT experts, C-level executives, and employees from IT companies that develop IT services and products (also AI-enabled services) for clients across diverse sectors, including maritime, media, finance, and law. Participants were selected through purposive sampling to ensure a breadth of perspectives from individuals directly engaged in developing and implementing AI-driven solutions across industries. Question sections cover:

- general perspective on automation and AI,
- impact of AI on required competencies,
- transformation of the labor market,
- future of employment and education,
- impact of AI on professional competencies,
- perception of the future of the labor market.

In-depth interviews with IT experts were conducted in March 2025.

4. RESULTS AND FINDINGS

In-depth interviews with IT experts, representatives of IT services and products directed to various industries (maritime, financial, creative, legal) made it possible to obtain a broader perspective on topics related to how AI changes the labor market. The experts who took part in the research represent companies of various sizes and scale of operations, most of them operating on the European market and some globally (United States, India, etc.) – the collection of information obtained is, therefore a large supplement to the practical knowledge collected earlier as a result of the literature review.

The first part of the questions concerned the general perspective on automation and AI. Most surveyed companies have implemented automation or AI tools in the last 2 years. Some of the positions of the respondents (i.e. C-level) have changed as a result of automation/implemented AI-based solutions, this mainly concerns representatives of the creative and finance industries as well as IT consulting services. Changes related to the increasingly widespread introduction of AI apply even to the highest positions. Interestingly, other (lower positions) in their companies have changed more due to automation or the introduction of AI-based solutions.

The majority admitted that there has been a noticeable increase in the number of jobs directly related to AI and new technologies in their professional fields. Those who did not notice the emerging AI-related job offers in their domain of activity were representatives of IT services for the legal, creative, and maritime sectors.

The responses were varied when asked about changes in employment in the industry observed due to the development of automation and artificial intelligence. As follows:

- "Some senior developers were moved to projects related to Co-Pilot and AI integration with platforms, so we had to hire new developers";
- "I do not observe any changes in employment. In the sense that employment decreases or increases due to automation and AI" (law sector);
- "Many entities use AI to streamline work, e.g. programmers. For some companies, this is an increase in efficiency, but for others it helps reduce the need for inexperienced and incomplete employees (who can be replaced by AI tools)";
- "There is a visible decline in employment for freelancers, especially in the field of 2D graphics and voice-over recordings" (creative sector);
- "New positions are being created in the automation and transfer teams due to different demands in the departments" (finance sector);
- "There are fewer reasons to employ young people with experience, because such work results are already provided to them by an AI machine";
- "It is clear that people who deal directly with AI are less sought after, and knowledge of AI and automation tools related to the position held is more valued, e.g. a programmer using a programming environment supported by AI";
- "We are hiring new profiles related to AI/Data Science. We have added questions during technical verification about experience related to GenAI/AI technologies";
- "Weak developers/beginners have become redundant";
- "More AI specialists are needed";
- "The development of automation and artificial intelligence has not affected the changes in employment in the company (which provides IT services and products for the maritime industry), which results from the fact that they play a supporting role for the activities undertaken by the headquarters located in another country. At the same time, as an industry (maritime), we are not exposed to the introduction of many new solutions in the area of AI, which in this sector appears rather in the area of initiatives supporting the process of creating products, i.e. all kinds of copilots (such as GitHub Copilot)" (IT for maritime).

The development of automation and AI leads to employment restructuring, not to even loss or gain of jobs. While some sectors and roles remain relatively unaffected, others are seeing both displacement (particularly low-skilled or creative freelancers) and the emergence of new AI-related roles. Organizations increasingly value AI skills within existing roles, signaling a shift toward hybrid human-AI collaboration as a standard employment model. The most significant change in the area of a position in the organization that was wholly or partially replaced/changed by automation or AI was indicated by a respondent from the creative industry (media and film). This points to copywriting for own marketing and film scripts, partly for 2D graphic designers and voice-over artists – film sketches are now created based on texts and AI voice. In the IT sector, part of the developer, DevOps, and tester workshop was identified as partially replaced/changed by automation or AI.

The answers were varied when asked whether the company sees more benefits or threats resulting from implementing AI in its workplace. Most companies at this stage of AI development and implementation see benefits such as: shortening the time of searching for information and previous use cases thanks to localized AI models. The work of the sales and promotion department has also increased, and the number of leads has increased. The main threat that companies see is juniors' inability to use tools, which forces the creation of internal policies and regulations regarding the use of AI. The threats, therefore, mainly concern confidentiality and data. The benefits are speeding up work (searching and writing first versions of the text). The only person who saw more threats was the media and film industry representative. He pointed to more threats because some orders for film and advertising materials ordered by companies will start to be implemented within the company structure, reducing outsourcing. One of the experts indicated the main benefit as his employees' more excellent work efficiency. At the same time, he indicated the threats as those related mainly to addressing security risks and verifying AI-generated content (whether it is correct or not hallucinatory).

An interesting perspective was presented by an IT representative for the maritime industry, who stated that: "due to the classification of most manufactured products (in maritime industry) as 'mission critical', the life cycle and update possibilities, the implementation of AI directly in the solutions used is very limited. Understanding artificial intelligence as the ability to interpret data, we implement

solutions in the area of interpretation of navigation data, video data or in the area of voice control and these are the actual benefits of implementing AI, but at the moment these are only fractions of the solutions we provide. The basic threats we see are related to the lack of solutions for recognizing hallucinations and too much trust in AI-generated solutions".

A representative of the media and film industry expressed the greatest concern regarding the threat of reducing positions, tasks, or specific roles in the organization. He fears that automation will negatively impact his professional stability. When asked if the company cares about employee development in the context of equipping them with digital competencies (e.g., offering employees training in the use of AI tools), the majority confirmed such training. This means that representatives of IT companies are aware of the need for education, but only 2/3 of respondents gave an affirmative answer.

In the part of the interview concerning the skills needed and currently sought on the job market, one of the experts emphasized that now we have a breakthrough time where openness to new ways of operating and using IT tools will undoubtedly be important. Respondents identified the following new skills as currently most sought-after in their industry:

- skills related to big data, AI and machine learning, software and application development, and UI/UX design,
- key technologies include Python, as well as ML frameworks such as TensorFlow and PyTorch,
- a growing demand for specialists who can integrate AI with existing systems and for developers familiar with MLOps,
- skills related to current technologies, e.g. cloud administrators, programmers in new languages and frameworks,
- specialists who can create and integrate AI solutions are in high demand. In the era of Big Data, the ability to process and interpret large amounts of information is key. Data analysts support strategic decision-making by identifying trends and relationships in data. Data Science Engineers & AI Consultant, MLOps.

An important aspect was taken up by an expert from the IT industry for maritime. He points to the greatest deficit of soft skills (even among purely technical positions because even there, at least a minimum level of interaction and proper communication is required), and it is not related to the development of AI but rather to generational changes.

Experts were asked which skills they consider important given the current pace of technological change comparing the context from the AI side. Their responses are presented as percentages in Fig. 1.

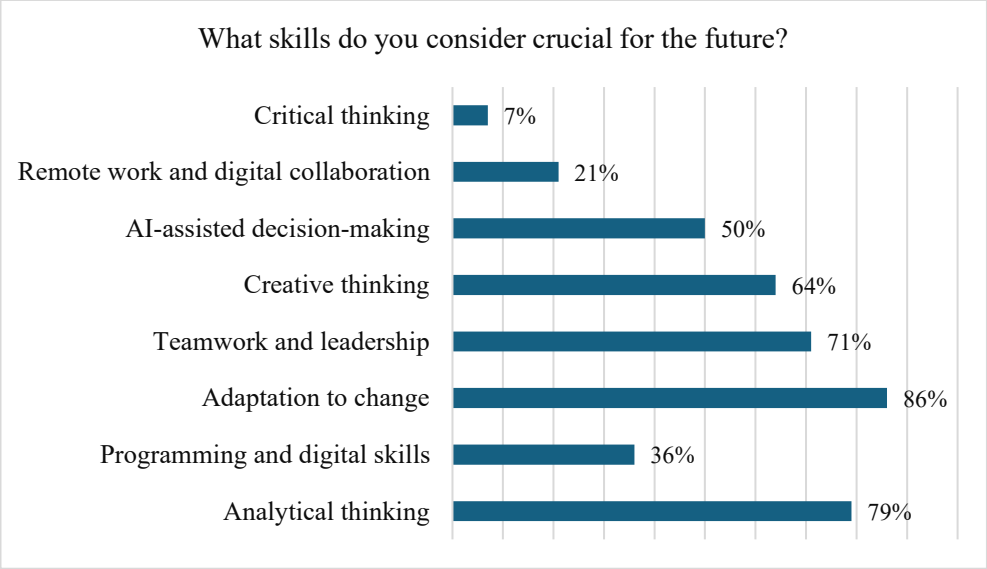


Figure 1. Skills considered as crucial for the future competency development
Source: own elaboration.

The following were identified as key skills for the future:

- Flexibility and resilience – quick adaptation to change;
- Analytical and critical thinking – the ability to make decisions in a world dominated by AI;
- Creativity and problem-solving – AI automates standard tasks, but it will not replace strategic thinking;
- Leadership and social competencies – AI supports, but people still manage;
- Lifelong learning – the ability to quickly and effectively learn new technologies and not only technologies. Simply the ability to adapt and learn;
- Programming and digital skills.
- Thinking critically, not taking everything for granted,
- AI-Enabled Decision Making,
- Remote Work and Digital Collaboration,
- Empathy and all kinds of social skills.

During the interview, experts gave varied answers to the question about the changes in employment expected in their industry over the next 5 years. Most agreed that we are facing a qualitative change in positions (this means that new tasks and new roles will be created). Some pessimistically indicated that there would be fewer jobs, while others were more optimistic, claiming that there would be more jobs. One of the experts mentioned that: "The development of AI is dynamic, but certain trends are already visible. Juniors and support workers will have the biggest problem, because their tasks can increasingly be automated. GenAI models, such as Clause Sonnet 3.7, are becoming better and better at programming, so it is not known whether there will still be a need for 'code typists' in 5 years. Similarly in graphics – AI generates images at a professional level, so there will be less and less room for people without a creative approach. Instructional design in e-learning is also undergoing a transformation – platforms for automatic creation of lessons are becoming more advanced, so instead of five average specialists, one expert with excellent knowledge of AI and the latest methodologies is enough. AI can write and execute tests, so the number of manual testers may significantly decrease. On the other hand, Project Managers will still be key – great leaders, able to manage people, communication and implementation of technologies. Interpersonal skills, strategic thinking and the ability to adapt will be really key."

It is worth noting that there are market sectors where the implementation of AI will be a natural consequence of the sector's development due to its strong correlation with modern technology. Examples include logistics, data analysis, and mass production. Even now, AI is replacing telemarketers, customer service representatives, and even cashiers.

However, some areas of economic activity remain reliant on human labor. Examples include the beauty and hairdressing industries, as well as the work of doctors. Teachers and educators should also be mentioned, as these professions involve building relationships between people and require exceptional interpersonal skills.

The topic was raised as to whether further development and implementation on a larger scale of AI-based tools will contribute to wage growth in the technology sectors. Some experts answered that it would not affect wages, while others claimed that further development of AI would contribute to a decline in wages in the technology sector.

During the in-depth interview, the topic of changes that AI will bring more broadly emerged, that is, in the general context of the labor market and professional competencies. Based on the collected statements, several main conclusions can be distinguished regarding the impact of artificial intelligence on the future of the labor market and professional competencies:

1. A transformation of the labor market structure awaits us:

- AI will cause a deep change in the employment structure. Many professions will disappear or be severely limited, especially those based on routine and repetitive tasks (e.g., administration, accounting, call centers, some programming professions, and even radiology or computer graphics).
- At the same time, new roles will appear, e.g. AI specialists, AI system testers, security experts, premium content creators, people managing data and AI interfaces.

2. Growing importance of new competencies:

- Digital, analytical competencies, creativity, flexibility, and the ability to work with AI will become key.
- Using AI tools, low-code/no-code, and understanding their operation will become standard requirements in many industries.
- The importance of soft skills, such as empathy, critical thinking, and interpersonal communication, is growing, especially where AI does not replace humans.

3. AI as an assistant, not just a replacement:

- AI will not necessarily replace humans but will become their efficient assistant. People who can work well with AI will be more competitive and effective.
- The use of AI can significantly increase an individual's productivity, reducing the need for large teams.

4. The need for re-industry and education:

- Mass re-qualification of employees will be required. The education system and the labor market must prepare for continuous learning and adaptation.
- Interdisciplinary education and lifelong learning will be important.

5. Social and ethical challenges:

- There will be a risk of excluding a part of society from the labor market, especially people without digital skills.
- There may be an increase in social inequalities, the emergence of an "unemployable" group, and pressure on social welfare systems.
- AI may disrupt the relationship between the creator and the system being created, deepening the problem of users' lack of understanding of how tools work.

6. New sectors and areas of growth:

- Development will occur, among other things, in the following industries: AI, IT, fintech, health, ecology, e-commerce, and intralogistics.
- It will be possible to evolve new professional and scientific areas, which are still difficult to define today.

One of the experts gave an example of huge changes: “In my opinion, we are in the first 5% of changes that will occur due to the automation of work and services using AI. The e-commerce market will grow significantly, the intralogistics industry has been preparing for automation and shortening the supply chain for years. Giving up standard ways of delivering cargo, e.g. in REWE or Zalando warehouses, currently changes the entire structure of the building architecture, so that it is adapted to the convenience of robots, not people. This will speed up the supply chain, change the speed of the e-commerce market, but without taxing corporations with an additional tax on automation, it will not significantly affect the prices of deliveries, which are already low, but will deprive low-skilled people of work.” (…) “In the longer term, the introduction of a meta-programming language by AI (e.g. to a purely binary language), will speed up communication between devices, but will make us stop understanding it and having insight into the architecture of changes. This will cause a large reduction in jobs on the programmer market, automation, but will also lead to the development of science in directions that are currently difficult for us to think about, due to human limitations in the structure of thinking, which does not allow us to think beyond two ideas.”.

Another issue raised in the in-depth interview concerns the perspective of which industries are most at risk of job losses as a result of the introduction of AI-based tools. Experts emphasized that AI does not eliminate jobs so much as change their nature, but some industries are particularly vulnerable to job cuts.

The expert highlighted that e-commerce and intralogistics are undergoing significant shifts, with warehouses being redesigned to suit robots rather than humans. This change will accelerate supply chains and market responsiveness. However, without implementing a tax on automation, it will not affect already low delivery prices and will likely result in significant job losses for low-skilled workers. An essential aspect was highlighted: further automation and the introduction of AI will require many changes in both the law and the tax system.

Undoubtedly, AI's role and significance are evident in automation and robotics processes. The development of new communication technologies, such as 5G, further supports this trend. In recent

years, communication has undergone a revolutionary transformation. A similar scale of transformation is expected in sectors such as energy, transportation, defense, and agriculture.

AI's importance will continue to grow in established areas such as power grids and logistics. It will undoubtedly expand into transportation, food production, and autonomous vehicles (Policy for the Development of Artificial Intelligence in Poland from 2020, 2020).

At the beginning of 2025, Poland's Ministry of Digital Affairs presented a new version of the draft Artificial Intelligence Systems Act, incorporating over two thousand comments submitted during public consultations. The core of this regulation is to establish a market oversight system and strengthen AI security measures, which is particularly important as AI expands into sectors such as the labor market.

The regulation will also introduce new support mechanisms for innovators. The planned oversight model aims to enable effective AI monitoring while minimizing interference in business operations. Additionally, the new provisions will regulate the financing of AI research using state budget funds and EU funding. The Minister responsible for digitalization will receive special competencies, primarily in supporting scientific and development projects, which will undoubtedly enhance the competitiveness of Poland's AI sector. Legal regulations should serve as a safety buffer for the large-scale implementation of AI systems (Draft Act on Artificial Intelligence Systems, 2025).

Table 1. A structured table summarizing the vulnerable industries and roles impacted by AI-driven changes

Industry/Sector	Roles/Functions Affected	AI Impact/Reason
Administration & Accounting	Routine office tasks, document analysis	AI automates repetitive processes (e.g. document analysis, workflow automation)
Customer Service	Call centers, technical support, receptionists, telemarketers	Chatbots and AI systems handle inquiries and support efficiently
Retail	Checkout operators, warehouse workers	Self-service tech, predictive systems, and automated logistics reduce jobs
Manufacturing	Assembly line workers performing simple operations	AI and robotics are replacing manual labor in production
Transport & Logistics	Truck drivers, couriers	Autonomous vehicles and route optimization tools threaten traditional roles
Media & Marketing	Copywriters, graphic designers (for standard projects)	Generative AI creates content and visuals, reducing demand for basic creative work
Entertainment (Acting)	Commercial actors, extras, voice-over artists	AI-generated avatars and voices can replace live performers
Finance	Credit analysts, investment advisors	AI handles data analysis and financial decision-making faster and more accurately
Legal & HR	Legal assistants, HR analysts, recruiters	Document review, contract screening, and resume filtering are increasingly automated
Agriculture & Construction	Manual laborers in basic tasks	Drones, robots, and predictive maintenance reduce physical job needs
Healthcare	Lower-level doctors, radiologists	AI image analysis and diagnostic tools support or replace initial evaluations

Consulting & Research	Analysts, researchers	AI enhances or replaces routine data gathering and analysis
Creative Industries	Advertisers, content creators, music producers	AI generates content (text, images, audio), reducing need for human input
Translation	Translators	Machine translation tools are increasingly accurate and widely adopted
IT (Junior Roles)	Beginner/front-end developers	AI tools can generate and debug code for basic/non-critical tasks

Source: own elaboration.

One of the experts gave a positive example of change, saying: "I would not consider this aspect in the category of vulnerable to job loss. Industries will undergo reconstruction as a result of automation or the use of AI tools. Repetitive activities will be replaced, the use of AI mechanisms will certainly open up new possibilities and services at a different level of complexity, better quality services or greater availability. Let's imagine the medical industry and the area of selecting medicines for the elderly or people with many diseases. Let's imagine that AI can analyze the mutual influence of medicines on each other and the influence of diseases on each other. Additionally, it can effectively indicate threats, exclusions or favorable connections. Thanks to this, the medicine selection service will be much more effective, it will eliminate unnecessary mistakes and the fact that it works quickly will make the service cheaper and more widely available. This is such a positive example, where no one will lose their job. I think that we should generally look positively and look for development and opportunities in every industry."

During the interview, the topic of education and changes in the education system that would be necessary to better prepare employees for future challenges were touched upon. Experts indicated that the education system needs significant changes to prepare workers for the future. There should be a greater emphasis on practical digital skills, in particular training in generative AI tools, big data, AI and machine learning, software development, cybersecurity and emerging technologies such as IoT and DevOps. Curricula need to be more closely aligned with current labor market needs, and educational institutions should lead innovation rather than follow trends. Early childhood education should emphasize STEM subjects, while universities need to strengthen and modernize their technical programs, preferably led by practitioners. There also needs to be a complete shift from mechanical memorization to developing and applying different types of intelligence. In addition, internships should be integrated into the curriculum and conducted in real business environments. Finally, improving salaries and career attractiveness in teaching roles is crucial to attracting qualified professionals into education.

5. DISCUSSION

AI will bring deep, irreversible changes in the way of working, required competencies, and employment structure. The key will be to skillfully combine technological and human competencies to survive in the market and use the opportunities that this revolution brings. The education system should be restructured to provide continuous support for individuals in acquiring essential, up-to-date skills and effectively navigating the evolving demands of the labor market.

The in-depth interviews indicate in the given areas:

1. Employment Structures and Professional Roles:

- AI is reallocating roles, particularly for experienced professionals (e.g., senior developers moving to AI-integrated projects). New roles are appearing, especially in AI, Data Science, and automation teams (e.g., in finance and IT sectors).
- Companies are increasingly integrating AI experience into recruitment processes.
- There is a differentiated sectoral impact: creative industries (e.g., 2D graphics, voice-over work) and freelancers are experiencing a decline in employment, suggesting that automation is

replacing some artistic and repetitive tasks; the legal and maritime sectors report minimal to no impact on employment, mainly due to slower AI adoption or supporting, non-core AI roles.

- There is a decrease in demand for entry-level or weaker performers, especially junior developers and inexperienced workers, as AI tools can highly substitute basic-level output. In turn, high-performance professionals with AI experience are in greater demand.

2. Employee perceptions and expectations regarding AI:

- More benefits than threats at the current stage of development. This includes faster access to information through localized AI models, increased efficiency in sales and promotion, and improved overall productivity, particularly in generating initial content drafts (enhanced employee efficiency is the main benefit).
- The primary concerns relate to data confidentiality, misuse or lack of understanding of AI tools – especially by junior staff – and the resulting need for internal guidelines.
- Great concern that automation would reduce outsourcing of creative tasks, potentially threatening job stability.
- Content verification and security risks (experts caution against over-reliance on AI results, especially given the inability to reliably detect hallucinations).

3. Education and skills development:

- AI literacy and tool proficiency (e.g., use of AI-supported programming environments) are highly valued (the emphasis is shifting toward domain professionals who can effectively use AI tools rather than AI engineers alone).
- The importance of employee development in digital competencies – such as training in AI tools – but only about two-thirds of IT companies currently offer such programs, suggesting room for broader implementation.
- The most in-demand skills include expertise in big data, AI, machine learning, software and application development, UI/UX design, and proficiency in technologies like Python, TensorFlow, and PyTorch. There is also a growing need for professionals skilled in integrating AI with existing systems, MLOps, cloud computing, and new programming languages and frameworks.
- There is a clear soft skills gap among technical professionals (pointing to generational changes, not technological ones).
- The key competencies of the future include analytical and critical thinking, flexibility, resilience, creativity, strategic problem-solving, leadership and social skills. Lifelong learning, adaptability and the ability to make decisions using artificial intelligence are also key, alongside remote working skills, digital collaboration, empathy and effective communication.

6. CONCLUSION

This study investigates the emergence of new competencies and shifting workforce perceptions within the information technology sector, with particular emphasis on the necessity for educational and human resource strategies to adapt in response to anticipated labor market trends in Poland. Employing a mixed-methods research design, the study integrates a comprehensive review of scientific literature and global analytical reports with qualitative data derived from in-depth interviews conducted with experts in the Polish IT industry.

The findings affirm that the future of work, particularly within the IT industry, is undergoing an accelerated transformation driven by artificial intelligence and automation. As revealed through empirical evidence and expert interviews, the integration of AI is redefining existing job roles and organizational workflows and generating an urgent demand for new hybrid competencies that blend technical fluency with human-centric capabilities. Both quantitative data (WEF 2025 employment forecasts, other reports) and qualitative observations (expert interviews, thematic literature) indicate that AI and automation are reshaping labor markets and prompting urgent regulatory, economic, and social adaptation.

This aligns with the global trends outlined in the World Economic Forum's Future of Jobs Report 2025 (WEF 2025), which projects that by 2030, 22% of current jobs will be structurally transformed – with 170 million jobs created and 92 million displaced. Remarkably, this transformation is not a zero-

sum game but rather a qualitative shift: tasks are increasingly divided between humans (33%), machines (33%), and human-AI collaboration (34%). This triadic distribution is already becoming a reality within the IT industry, as seen in the rise of AI-enhanced programming environments, DevOps automation, and GenAI-supported development workflows.

The analyzed reports, thematic literature, and interviews with experts clearly indicate that retraining and improving qualifications are necessary. According to the WEF (2025), 59% of the global workforce will require training by 2030 – an estimate mirrored by our study, which found that two-thirds of IT companies already engage in digital skill development, though often in limited scope. The skills identified in our interviews – AI literacy, MLOps, data science, cloud integration, and soft skills like communication and empathy – mirror the WEF's fastest-growing competencies: AI & big data, technological literacy, creative thinking, and resilience.

Some sectors are undergoing transformative changes, with warehouses increasingly designed for robotic operations rather than human labor. This transition is set to accelerate supply chains and boost market responsiveness, but may intensify job losses among low-skilled workers unless accompanied by structural reforms, such as automation taxes. The spread of AI and automation is evident across multiple industries (bolstered by advancements in communication technologies like 5G).

Furthermore, both data sets highlight an evolving employment landscape: while lower-skill, routine-based roles face automation-driven decline (e.g., junior developers, manual testers), new, high-value roles emerge. These include AI system integrators, cybersecurity professionals, ethical AI advisors, and domain experts with advanced digital fluency. The IT experts interviewed anticipated that AI would not eliminate jobs but restructure them, demanding interdisciplinary skill sets and adaptive leadership.

The social dimension of this transformation should not be ignored. WEF data (2025) warns of growing inequality among those without access to upskilling opportunities. Our findings confirm these concerns, especially when it comes to generational and soft skills gaps. There is broad agreement among practitioners that lifelong learning, ethical judgment, and the symbiosis of humans and AI will define the employability and sustainability of digital economies. Ultimately, the convergence of these studies with global forecasts clearly indicates that to succeed in the AI era, the IT industry – and the broader job market – must change the status quo. This means redesigning education and organizational structures to prioritize human-centric innovation. AI will undoubtedly be a catalyst for this growth. However, uniquely human traits – creativity, empathy, and critical thinking – will guide its responsible implementation and ensure that the future of work is inclusive, resilient, and purpose-driven.

One limitation of the article is the scope of the data: The data analysis focuses on both global data (market-wide reports) and data mainly related to the outlook of the Polish market and neighboring countries (material from in-depth interviews), which may limit the possibility of generalizing the results to other countries.

Another limitation may be rapid technological advances: The rapid evolution of AI technology means that market data and perspectives can quickly become outdated, requiring constant research to maintain their relevance. Broadening the scope of analysis to encompass a more diverse range of countries would enhance the comprehensiveness of insights into the global implications of artificial intelligence on labor market dynamics.

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28th European Conference on Artificial Intelligence (ECAI 2025)

HUMAN CAPITAL AS A KEY SUCCESS FACTOR IN SMART ENTERPRISE MANAGEMENT: THE USE OF IT AND AI TOOLS IN BUILDING THE COMPETITIVE ADVANTAGE OF POLISH MANUFACTURING COMPANIES

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ABSTRACT

Purpose: *To investigate the role of human capital in enhancing intelligent enterprise management, with a particular focus on how Polish manufacturing companies utilize IT and AI tools to build competitive advantage.*

Need for the study: *As organizations face rapid technological change, understanding the synergy between digital transformation and human capital becomes essential for maintaining competitiveness. Despite growing automation, human competencies continue to be essential for innovation and decision-making.*

Methodology: *The study used data analysis from the CATI and CAWI 365 survey of Polish manufacturing companies. The analysis was structured around the internal and external enterprise conditions, the impact of IT and AI-based systems and tools supporting human capital management and employee development, as well as changes in systems supporting intelligent management in manufacturing enterprises in Poland.*

Findings: *Companies identify internal conditions and workforce competencies as key enablers for IT and AI adoption. Expectations for the growing impact of AI in the next five years are high, particularly in talent management and decision-support systems. The effectiveness of employee development tools (especially AI-based training) is assessed as moderate. Technological maturity and regional disparities influence perceptions and implementation success.*

Practical Implications: *Organizations should prioritize strategic investment in human capital, including AI-integrated training, to foster innovation and adaptability. Policymakers may consider supporting SMEs in their digital transformation journey, especially in underrepresented regions.*

Keywords: Human Capital; Intelligent Enterprise Management; Artificial Intelligence in Management; Knowledge-Based Decision-Making; Talent Management; Digital Transformation

Jel codes: M12; M15; O15; O33; L23; J24

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1. INTRODUCTION

Modern organizations operate in a dynamic and complex environment where the ability to adapt quickly to change is a critical success factor. In this context, human capital plays a fundamental role as one of the most valuable assets of an enterprise (Ciekanowski, 2014; Wujarso et al., 2021). Defined as the sum of employees' knowledge, skills, experience, and competencies, human capital directly influences an organization's ability to achieve a competitive advantage (Beyer & Leoński, 2016; Wilson & Herceg, 2022). In the era of digitalization and automation, despite the growing significance of artificial intelligence (AI) and information systems, human competencies continue to play a pivotal role in decision-making processes, innovation, and shaping organizational culture (Kasemsap 2017). Research indicates that the integration of human capital with digitalization leads to increased competitiveness and innovation (Czerniachowicz & Świadek, 2014; Shabbir & Petraite, 2023). Intelligent enterprise management is a concept that integrates modern technologies with advanced management methods, enabling the optimization of business processes, increased operational efficiency, and better resource utilization (Nikonorov & Tutukin, 2019; Mikuła, 2020). A key aspect of this approach is the organization's ability to create value through the harmonious combination of technology and human competencies (Kichigin & Gonin, 2020). This requires not only the implementation of analytical tools and automation but also the effective management of human capital, which remains the primary source of innovation and creativity (Nowicka & Ciekanowski 2019; Marlina et al., 2023).

Industry 4.0 and its key technologies – such as artificial intelligence, real-time data analytics, and process automation – are significantly transforming human resource management in organizations. AI-driven talent management systems, knowledge-sharing platforms, and predictive analytics enable enterprises to better align employee competencies with the dynamic demands of the market (Frankowska et al., 2017; Ciliberto et al., 2021; Dhinakaran et al., 2023; Piccarozzi, 2024). At the same time, the development of intelligent systems, including enterprise resource planning (ERP) and AI-driven HR analytics, allows for real-time monitoring of workforce efficiency and optimization of decision-making processes (Kulshrestha, 2024). Although automation continues to advance, human beings remain the key factor determining an organization's success. Technology enhances operational efficiency and helps streamline organizational processes. However, it cannot fully substitute human competencies in areas such as strategic decision-making, relationship-building, and innovation. Therefore, the effective use of human capital continues to be a central priority in intelligent enterprise management during the era of digital transformation (Marku, 2024; Gitling, 2024).

This article aims to analyze the impact of human capital on the effectiveness of intelligent enterprise management and to identify key challenges and strategies for its optimal utilization. The study focuses on the role of human capital in modern organizations, the significance of employee competencies in the context of technological advancements, and the ways to build a competitive advantage through effective human resource management in the digital era. The research is based on the analysis of a representative sample of manufacturing companies in Poland, using both quantitative and qualitative methodologies. A large-scale survey was conducted to assess the implementation of IT and AI systems in enterprises, to support human capital management and employee development, and to realize intelligent management aimed at enterprise development and building competitive advantage.

The article is structured into five sections. The first section presents the theoretical foundations of intelligent enterprise management and the role of human capital in the context of Industry 4.0. The second section discusses the impact of digitalization and artificial intelligence on human resource management, analyzing key technologies and their application in optimizing HR processes. The third section outlines the research methodology and describes the characteristics of the studied sample. The fourth section presents an analysis of the empirical findings, highlighting the impact of internal and external conditions of the operation and development of manufacturing enterprises in Poland related to modern technology and aided by artificial intelligence on decision-making and management of human capital. The final, fifth section provides conclusions and practical recommendations for enterprises seeking to effectively integrate modern technologies with human capital management while fostering a culture of innovation, adaptability, and collaboration.

2. LITERATURE REVIEW

Human capital is a key component of intelligent organizations, and its significance is growing in the age of digitalization. In the scientific literature, human capital is defined as the sum of employees' competencies, knowledge, and skills that contribute to increasing an organization's value (Szopik-Depczyńska & Korzeniewicz, 2011; Czerniachowicz, 2016; Bashynska & Prokopenko, 2023). Digital transformation has reshaped traditional approaches to human resource management (HRM), compelling organizations to adopt new talent management strategies in which digital technologies play a pivotal role (Wieczorek-Szymańska 2019; Nyathani, 2023). Modern manufacturing enterprises are increasingly integrating intelligent HRM systems based on data analytics and artificial intelligence (AI), enabling the effective utilization of employees' potential (Czerniachowicz, 2022; Vladimirovna, 2024).

The application of AI in HRM focuses on three main areas: talent management, predictive human resource analytics, and competency management. AI-driven HRM facilitates better job-candidate matching, employee performance analysis, and the identification of training needs (Rony & Yahaya, 2021). The integration of enterprise resource planning (ERP) systems, HR analytics, and real-time employee monitoring enables labor market trend forecasting and optimization of HR processes (Burton, 2019). Companies that implement AI systems for employee engagement monitoring and predictive turnover analysis report increased operational efficiency and reduced recruitment costs (Faheem et al., 2024).

AI-driven management is transforming leadership models by shifting the focus from traditional methods to algorithm-supported managerial decision-making (Ahmed et al., 2024). Intelligent analytical systems allow leaders to manage teams more effectively, anticipate organizational changes, and enhance employee engagement. The literature emphasizes the importance of innovation-driven strategies, including the development of organizational cultures that foster digital competency growth and flexible career paths (Szopik-Depczyńska, 2016; Klimas & Czakon, 2022; Fenwick et al., 2024). The application of AI in leadership development enables the creation of personalized mentoring programs and the identification of future leaders based on behavioral data analysis (Zehir et al., 2019).

However, the literature review indicates that AI implementation in human capital management entails numerous technological, organizational, and ethical challenges (Cappelli et al., 2019). Among the most important ethical concerns are the lack of transparency of the algorithms, the risk of algorithmic bias in recruitment processes, and the protection of employees' personal data (Raghavan et al., 2020, Vrontis et al., 2023). It is therefore necessary not only to technically improve solutions, but also to develop responsible HR policies that ensure fairness, transparency and regulatory compliance. Organizations must address issues related to personal data protection, the ethical use of AI, and the transparency of decision-making algorithms (Vrontis et al., 2021, Maheswari et al., 2024). Scholars highlight the risk of algorithmic bias, which may lead to inequalities in recruitment and promotion processes (Raghavan, 2020). Additionally, the rapid development of artificial intelligence (AI) requires continuous adaptation of human resource management (HRM) strategies and investments in digital skills development, which may pose a challenge for small and medium-sized enterprises (SMEs). Research indicates that SMEs often face difficulties in integrating new technologies due to limited resources and digital competencies (Vrontis & Christofi, 2021; Czerniachowicz, 2023). Moreover, the necessity of continuously updating HRM strategies in response to AI's dynamic evolution adds an additional burden for SMEs (Strohmeier & Piazza, 2015).

3. METHODOLOGY

The study was conducted using the survey method, in the CATI (Computer-Assisted Telephone Interview) and CAWI (Computer-Assisted Web Interview) survey technique. The second of the indicated methods was used in the case of the respondent indicating the preferred form of an online survey completed independently. The research tool used was an original survey with a metric and main questions. The survey was conducted from November 2024 to January 2025, and n=365 companies conducting production activities, PKD C section (Polish Classification of Activities), from all over Poland participated in the study (the database developed for the study had 475 records).

The primary objective of the survey-based research was to identify the key determinants of development among manufacturing enterprises in Poland, with a particular focus on factors that foster

intrapreneurship and their influence on innovation processes within organizations**.** The study also aimed to evaluate the strength and significance of these determinants in the context of rapidly changing market conditions. Special attention was given to the analysis of entrepreneurial and innovation-oriented behaviors within organizations, as well as to the evolving nature of systems that support entrepreneurial mindsets in the areas of human capital management, digitalization, and intelligent enterprise management.

Among the 365 surveyed companies, 229 (63% of the total sample) were small enterprises employing between 9 and 49 employees. The second group, comprising 37% of the sample (136 companies), consisted of medium-sized enterprises with 50 to 249 employees. In terms of employee demographics, men constituted a slight majority (51%), while women accounted for 49% of the workforce within the surveyed firms. Nearly all employees (97%) had higher education degrees. Secondary and vocational education played a marginal role, with many companies employing no individuals with such educational backgrounds. These data suggest a high level of specialization among employees, which may indicate that the surveyed firms operate in sectors requiring advanced knowledge and expertise. In terms of capital structure, 87% of the firms were entirely domestically owned. Only 13% had a mixed ownership structure (41 firms) or were fully foreign-owned (8 firms). The companies participating in the study were distributed across all administrative regions (Voivodeships) of the country (Figure 1).

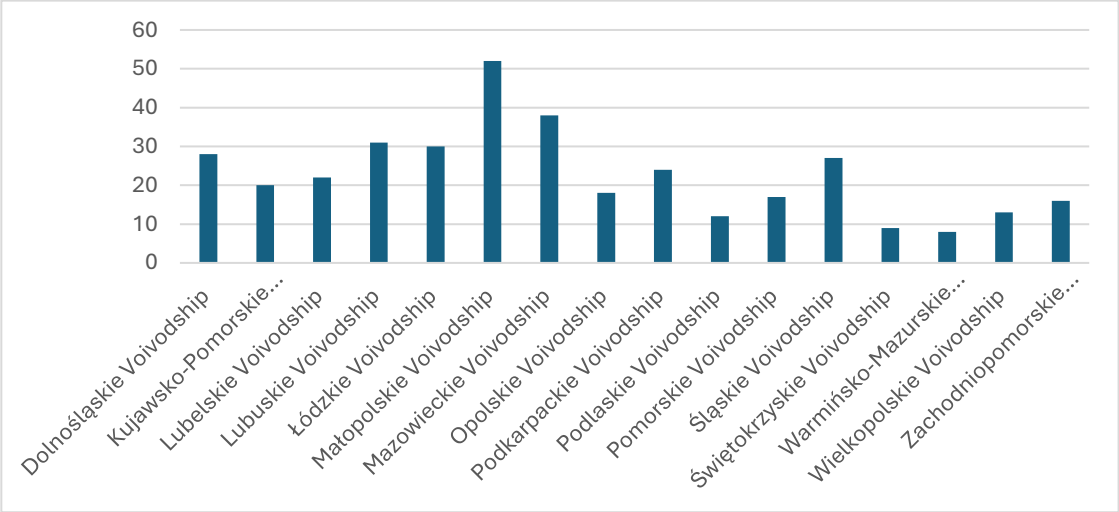


Figure 1. Distribution of the interviewed companies according to the place of registered activity in the voivodeships in Poland

Source: own study.

The most represented regions in the study were the Małopolskie Voivodeships (14.25% of all firms), the Mazowieckie Voivodeships (10.41%), and the Lubelskie Voivodeships (8.49%). The least represented regions were the Podlaskie Voivodeships (3.29%), Świętokrzyskie Voivodeships (2.42%), and Warmińsko-Mazurskie Voivodeships (2.19%). In terms of years of operation, the majority of surveyed firms were established between 2015 and 2019 (32%) or in 2020 or later (26%). The least represented group consisted of the oldest enterprises, founded before 1994, with only six such firms included in the sample (2% of the total). Some of the youngest companies had only one year of market experience, while the oldest had been in the market for 33 years.

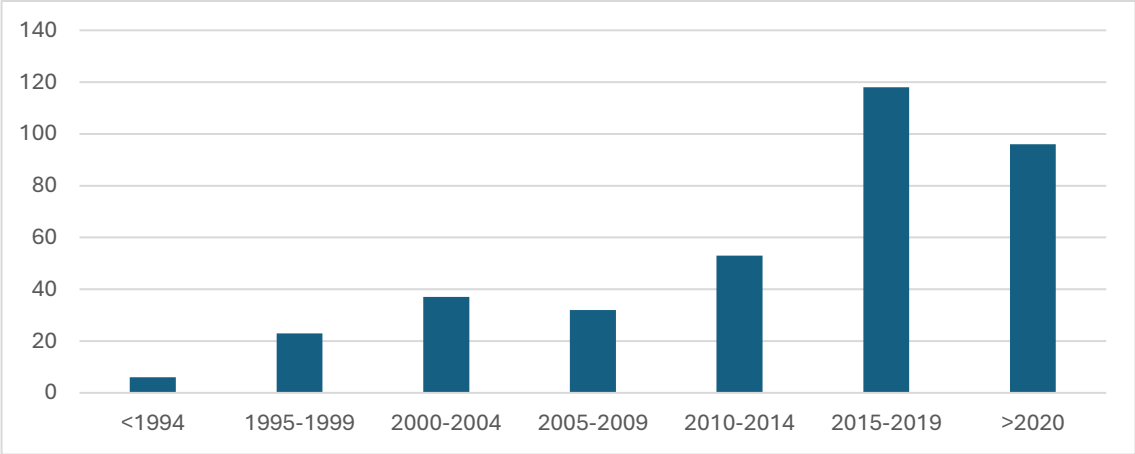


Figure 1. The distribution of surveyed companies by the year of business establishment
Source: own study.

This article presents an analysis of selected questions, the examination of which allowed for the identification of the following aspects:

- The assessment of existing internal conditions within the enterprise and their anticipated importance in the future, particularly in the context of developing IT tools and the application of artificial intelligence (AI).
- The influence of external factors – such as the advancement of digital technologies, AI, and decision-support systems – on organizational operations and their projected relevance over the next five years.
- The effectiveness of methods and tools supporting employee development, including the organization of training in creativity, innovation, problem-solving, and project management using AI.
- The efficiency of IT infrastructure and tools that enhance organizational innovativeness.

The analysis was based on responses provided by enterprises to the following questions:

Question 2a) Please assess the current internal conditions of your enterprise and indicate which will be most significant in the future [Development of IT-supporting tools and the use of AI] – Past experiences

Question 2b) Please assess the current internal conditions of your enterprise and indicate which will be most significant in the future [Development of IT-supporting tools and the use of AI] – In the next five years

Question 3a) Please assess the impact of external conditions on your organization and their expected significance in the future [New technologies, development of digital technologies, artificial intelligence (AI), and decision-support systems] – Past experiences

Question 3b) Please assess the impact of external conditions on your organization and their expected significance in the future [New technologies, development of digital technologies, artificial intelligence (AI), and decision-support systems] – In the next five years

Question 5a) Please assess the effectiveness of methods and tools supporting employee development and Human Capital Management (HCM) [Organization of regular training in creativity, innovation, problem-solving, project management, and entrepreneurial skills using AI]

Question 5c) Please assess the effectiveness of IT and AI tools supporting organizational development [Provision of access to modern infrastructure and tools supporting innovation processes]

Question 10 a) What changes are occurring in systems supporting intelligent management within enterprises? How significant are these changes? Please identify 10 changes and assign each a weight from 1 (least significant change) to 10 (most significant change). [the introduction of new technologies and (AI)].

Responses to the above questions were collected using a five-point Likert scale (where 1 meant the lowest rating and 5 meant the highest). The analysis of the responses was conducted using descriptive statistical methods in Microsoft Excel.

4. RESEARCH RESULTS

As part of the conducted research, an analysis was carried out regarding enterprises' opinions on key factors influencing their operations and future development. For the purposes of this study, responses to selected questions (as outlined in the previous section) were analyzed. The examined issues concerned both internal and external conditions affecting business operations, as well as tools and strategies supporting organizational and employee development. Particular emphasis was placed on the role of emerging technologies, including artificial intelligence (AI) and decision-support systems, across various areas of business activity. Survey, responses were analyzed based on two main criteria: the geographical location of the firms (by voivodeship) and their length of operation in the market. Since most of the responses were provided using the Likert scale (Questions 2, 3, and 5) and a ten-point scale (Question 10), box plots were chosen to illustrate the results. These plots display the median (the central line within the box), the quartiles (the upper and lower edges of the box), and the extreme values (the whiskers of the plot).

The results presented in Figures 3 and 4 show the distribution of Likert scale ratings (Question 2a) provided by companies, broken down by voivodeship (Figure 3) and by year of establishment (Figure 4), in the context of their past experiences with internal organizational conditions that have influenced the implementation of IT and AI solutions within the enterprise.

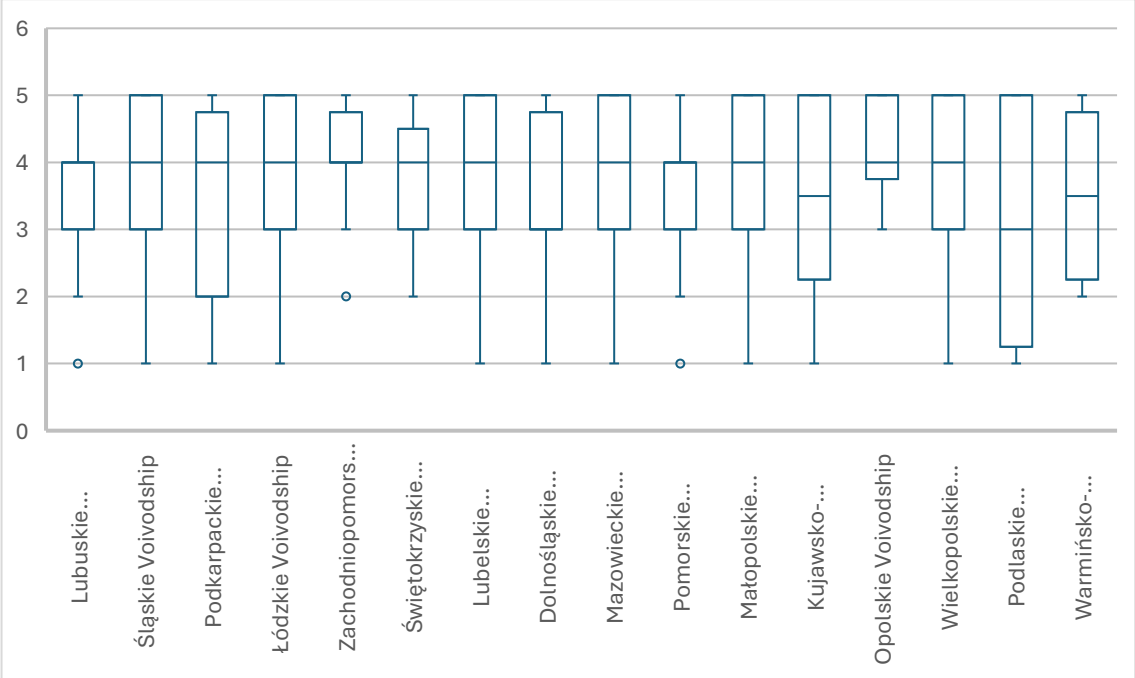


Figure. 3. The distribution of assessments of experiences related to internal conditions and their impact on the implementation of IT and AI solutions in enterprises, broken down by voivodeships in Poland. Previous experience

Source: own study.

Analysis of Figure 3 reveals that the median ratings reported by enterprises in most voivodeships tend to cluster around the value of 4 (11 voivodeships), which generally suggests positive assessments of past experiences related to internal conditions for implementing IT tools and utilizing AI. However, some variation is evident – in certain regions such as Podlaskie Voivodship, Podkarpackie Voivodship, and Kujawsko – Pomorskie Voivodship, substantial variability is observed, indicating more extreme experiences among some firms. At the same time, voivodeships such as Zachodniopomorskie Voivodship and Dolnośląskie Voivodship demonstrate relatively high median scores, which may suggest more developed infrastructure for IT and AI utilization or greater experience in this domain. It is also worth noting the presence of outliers in several regions, such as Lubuskie Voivodship, Zachodniopomorskie Voivodship, and Pomorskie Voivodship. These may point to specific cases of

firms with significantly different experiences compared to the prevailing trend in their respective regions.

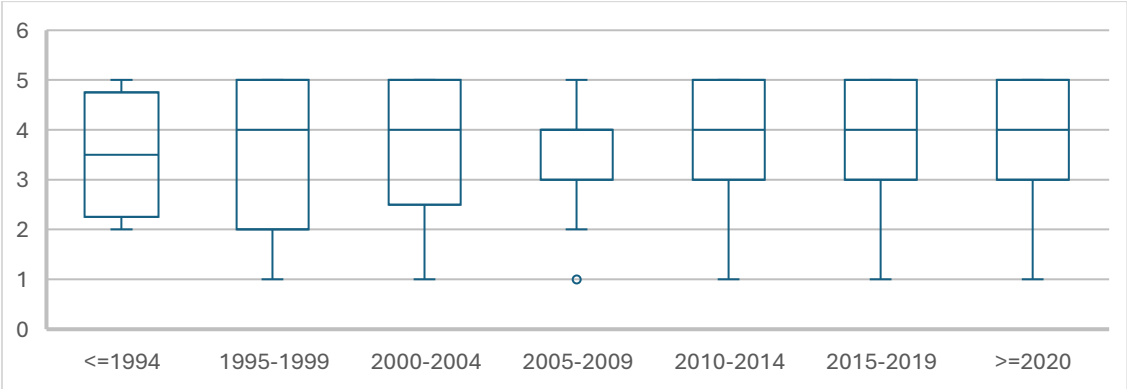


Figure. 4. The distribution of assessments of experiences related to internal conditions and their impact on the implementation of IT and AI solutions in enterprises, broken down by the year of company establishment. Previous experience

Source: own study.

Figure 4 presents the results of company evaluations regarding internal conditions experienced to date in the implementation of IT tools and the use of artificial intelligence (AI). The analysis was conducted based on the duration of the enterprise's presence in the market, as determined by the year of establishment. The findings indicate that firms established in different years generally assess their past experiences at a similar level. In most cases – excluding the oldest companies – the median rating is 4, suggesting that enterprises perceive their internal conditions for IT and AI implementation as favorable. Firms founded before 1994 exhibit moderate variability in their assessments, with a median of 3.5. The greatest variability is observed among companies established between 1995 and 1999. In contrast, enterprises founded between 2005 and 2009 show the lowest variability, which may indicate a more uniform perception of their past experiences. However, this group also includes an outlier, pointing to the presence of one or more firms that rated their experiences significantly lower than the group average. Fugure 5 and 6 present company assessments of the anticipated importance of internal conditions for the implementation of IT tools and the use of AI over the next five years (Question 2b).

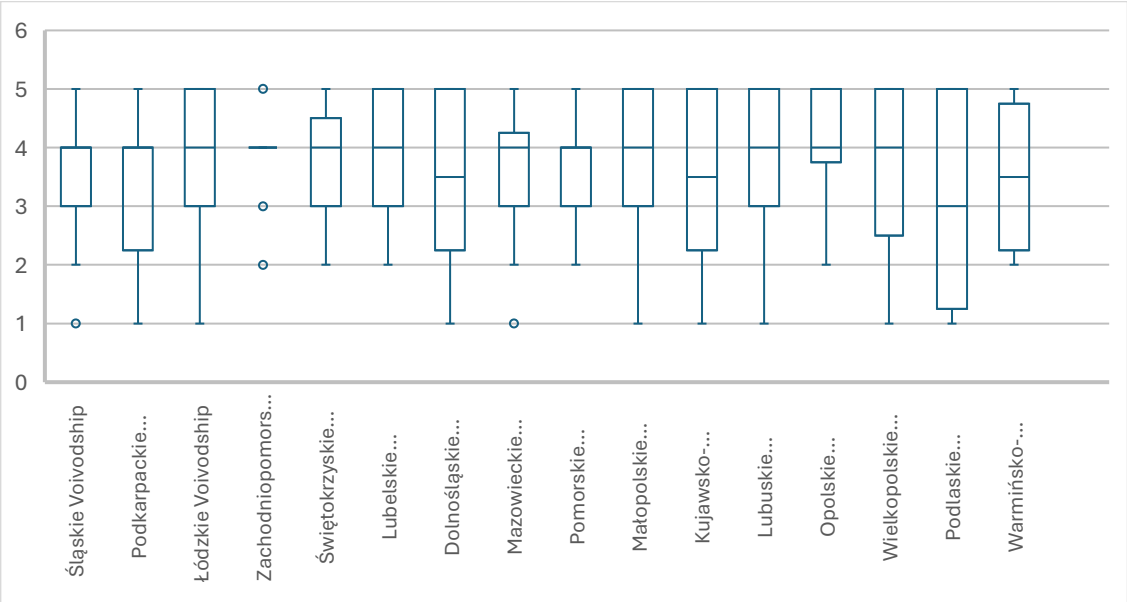


Figure 5. The distribution of assessments of experiences related to internal conditions and their impact on the implementation of IT and AI solutions in enterprises in the future (next 5 years), broken down by voivodeships in Poland.

Source: own study.

In certain voivodeships, such as Podlaskie Voivodship, Dolnośląskie Voivodship, and Kujawsko - Pomorskie Voivodship, wider interquartile ranges can be observed, suggesting greater uncertainty or diversity in predictions regarding the future impact of IT and AI implementation on internal organizational conditions. In contrast, voivodeships such as Śląskie Voivodship and Pomorskie Voivodship exhibit more compact distributions of assessments, indicating that firms in these regions hold more consistent expectations about the future significance of IT and AI. Similar to the pattern observed in 'past experiences' (Question 2a), several voivodeships (e.g., Mazowieckie Voivodship, Śląskie Voivodship and Zachodniopomorskie Voivodship) display the presence of outliers, which may reflect firms anticipating a markedly different impact of new technologies on internal organizational conditions compared to the general trend within their region The analysis of the chart suggests that enterprises in most voivodeships anticipate a growing importance of IT and AI implementation for internal business conditions over the next five years, as reflected by a median score of 4 in eleven regions. The increase in median values compared to past experiences indicates that tools based on emerging technologies are expected to play an increasingly significant role in the strategic operations of enterprises in Poland.

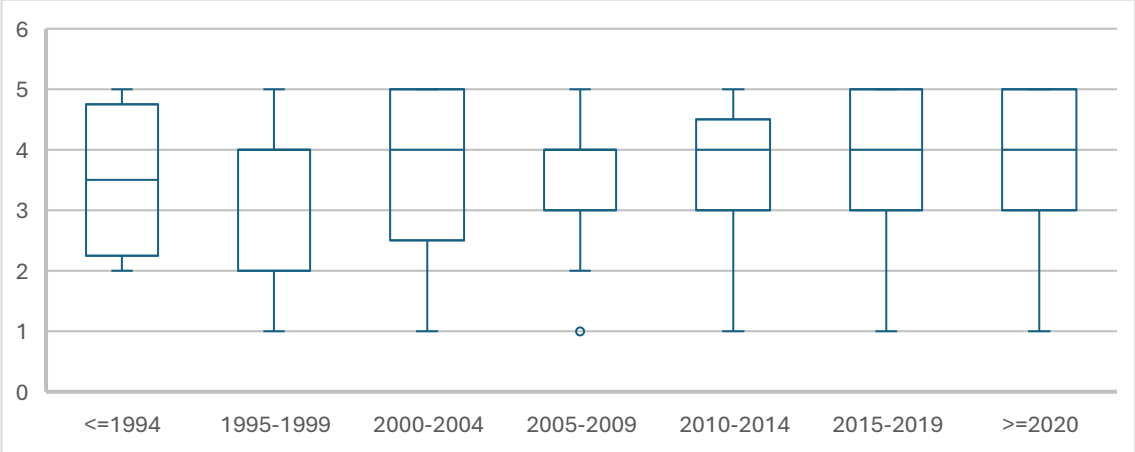


Figure 6. The distribution of assessments of experiences related to internal conditions and their impact on the implementation of IT and AI solutions in enterprises in the future (next 5 years), broken down by year of company foundation

Source: own study.

Chart 6 presents companies' predictions regarding the future significance of internal organizational conditions in the context of implementing IT tools and utilizing artificial intelligence (AI) over the next five years. The analysis was conducted with respect to the length of time the companies have operated on the market (based on the year of establishment). Overall, firms – regardless of their founding year – assess the importance of internal conditions for IT and AI implementation at a generally good level. Most median scores, except for the oldest group of companies (median of 3.5), are equal to 4, suggesting that enterprises anticipate a strong influence of these factors in the coming years. Companies established before 1994 evaluated the role of internal conditions in IT and AI implementation moderately positively, with a median score of 3.5. The range of responses in this group, spanning from 2 to 5, may reflect the presence of well-established strategic approaches toward future technology adoption. On the other hand, companies founded between 1995 and 1999 exhibited greater variability in their assessments, possibly indicating some degree of uncertainty or diverse strategic perspectives within this cohort. The overall distribution of ratings suggests that the future use of AI and IT tools is widely perceived as significant for enterprise development.

The next question focused on assessing past experiences and the impact of external factors on the organization, including new technologies, the development of digital technologies, artificial intelligence (AI), and decision-support systems (Question 3a). Figures 7 and 8 illustrate these aspects in terms of regional distribution (Figure 7) as well as the length of time the company has operated in the market, based on the year of establishment (Figure 8).

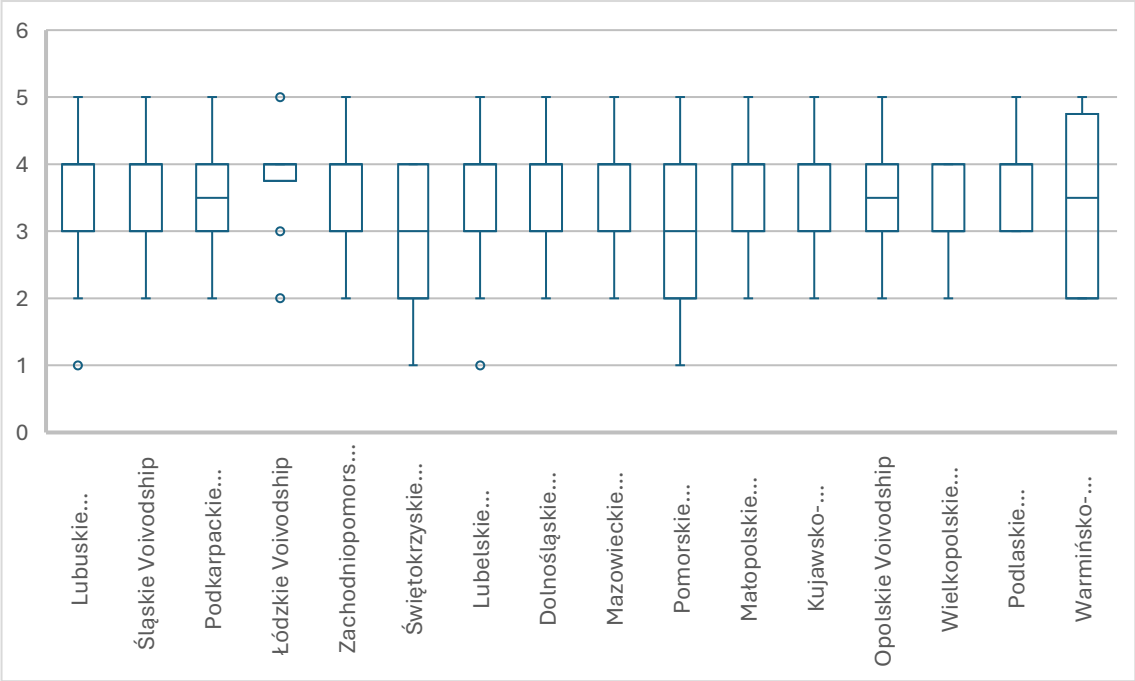


Figure 7. Distribution of ratings on the impact of new technologies, digital developments, artificial intelligence (AI) and decision support systems as external determinants on the management of surveyed companies by voivodeships in Poland. Previous experience
Source: own study.

The companies' past experiences indicate that the impact of external factors – such as new technologies and AI – on their operations is generally assessed as moderately positive to positive, with the median score approaching 4 in most voivodeships. Exceptions include the Podkarpackie Voivosdhip, Opolskie Voivosdhip, and Warmińsko-Mazurskie Voivosdhip (median of 3.5), as well as the Świętokrzyskie Voivosdhip and Pomorskie Voivodship (median of 3). Some regions demonstrate greater consistency in responses (e.g., Dolnośląskie Voivosdhip, Mazowieckie Voivosdhip, and Śląskie Voivosdhip), while others (e.g., Warmińsko-Mazurskie Voivosdhip, Świętokrzyskie Voivosdhip, and Pomorskie Voivosdhip) show more varied experiences. Outliers observed in regions such as Lubuskie Voivosdhip, Łódzkie Voivosdhip, and Lubelskie Voivosdhip suggest that in some firms, the perceived impact of new technologies differs significantly – being either very low or very high. This variation may be attributed to the fact that some companies are actively utilizing AI and decision-support systems, while others are only beginning their digital transformation. Overall, the results suggest that while companies are aware of the relevance of technology in their market environment, the level of implementation and perception of its impact varies across regions.

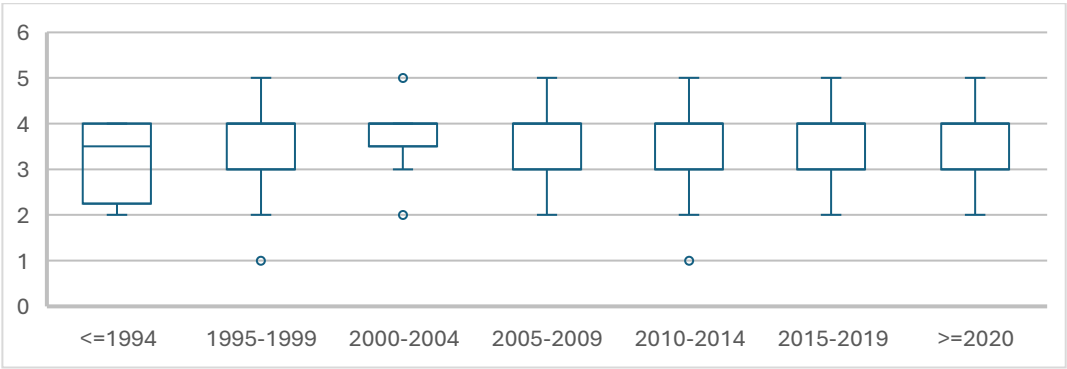


Figure 8. The distribution of ratings on the impact of new technologies, digital developments, artificial intelligence (AI) and decision support systems as external determinants on the management of surveyed companies, broken down by the year of company establishment. Previous experience
Source: own study.

Based on the length of time in operation (Figure 8), companies assessed the past impact of external factors at a moderate to good level (median between 3.5 and 4), with a predominance of positive evaluations. Older firms (established in or before 1994 and between 1995–2004) exhibited greater variation in experiences, which may stem from differing adaptation strategies. In contrast, younger companies (established in 2005 or later) reported more consistent assessments, suggesting that digital technologies and AI have been an integral part of their operations from the outset. The presence of outliers indicates that not all companies perceive new technologies as having a significant impact on their organization. This may be due to industry-specific characteristics or differing development strategies.

The next question (Question 3b) concerned the anticipated impact of external factors within the organization—such as new technologies, the development of digital technologies, artificial intelligence (AI), and decision-support systems—over the next five years (Figures 9 and 10).

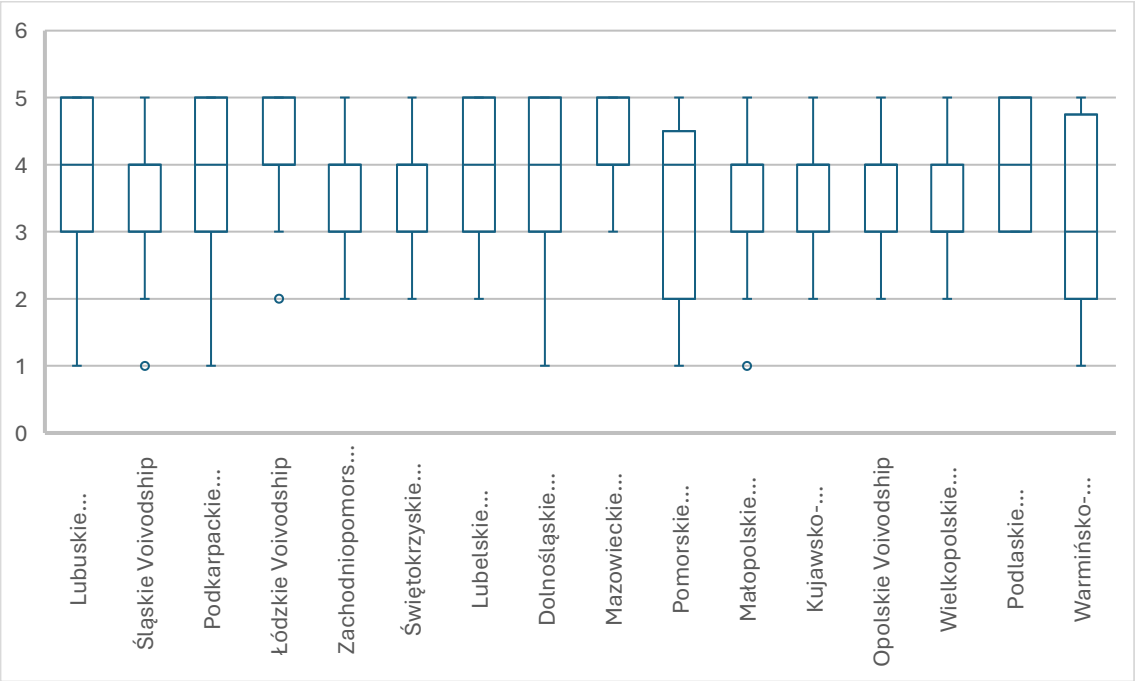


Figure 9. The distribution of opinions on the impact of the development of new technologies, digital technologies, artificial intelligence (AI), and decision support systems as external factors on business management (next 5 years), broken down by voivodeships in Poland
Source: own study.

The results indicate that companies in Poland generally anticipate a growing role for new technologies, artificial intelligence (AI), and decision-support systems in the near future. In most voivodeships, the evaluations are higher compared to past experiences – with the median reaching a value of 4 in fifteen regions – which suggests that enterprises are increasingly aware of forthcoming changes and their potential impact. Particularly high scores are observed in regions such as Mazowieckie Voivosdhip and Podlaskie Voivosdhip. Several voivodeships (e.g., Zachodniopomorskie Voivosdhip, Świętokrzyskie Voivosdhip, Kujawsko-Pomorskie Voivosdhip, Opolskie Voivosdhip, and Wielkopolskie Voivosdhip) exhibit a relatively uniform vision regarding the future role of technology in business operations. This may be attributed to a higher level of technological maturity among firms and better access to innovation-supporting infrastructure. In contrast, regions such as Warmińsko-Mazurskie Voivosdhip and Pomorskie Voivosdhip display greater variability in responses – from relatively low to very high scores – indicating that while some companies perceive significant opportunities arising from technological advancements, others remain uncertain about their potential impact. Compared to previous experiences, firms now appear more aligned in their expectations regarding the influence of new technologies, as evidenced by a lower number of outliers. This may reflect a growing awareness of the importance of these technologies and the gradual implementation of innovation strategies.

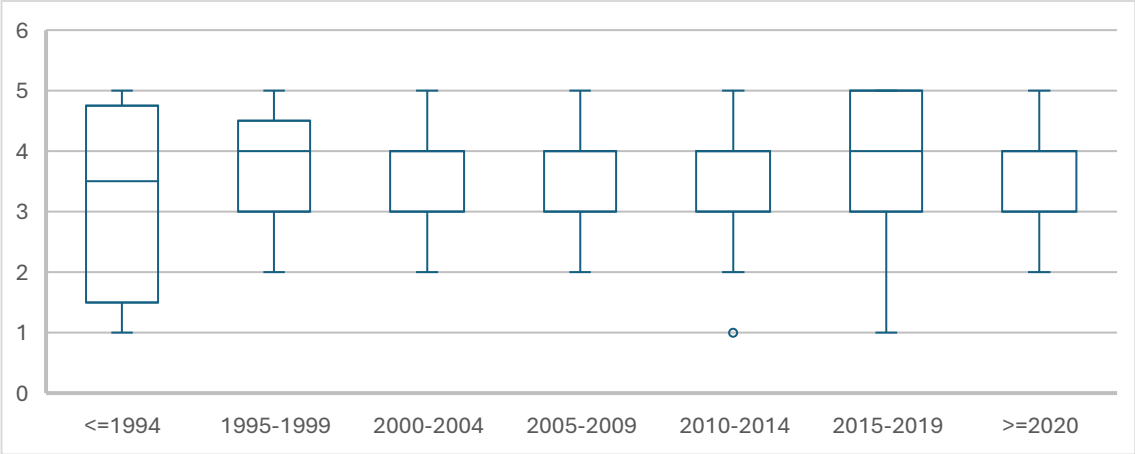


Figure 10. The distribution of opinions on the impact of the development of new technologies, digital technologies, artificial intelligence (AI), and decision support systems as external factors on business management (next 5 years), broken down by the year of company establishment
Source: own study.

Considering the duration of companies' market presence, the inquiry into the anticipated future impact of external factors – especially emerging technologies, digital advancements, artificial intelligence (AI), and decision-support systems – indicates that, overall, enterprises expect these factors to exert a substantial influence on their future operations. However, the extent of this anticipated impact varies among firms. The oldest companies (established in or before 1994) exhibit the greatest variation in assessments, which may reflect diverse attitudes toward new technologies – some recognizing their importance, while others remain more skeptical. Firms established between 1995 and 2009, as well as those founded after 2020, show greater alignment in their forecasts, with median scores of 4, suggesting that these technologies are more prominently integrated into their strategic planning. Among firms established between 2010 and 2014, outliers are present, indicating that not all companies perceive the influence of new technologies, AI, and decision-support systems as positive for their operations.

The next question examined (Question 5a) concerned the assessment of the effectiveness of methods and tools supporting employee development and Human Capital Management (HCM), such as the organization of regular training sessions focused on creativity, innovation, problem-solving, project management, and entrepreneurial skills, incorporating the use of AI. The survey results were analyzed in terms of the geographical location of the company (Figure 11) and the company's age based on the year of establishment (Figure 12).

The analysis of Figure 11 suggests that the effectiveness of methods and tools supporting employee development – including AI-based training – is generally rated as neutral, with a median score of 3 observed in 10 voivodeships, or moderately positive in three regions (median score of 4). In voivodeships such as Podlaskie Voivosdhip and Warmińsko-Mazurskie Voivosdhip, the results indicate relatively low median scores (2 and 2.5, respectively), suggesting that companies in these regions may not perceive significant value in the training methods currently in use. Firms in some regions, such as Świętokrzyskie Voivosdhip and Lubuskie Voivosdhip, show greater consensus in their assessments, whereas regions with more dispersed scores (e.g., Podlaskie Voivosdhip) reflect a broader diversity of experiences. Compared to previous evaluations concerning the impact of digital technologies and AI on enterprises, assessments of the effectiveness of regular training in creativity, innovation, problem-solving, project management, and entrepreneurial skills using AI appear less varied. This finding indicates that companies view such training as moderately useful, but not of transformative importance.

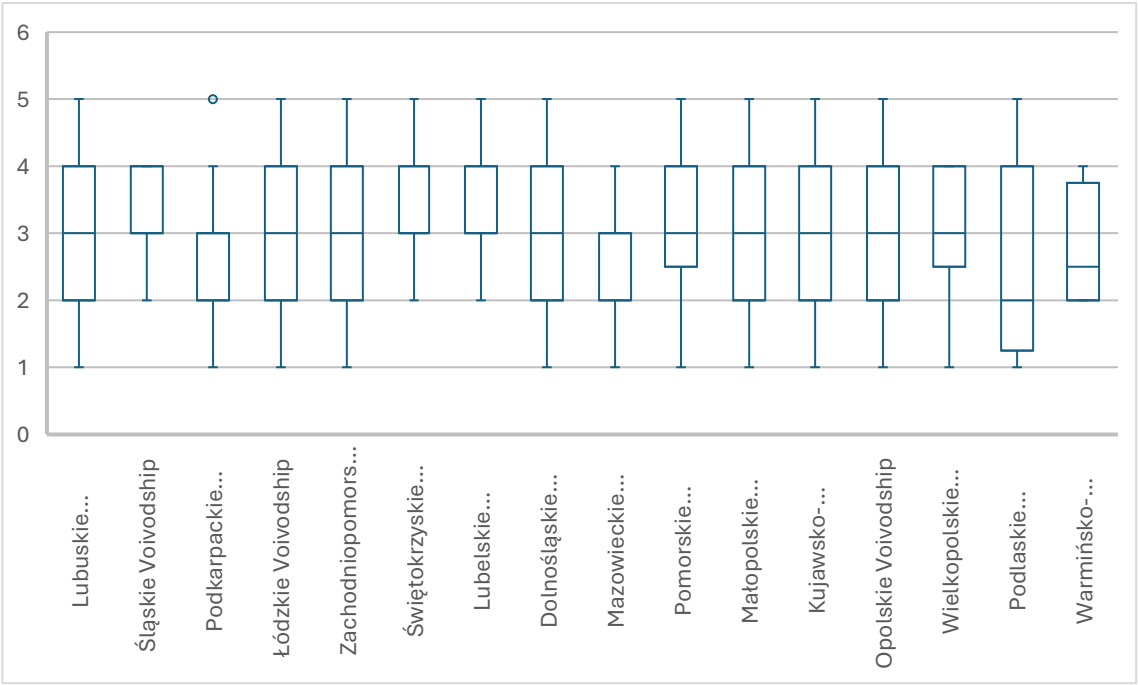


Figure 11. Distribution of evaluations of the effectiveness of forms and tools supporting employee development and human capital management in the surveyed company by voivodeships in Poland
Source: own study.

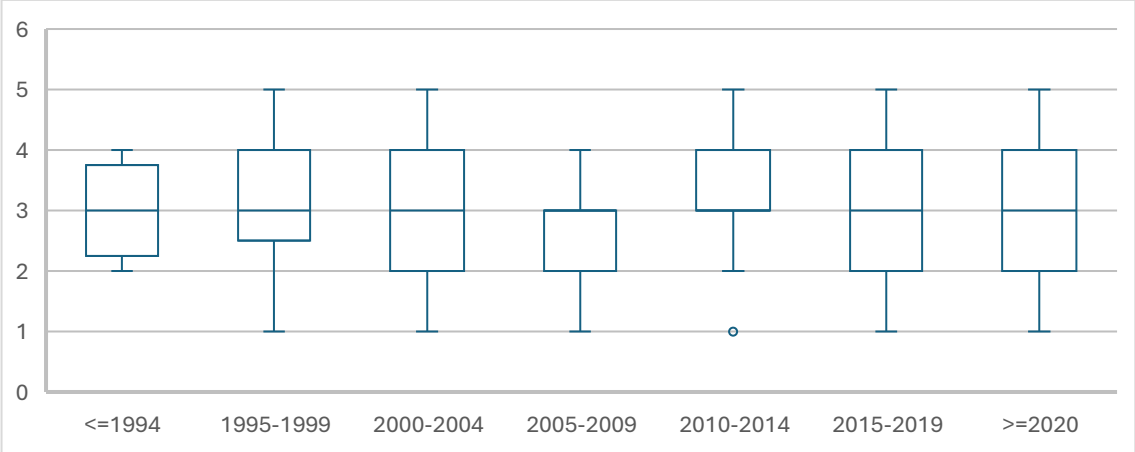


Figure 12. The distribution of evaluations of the effectiveness of forms and tools supporting employee development and human capital management in the surveyed companies, broken down by the year of company establishment
Source: own study.

A similar pattern emerges when analyzing the effectiveness of regular training in creativity, innovation, problem-solving, project management, and entrepreneurial skills using AI in relation to the length of time a company has been operating in the market (Figure 12). Most firms rated the effectiveness of such training, including project management and entrepreneurial skills development with AI, at a moderate level (median score of 3). Older companies (established in or before 1994) showed the least variation in responses, suggesting a consistent but moderate level of experience with implementing modern Human Capital Management (HCM) methods. Firms established between 1995 and 2004, as well as those founded after 2015, exhibited a wider range of responses, which may indicate differing levels of adoption of contemporary HCM practices. Among companies founded between 2010 and 2014, outliers were also observed, suggesting that some of these firms may be facing challenges in adapting to new forms of employee training.

The limited effectiveness of employee development tools may be due to a mismatch between training content and the actual needs of the organization, low employee involvement in e-learning processes, or a lack of integration of training with daily work tasks. In the future, it would be advisable to study the relationship between the personalization of training content and its effectiveness.

One of the final questions selected for analysis (Question 5c) concerned the assessment of the effectiveness of IT and AI tools in supporting organizational development. The results of the analysis are presented in Figures 13 and 14.

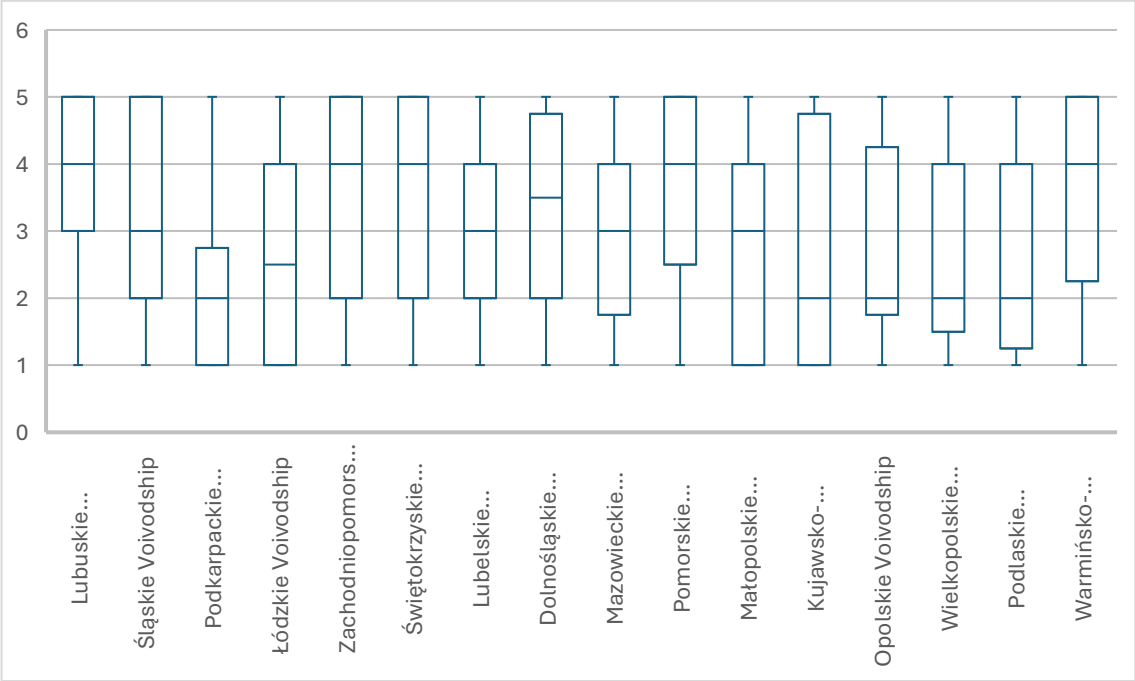


Figure 13. Distribution of assessments of access to modern infrastructure and tools supporting innovation processes in the area of IT and AI forms and tools supporting the development of the surveyed organizations by voivodeships in Poland

Source: own study.

The results reveal regional differences in the assessment of the effectiveness of IT and AI tools in supporting organizational development, with median values ranging from 2 to 4. The highest evaluations were recorded in the Lubuskie Voivosdhip, Zachodniopomorskie Voivosdhip, Świętokrzyskie Voivosdhip, Pomorskie Voivosdhip, and Warmińsko-Mazurskie Voivodeship, suggesting that companies in these regions consider access to modern infrastructure and tools supporting innovation processes as a key factor in fostering organizational innovativeness. In contrast, regions with a wider spread of responses—such as Kujawsko-Pomorskie Voivosdhip, Łódzkie Voivosdhip, and Małopolskie Voivosdhip —exhibit greater variation in the perceived effectiveness of these tools. This disparity may stem from uneven access to advanced technological solutions across regions.

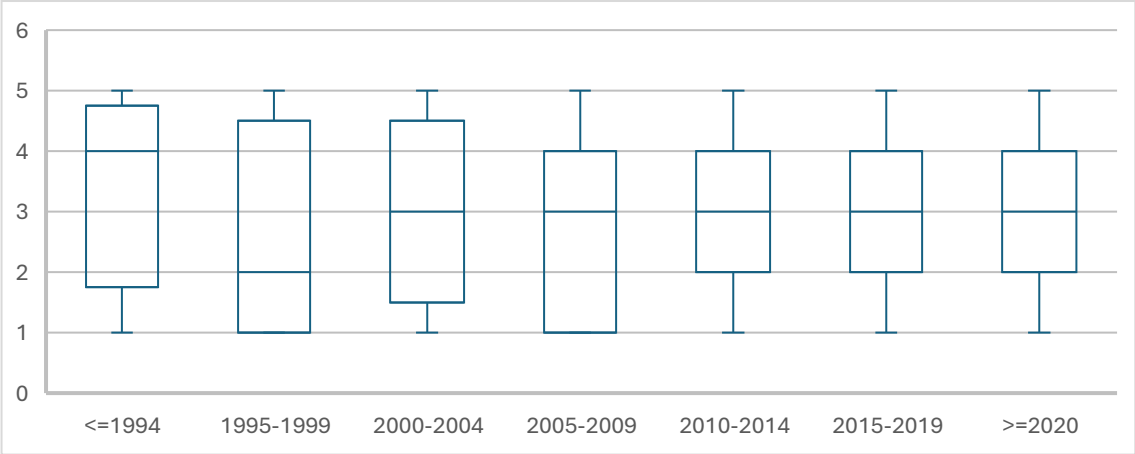


Figure 14. Distribution of assessments of access to modern infrastructure and tools supporting innovation processes in the area of IT and AI forms and tools supporting the development of the surveyed organizations, broken down by the year of company establishment
Source: own study.

Access to modern infrastructure and tools supporting innovation processes, assessed in relation to the number of years a company has been operating, is generally rated moderately positively. Older companies (established in or before 1994) exhibit a wide range of responses; however, a median score of 4 suggests that the majority of firms in this group recognize the value of having access to modern infrastructure and innovation-supporting tools. The greatest variability in responses – with a predominance of moderately negative evaluations (median score of 2) – was observed among companies established between 1995 and 1999. This group includes firms with both moderately positive and negative experiences regarding the effectiveness of IT and AI tools in supporting organizational development. Companies established after 2000 tend to evaluate access to such infrastructure and tools more neutrally, with those founded after 2014 showing a more consistent perspective on the matter.

The final question selected for this analysis was Question 10a, which concerned the changes occurring in systems supporting intelligent enterprise management in the context of the implementation of new technologies and artificial intelligence (AI). Respondents evaluated this aspect using a ten-point scale, where 1 indicated the least significant change and 10 represented the most significant change. A total of 269 out of the 365 surveyed companies responded to this question. The collected responses were analyzed in terms of the companies' geographical location, categorized by voivodeship (Figure 15), as well as by their market longevity, classified according to the year the company commenced its business operations (Figure 16).

The conducted analysis indicates that enterprises in Poland perceive technological change and the implementation of artificial intelligence (AI) as a moderately important factor for intelligent management systems, with the median of all responses equaling 5. However, the perceived significance of these changes varies across voivodeships. Except for firms located in the Lubelskie Voivodship, Pomorskie Voivodship, Kujawsko-Pomorskie Voivodship, Wielkopolskie Voivodship, and Warmińsko-Mazurskie Voivodship, companies demonstrate greater variability in their responses, which may be attributed to local economic conditions and differential access to emerging technologies. Enterprises from three voivodeships evaluated the integration of new technologies and AI into intelligent management systems as particularly important. These include: Pomorskie Voivodship, with a median score of 8 and response variability ranging from 3.5 to 8.5; Lubelskie Voivodship, with a median of 7 and a range from 5 to 8; and Warmińsko-Mazurskie Voivodship, with a median of 6 and variability from 3 to 9.

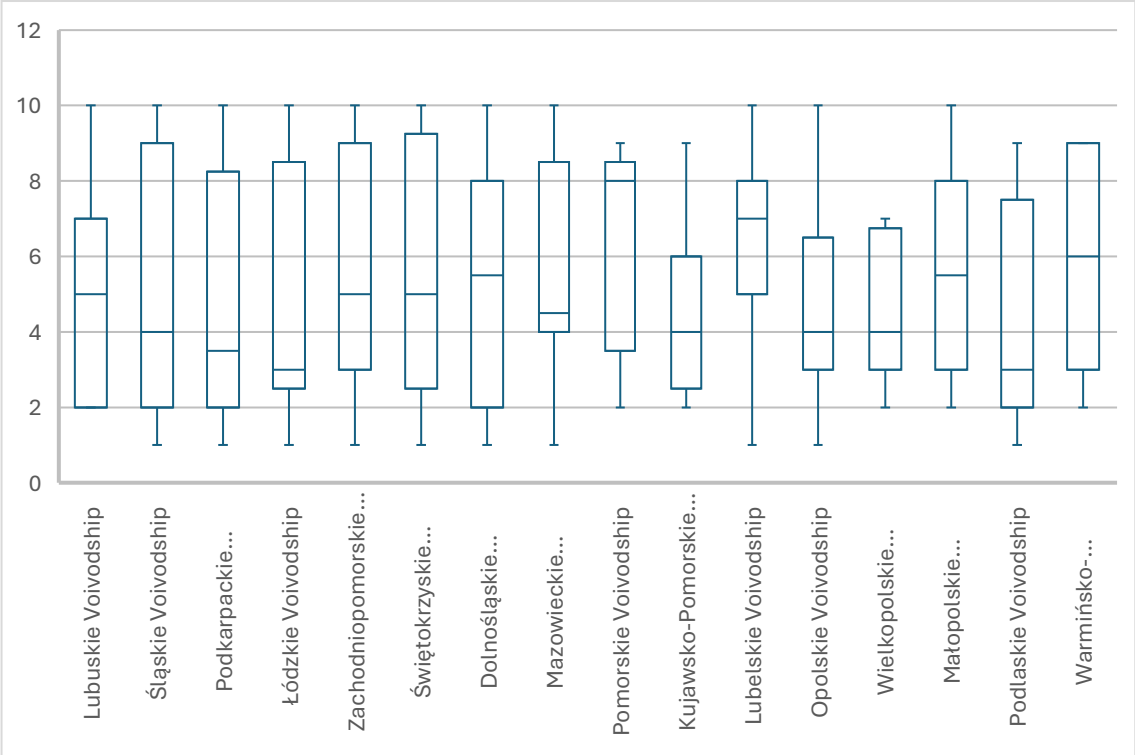


Figure 15. The distribution of ratings of changes in systems supporting intelligent enterprise management in the context of the introduction of new technologies and AI, by voivodeships in Poland
Source: own study.

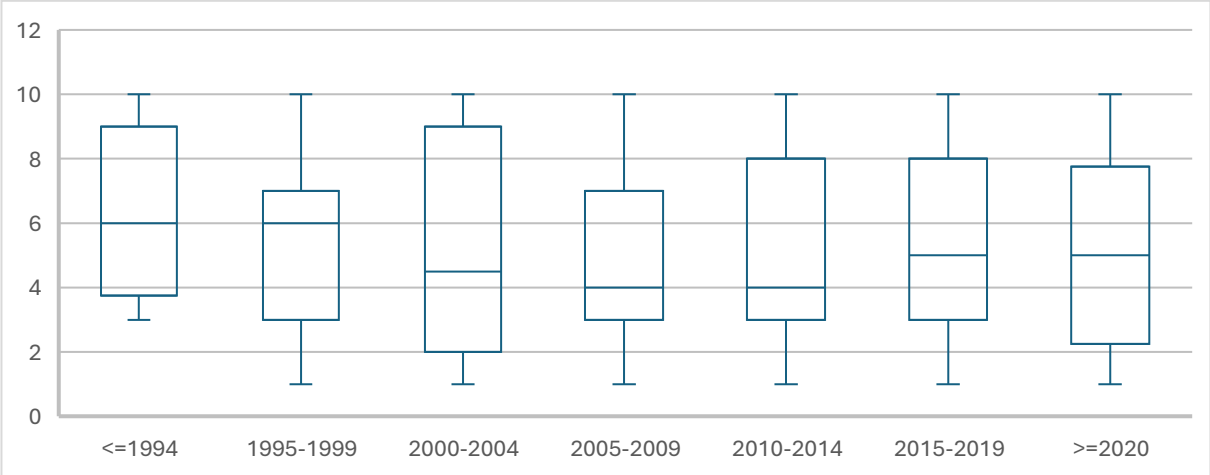


Figure 16. The Distribution of ratings of changes in systems supporting intelligent enterprise management in the context of the introduction of new technologies and AI, broken down by the year of company establishment
Source: own study.

The analysis of the perceived significance of changes in systems supporting intelligent enterprise management in the context of implementing new technologies and artificial intelligence (AI), based on the year of company establishment, reveals that the oldest firms (established in or before 1994) consider these changes to be important. This group reported a median score of 6, with interquartile values ranging from approximately 4 to 9, and an overall response range from 3 to 10. In contrast, all other groups exhibit the full spectrum of responses; however, they differ in terms of response variability (interquartile ranges) and median values.

Companies established between 1995 and 1999, despite showing the full response range and interquartile variability from 3 to 7, also perceive these changes as important, with a median score of 6. Younger firms, founded between 2000 and 2014, assessed the significance of changes slightly below the overall average, reporting a median of 5 and a mean of 5.2. The most recently established companies, founded after 2015, rated the importance of changes in systems supporting intelligent management in the context of new technologies and AI as moderately significant.

5. DISCUSSION

The findings of this study provide valuable insights into the evolving dynamics of human capital management in the context of digital transformation within Polish manufacturing enterprises. The research confirms that, despite the rapid advancement and adoption of IT and AI technologies, human capital remains a critical pillar of intelligent enterprise management. Organizations recognize the need for strategic alignment between employee competencies and technological capabilities to sustain innovation, agility, and competitive advantage in the Industry 4.0 era.

A key observation arising from the data is the growing optimism regarding the role of emerging technologies in shaping internal and external operational conditions over the next five years. The surveyed companies anticipate a significant increase in the influence of AI-driven tools – particularly in areas such as decision-support systems, talent management, and predictive analytics. This forward-looking perspective suggests that enterprises are preparing to transition from traditional human resource management practices to more data-driven, AI-supported models. However, the variation in responses across voivodeships and among companies with different market tenures indicates uneven readiness and differing degrees of digital maturity.

The study also highlights that while access to IT and AI infrastructure is viewed as increasingly vital for innovation, the current effectiveness of AI-based employee development initiatives is perceived as only moderate. This suggests a potential misalignment between the design and implementation of such programs and the actual developmental needs of the human resources. Companies may face challenges in translating technological potential into tangible improvements in human capital capabilities. Therefore, a more tailored and needs-based approach to training – supported by continuous assessment and feedback mechanisms – is necessary to maximize the benefits of AI-enhanced learning systems.

Regional disparities further underscore the importance of context-specific strategies. Firms in more technologically advanced regions tend to report higher satisfaction with their internal conditions and infrastructure, while those in less developed areas exhibit greater uncertainty and variability in their assessments. This disparity calls for targeted support from policymakers, especially in enhancing digital competencies and infrastructure among SMEs operating in underrepresented regions.

Another notable finding is the divergent perspectives among firms depending on their year of establishment. While younger firms often show greater digital preparedness, they also exhibit more fragmented assessments, possibly due to a lack of standardized strategic frameworks for technological integration. In contrast, older firms – despite sometimes lagging in digital adoption – appear to possess more stable and structured approaches to change management, which may facilitate more coherent integration of new technologies into organizational systems.

In light of these insights, it becomes evident that achieving synergy between human capital and advanced technologies requires more than just infrastructure investment. It demands a cultural shift within organizations – one that emphasizes lifelong learning, fosters digital fluency, and promotes collaborative innovation. Organizations must not only equip their employees with technical skills but also develop soft skills such as adaptability, creativity, and problem-solving, which are essential in navigating the complexities of intelligent enterprise systems.

Ultimately, the discussion reveals that the successful transformation of manufacturing enterprises in Poland hinges on the ability to harmonize human and technological assets. This synergy is pivotal to sustaining long-term competitiveness in a digitalized economy. Future initiatives – both at the organizational and policy levels – should therefore prioritize integrated strategies that reinforce this alignment, ensuring that the evolution of technological infrastructure goes hand in hand with the empowerment of human potential.

6. CONCLUSION

The findings of this study underscore the pivotal role of human capital in managing intelligent enterprises amid ongoing digital transformation. Despite the growing prominence of modern technologies – particularly artificial intelligence (AI) and advanced decision-support systems – the expertise, experience, and skills of employees remain fundamental to fostering innovation and ensuring organizational adaptability in dynamic economic conditions.

While these technologies enhance operational efficiency and streamline decision-making processes, they cannot replace human input in key strategic areas such as planning, organizational culture development, and innovation. The study reveals that Polish manufacturing firms increasingly recognize the importance of integrating digital tools with human capital management, especially in anticipation of accelerating technological change. Notably, companies expect AI and IT solutions to play a more prominent role in talent management, predictive analytics, and employee skill development over the next five years.

At present, however, the effectiveness of AI-assisted training and other employee development initiatives is viewed as moderate. This suggests a mismatch between training programs and the real needs of organizations and their workforce, pointing to the necessity for more personalized and context-sensitive approaches.

The results also highlight substantial variation across regions and among companies at different stages of market maturity. Older firms and those based in more technologically advanced regions tend to report more favorable experiences and greater openness to innovation. In contrast, younger companies – despite often being more digitally prepared – demonstrate more varied assessments, likely due to limited experience or the absence of established change management frameworks. This heterogeneity emphasizes the need for differentiated strategies in supporting digital transformation at both organizational and regional levels.

Future research should further examine how AI-driven transformation influences innovation dynamics within enterprises. A more granular understanding of how digital tools either support or impede organizational creativity and knowledge-sharing would be especially valuable. Additionally, analyzing sectoral and regional differences in the adoption of AI-based human capital management systems could offer deeper insight into factors shaping technological readiness and long-term competitiveness.

A particularly promising avenue for further study involves the role of human capital strategies in fostering intrapreneurship. Since intrapreneurial initiatives are crucial to sustained innovation and competitive advantage, future research should investigate how companies can cultivate entrepreneurial mindsets and use AI-enabled tools to support internal ventures. Ultimately, the core challenge lies in achieving synergy between technological advancements and human capabilities—one that not only drives efficiency but also nurtures a culture of continuous learning, adaptability, and strategic renewal.

Although this study is based on a large and representative sample of Polish manufacturing firms, its scope is limited to a single country and sector. As such, the generalizability of the findings to other contexts may be constrained by cultural, institutional, or industry-specific factors. Cross-sectoral and international comparative studies would therefore be valuable in testing the broader applicability of these conclusions. Additionally, as the study relies on self-reported survey data, the potential for response bias should be acknowledged, given that managerial perceptions may not always reflect actual practices or outcomes. Finally, due to the rapidly evolving nature of digital technologies, longitudinal or comparative research approaches may be needed to assess the durability and relevance of the observed trends over time.

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THE IMPACT OF INTELLIGENT MANAGEMENT METHODS ON THE CREATIVITY LEVEL OF EMPLOYEES IN THE CREATIVE SECTOR

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ABSTRACT

Purpose: *This paper examines the relationship between intelligent management methods and the level of creativity among employees in the creative sector. It aims to assess how modern tools such as Design Thinking, Agile, and AI technologies support creative performance.*

Need for the study: *In the era of digital transformation and the knowledge economy, it is essential to understand how intelligent management tools impact creative behavior and innovation potential in the workforce. The creative sector plays a vital role in regional development, yet its integration with AI-based management strategies remains understudied*.

Methodology: *The study is based on the KANH-III Creative Behavior Questionnaire. It surveyed 125 employees from 89 creative sector companies in the West Pomeranian region using the CAWI method.*

Findings: *Results indicate a high level of nonconformist and heuristic behavior, suggesting strong creative potential among respondents. Intelligent management tools are found to contribute positively to creative attitudes.*

Practical Implications*: The findings offer insights into developing intelligent management strategies that support innovation and enhance human capital potential in the creative sector.*

Keywords: creativity, intelligent management, AI tools, creative sector, innovation

JEL: L26, O31, O32, J24

1. INTRODUCTION

Today's companies, striving for dynamic growth and increased competitiveness, attribute key importance to creativity as a driver of innovation. Creativity is increasingly expected not only in the workplace but also in broader societal and economic contexts. It enables individuals to assimilate new information more effectively, solve problems efficiently, and develop original, practical solutions. In today's knowledge-based economy, the ability to generate and implement innovative ideas is becoming a critical element of competitive advantage at both the individual and organizational levels (Czerwinska-Lubszczyk et al., 2022).

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Creativity plays a pivotal role in the creative sector, which encompasses industries focused on innovation, design, and artistic expression. Employees in this sector are expected to demonstrate high levels of creativity, as it is a fundamental requirement for successfully navigating a rapidly changing professional environment. The ability to think divergently, generate novel concepts, and adapt to evolving market conditions is crucial for the sustainable development of creative enterprises. Given the growing emphasis on creativity as a competitive asset, it is essential to systematically assess employees' creative potential in this sector. Such research enables a better understanding of creativity dynamics and provides valuable insights into whether professionals in the creative industry exhibit a high degree of creative thinking (Roszkowska, 2021).

However, in modern management, creativity is no longer perceived solely as an innate individual trait – it can be strategically cultivated through intelligent management methods. Approaches such as Design Thinking, Agile Management, and AI-driven decision-making provide structured frameworks that enhance employees' ability to think creatively and solve complex problems. Intelligent management tools, including knowledge management systems and AI-powered collaboration platforms, are increasingly utilized to facilitate and sustain creative processes within organizations (Jia, et al., 2023)

To maintain a competitive edge, companies in the creative sector are increasingly adopting intelligent management solutions such as AI-assisted brainstorming tools, digital prototyping, and real-time market analysis. These technologies allow organizations to enhance creative potential, optimize project workflows, and better respond to evolving industry demands. Therefore, researching employees' creativity levels in this sector is not only relevant but also essential in understanding how modern intelligent management methods shape creative performance (Patel, et al., 2024).

This article aims to assess the creativity level of creative sector employees in the West Pomeranian region. The study will be conducted using the KANH-III questionnaire, developed by S. Popek and R. Bernacka, which allows for diagnosing employees' creativity levels. Additionally, this research examines the role of intelligent management approaches in shaping creative potential. The analysis results contribute to a deeper understanding of creativity in the creative sector and provide a foundation for developing strategies that support creative competence development, particularly through the integration of modern management practices and AI-driven solutions.

2. LITERATURE REVIEW

In developing creative potential, it is important to distinguish between creativity and ingenuity, although the terms are often used interchangeably in business practice. Ingenuity refers to the thought process leading to ideas, while creativity encompasses the broader conceptual process through which new ideas are generated and transformed into innovations through structured problem-solving approaches (Nikitenko, 2022). Creativity is also associated with terms such as creative potential, creative work, or creative process. Every person has creative potential within themselves, which they can develop and apply using both cognitive and technological tools, transforming it into innovative solutions (Florida, 2004). Modern businesses are increasingly leveraging AI-powered technologies to enhance and accelerate creative problem-solving (Jia, Luo, Fang, & Liao, 2023).

E.P. Torrance provides an elaborate definition of creativity, indicating that it manifests itself in the search for new solutions in a problem situation—whereby a problem can be understood as both a task and a challenge (Torrance, 1995). It is a process involving the formulation of hypotheses, their testing, evaluation, and possible innovation. With the advent of intelligent management systems, AI-based decision-making, and digital collaboration platforms, the problem-solving process has become increasingly structured and data-driven, allowing organizations to facilitate and sustain creative processes more effectively Creativity can vary depending on an individual's predisposition, experience, and the environment, which either encourages or limits creative thinking. Modern organizations are increasingly utilizing AI-assisted creativity tools, such as AI-driven brainstorming applications and intelligent knowledge management platforms, to enhance these processes (Patel, Kumar, Najana, & Balakrishnan, 2024).

For an individual to be considered creative, they must meet specific criteria. AI-powered systems, such as generative artificial intelligence (GAI), are now capable of identifying creative behaviors by analyzing patterns in problem-solving and innovation output (Huang, Jin, & Li, 2024). Identifying new

problems and effectively using previously acquired knowledge to solve them is of key importance. Also important is the realization that the learning process is dynamic and requires constant experimentation, including trial and error, to achieve the desired results. AI-based analytical tools can assist in tracking these patterns, offering personalized learning pathways and feedback loops that enhance creative skill development. Additionally, creativity is associated with the ability to concentrate and consistently pursue set goals, which determines the effectiveness of the creative activities undertaken (Taylor, 1988).

Analyzing the issue of creativity based on modern and classical theories, it is possible to distinguish different levels of creative development (Nęcka, 2001):

- Fluent creativity is the most basic level, referring to the innate ability to generate ideas and adapt to environmental changes. AI-assisted learning models are increasingly being used to recognize and enhance this form of creativity.
- Crystallized creativity involves idea generation, problem identification, and strategic solution development. This level requires persistence and advanced analytical skills, which can be augmented through AI-driven decision support systems.
- Mature creativity develops through years of experience and specialized knowledge acquisition. AI-enhanced knowledge management platforms and expert systems assist professionals in navigating complex fields and making informed creative decisions.
- Outstanding creativity leads to breakthrough innovations and paradigm shifts in science, art, or industry (Janasz, 2013).

This classification allows for a more detailed understanding of the phenomenon and integrates well with AI-driven creativity assessments (Moruzzi, 2025). Some AI systems are now designed to evaluate creativity levels by analyzing cognitive styles, problem-solving efficiency, and adaptability to new challenges (Conway, 2024).

As a multidimensional phenomenon, creativity plays a key role in innovation-driven organizations at both the individual and team levels. Its various levels – from basic creativity, present in all individuals, to outstanding creativity, responsible for major breakthroughs – illustrate that creative potential is not uniform and can be shaped by different cognitive and technological influences. Understanding these levels enables a more precise assessment of creative abilities and helps organizations determine how to develop and utilize creativity effectively using intelligent management solutions.

Due to the growing importance of creativity in AI-augmented workplaces, diagnosing employees' creative potential is becoming increasingly crucial (Moruzzi, 2025). AI-powered analytics, such as creativity assessment platforms and digital collaboration hubs, provide new ways to measure and foster innovative thinking. Understanding what fosters or limits creativity in AI-driven workplaces allows organizations to optimize knowledge-sharing, interdisciplinary collaboration, and innovation processes (Conway, 2024).

An empirical study was conducted in creative sector enterprises located in the West Pomeranian region, which actively use modern management tools and AI-based technologies. The primary aim of the study was to diagnose the level of employee creativity and to analyze how technological and organizational solutions support the development of creative potential. The results will provide valuable insights into the actual impact of intelligent management methods – such as design thinking, generative AI, or agile models – on employee creativity. This diagnosis will also make it possible to better align tools and organizational strategies with the needs of creative teams, and it will help answer the question of whether the use of modern tools has a positive effect on the creativity levels of employees. As such, the findings will serve as a foundation for designing effective strategies to foster innovation in technology-driven work environments.

The creative sector in Poland is a relatively new but dynamically growing area of the economy. The concept began to gain significance in the 1990s, when the economic potential of culture and creativity in business contexts started to be recognized. Also referred to as the creative industry, this sector integrates artistic activity, technological advancement, and entrepreneurship. Its key foundations include creativity, employee talent, and innovation. Enterprises in this sector possess significant economic potential – they generate profits, create jobs, and contribute to the development of intellectual property and intangible assets (Bąkowska et al., 2020).

In Poland, the creative sector plays an increasingly important role in socio-economic development. Its importance is highlighted particularly in areas such as job creation, stimulation of economic growth,

and fostering innovation. Moreover, creative industries contribute to urban revitalization and enhance the tourist and cultural appeal of cities (Sagan, 2017).

Despite its relatively short history, the creative sector in Poland continues to grow rapidly, and its potential is more widely recognized at both local and national levels. The rising significance of the sector reflects global trends that promote a knowledge-based, innovation-driven economy, where creativity is viewed as a key determinant of competitiveness (Janus-Khouri et al., 2024).

In the West Pomeranian region, the creative sector plays a noteworthy role in the regional economic landscape, bringing together artistic, design, and technological activities. The region is home to the Zachodniopomorski Klaster Przemysłów Kreatywnych (Eregion), which fosters collaboration between businesses and institutions, promotes innovation, and encourages the exchange of knowledge and experience. In Szczecin, the Center for Creative Industries at the Academy of Art implements research and development projects and facilitates knowledge transfer between science and business. Additionally, regional initiatives such as the "Your Business Under the Flag of Success" competition promote entrepreneurial creativity and innovation. The West Pomeranian Voivodeship identifies creative industries as one of the priority sectors in its development strategy, acknowledging their potential to stimulate innovation and economic growth (Kowalewski, 2019).

Based on the above, the author assumed that a high level of creativity should characterize employees in the creative sector, as it is a key factor determining their effectiveness and capacity to generate innovative solutions. Accordingly, the study focused on analyzing this sector, with particular attention to assessing the level of creativity among its employees and determining the extent of individual differences. This approach enables a more accurate understanding of the creative potential present in the sector and allows for the evaluation of how creativity is expressed in professional practice.

As many creative sector organizations increasingly adopt AI-driven technologies – such as generative tools, intelligent design platforms, and data-informed creative planning – the study also provides an opportunity to reflect on whether and how such technologies influence the manifestation and development of individual creative abilities in the workplace.

3. METHODOLOGY

3.1 Participants

An invitation to participate in the study was extended to 307 enterprises purposively selected based on the previously defined criteria. A total of 89 entities confirmed their participation, representing nearly 29% of the target population. In total, 125 individuals employed in these 89 creative sector companies operating in the West Pomeranian region completed the survey.

The research sample was selected using a purposive sampling method, based on the following inclusion criteria:

- Only entities meeting the definition of the creative sector, according to the Polish Classification of Economic Activities (PKD-2007), were included in the study (see Table 1),
- The analysis covered companies registered in the West Pomeranian Voivodeship,
- The survey included companies with at least several employees, allowing for the identification of human resource management processes within the organization.

The structure of the surveyed sample, according to the PKD 2007 classification, was as follows:

- Section G - 7 entities (8%),
- Section J - 39 entities (44%),
- Section M - 34 entities (38%),
- Section R - 9 entities (10%).

The sample included employees, managerial staff, and participants of both sexes.

Table 1. Sections of PKD 2007 constituting the creative sector

Section	Department/class/subclass	Name
Section G	47.78.Z	Retail sale of other new products in specialized stores
Section J	58.11.Z	Book publishing
	58.13.Z	Newspaper publishing
	58.14.Z	Publishing of magazines and other periodicals
	58.19.Z	Other publishing activities
	58.21.Z	Computer game publishing business, programming
	59.11.Z	Activities related to the production of films, videos and television programs
	59.13.Z	Activities related to the distribution of films, videos and television programs
	59.14.Z	Film projection activities
	59.20.Z	Sound and music recording activities
	60.10.Z	Broadcasting of radio programs
	60.20.Z	Broadcasting of free-to-air and subscription television programs
Section M	71.11.Z	Architectural activities
	73.11.Z	Activities of advertising agencies
	73.12.A	Intermediation in the sale of advertising time and space on radio
	73.12.B	Intermediation in the sale of advertising space in print media
	73.12.C	Intermediation in the sale of advertising space in electronic media (Internet)
	73.12.D	Intermediation in the sale of advertising space in other media
	74.10.Z	Specialized design activities
	74.20.Z	Photographic activities
Section R	90.01.Z	Artistic performance exhibition activities
	90.02.Z	Activities supporting the exhibition of artistic performances
	90.03.Z	Artistic and literary creative activities
	90.04.Z	Activities of cultural facilities
	91.01.A	Libraries' activities
	91.01.B	Activities of archives
	91.02.Z	Museum activities

Source: own elaboration based on (Kasprzak, 2013).

3.2 Research Protocol and Stimuli

The study was conducted using a structured survey questionnaire. To ensure greater flexibility and broader reach, an indirect data collection method was applied through a computer-assisted web

interview (CAWI). The questionnaire was made available online and distributed to participants via email.

The current version of the questionnaire consists of 26 items and incorporates two continuum-based scales. The first dimension, Conformism-Nonconformism (K–A), evaluates the extent to which individuals tend to conform to or challenge established social norms. The second scale, Algorithmic Behavior–Heuristic Behavior (N–H), includes 13 items reflecting preferred cognitive styles, ranging from schematic, routine thinking to openness to novel, non-standard solutions.

Norms for this instrument were developed using a single-scale model for individuals aged 15 to 60. Separate scoring standards for men and women were established for the K–A scale, while the A–H scale was standardized jointly for both genders.

Response scores were assigned according to the following key (Bernacka et al., 2016):

- A (yes) – 4 points,
- B (somewhat yes) – 3 points,
- C (I have no opinion) – 2 points,
- D (rather not) – 1 point,
- E (no) – 0 points.

The exceptions are questions 15 and 24, for which the answer scores are reversed, except for answer C, whose value remains unchanged.

3.3 Research Apparatus

The research was based on the Creative Behavior Questionnaire – KANH-III. In 2016, R. E. Bernacka presented a revised and updated version of the diagnostic tool originally developed by S. Popek in 1989, giving it a new designation – KANH-III (Bernacka et al., 2016).

The KANH-III questionnaire was used in this study to assess the creativity level of employees working in the creative sector in the West Pomeranian region. According to the developers of the latest version of the tool, the reliability of the scales increases proportionally with the respondents' creativity levels. Therefore, organizations operating in the creative sector constitute a relevant target group for applying the KANH-III questionnaire, enabling its effective use in diagnosing creative potential in workplace environments.

All respondents completed the Creative Behavior Questionnaire – KANH III, assessing each of the 26 items using the five-point scale described earlier. The full content of the questionnaire is provided in Appendix 1 of this publication.

3.4. Analysis of Measurement Data

Interpretation of the KANH-III results is based on the assumption that lower total scores reflect a greater tendency toward conformism and a dominance of algorithmic behavior, characterized by schematic thinking and reliance on established action patterns. In contrast, higher scores indicate a stronger inclination toward nonconformism and a preference for heuristic behavior, associated with openness to novelty and a creative approach to problem-solving.

The scoring system enables a quantitative assessment of creative potential, facilitating the comparison of individual and group results across organizations. The reliability of the KANH-III scales, as noted by the tool's authors, increases with the respondents' creativity level, which reinforces the tool's validity in environments with high creative demands – such as the creative sector.

4. RESULTS

The main objective of this study was to assess the level of creativity among employees working in the creative sector in the West Pomeranian region. The research tool, the Creative Behavior Questionnaire – KANH-III, was applied using a five-point Likert scale with a neutral midpoint, allowing respondents to indicate the degree of agreement with each statement. The results were interpreted using sten norms, which enabled standardized evaluation and comparison. The distribution of sten scores is presented below in Tables 2–5.

Table 2. Sten norms for K-A scale - Conformism-nonconformism

Conformism-nonconformism Workers in the creative sector of the West Pomeranian province	
Points	**Sten**
≤9	1
10-14	2
15-19	3
19-23	4
24-28	5
29-33	6
34-38	7
39-43	8
44-48	9
≥49	10

Source: own elaboration.

Table 3. Sten norms for the N-H scale - Algorithmic-heuristic behaviour

Algorithmic-heuristic behavior Workers in the creative sector of the West Pomeranian province	
Points	**Sten**
≤22	1
23-25	2
26-28	3
29-31	4
32-34	5
35-37	6
38-40	7
41-43	8
44-46	9
≥47	10

Source: own elaboration.

Table 4. Sten norms for the scale (K-A+N-H) – Creative attitude

Creative Attitude Employees in the creative sector of the West Pomeranian region	
Points	**Sten**
≤33	1
34-41	2
42-49	3
50-57	4
58-65	5
66-73	6
74-81	7
82-89	8
90-97	9
≥98	10

Source: own elaboration.

Table 5. Determining the severity of employee behavior based on the sten score

Sten	Level
1-4	low (conformism, algorithmic behaviour, reproductive attitude)
5-6	average (neutral behaviour)
7-10	high (nonconformism, heuristic behaviour, creative attitude)

Source: own elaboration.

The average score for the Conformism–Nonconformism scale (K–A) among creative sector employees was 38.66, with a standard deviation of 6.35. Scores ranged from 9.00 to 51.00. According to the sten interpretation, this average falls within the 7th sten and above, indicating a dominant nonconformist attitude. Figure 1 illustrates that only four respondents exhibited a conformist profile, 24 scored within the average range, and 94 demonstrated a nonconformist orientation.

A factor analysis of this scale revealed four underlying dimensions that explain 49% of the variance. These include intrinsic motivation, critical independence, openness, and courage. Each factor comprises a set of paired statements reflecting either conformist or nonconformist tendencies. This confirms the prevalence of nonconformist attitudes in the studied group.

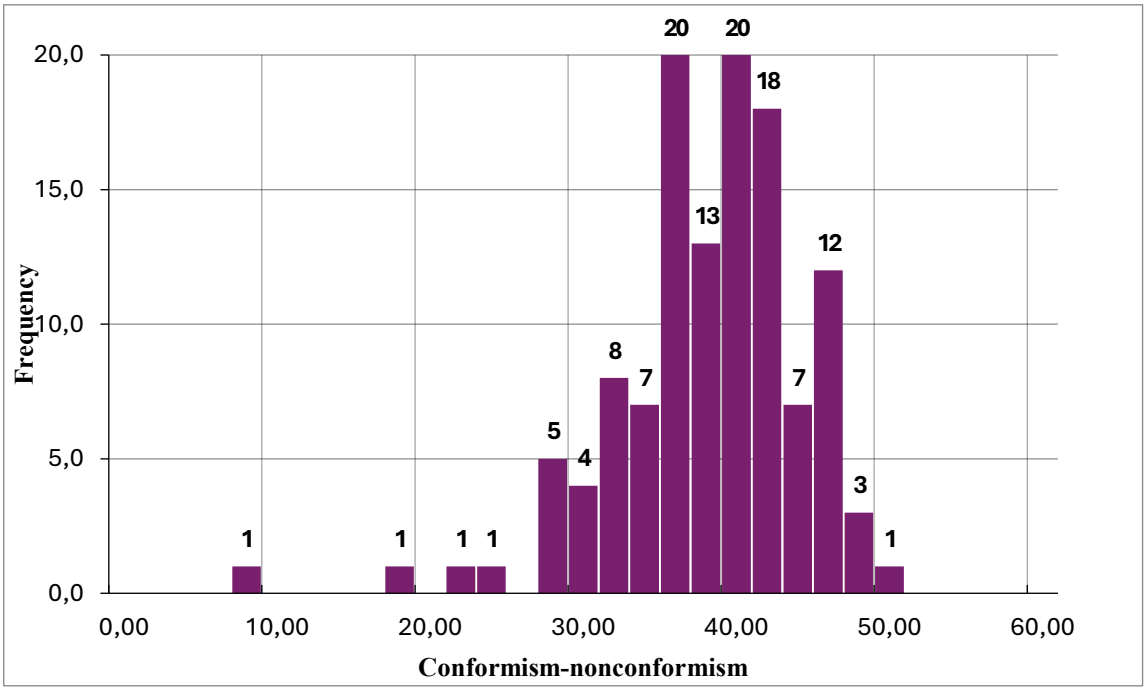


Figure 1. Results of the Conformism-Nonconformism scale for the surveyed sample of the creative sector of the West Pomeranian Voivodeship

Source: own elaboration.

Table 6. Factors I-IV of the scale used to assess the measurement of conformism-nonconformism behavior of the studied sample of the creative sector of the West Pomeranian province

	Factor I – intrinsic motivation	
Conformism	The number of the statement in the form	Nonconformism
Poor resilience and stamina	20	Resilience and perseverance
Submission	18	Consistency
Dependency	12	Independence
Independence	7	Self-organization
Lack of criticism	25	Self-criticism
	Factor II – critical independence	
Conformism	The number of the statement in the form	Nonconformism
Subordination	4	Domination
Intolerance	5	Tolerance
Low self-esteem	26	High self-esteem
Passivity	22	Activity
Stereotypical	9	Originality
	Factor III – openness	
Conformism	The number of the statement in the form	Nonconformism
Defensiveness	16	Openness
Intellectual rigidity	2	Adaptive flexibility
	Factor IV – courage	
Conformism	The number of the statement in the form	Nonconformism
Timidity	24	Courage

Source: own elaboration based on: (Bernacka et al., 2016).

Regarding the Algorithmic–Heuristic Behavior scale (N–H), the average score was 37.56, with a standard deviation of 6.92. The minimum and maximum scores ranged from 22.00 to 52.00. Based on the sten norms, these results suggest that heuristic thinking is the dominant cognitive style in the sample. Figure 2 shows that 19 respondents demonstrated algorithmic behavior, 36 fell within the average range, and 62 displayed heuristic behavior, typically associated with creativity and open-ended thinking.

Factor analysis of this scale identified four factors explaining 48% of the variance: reflexive openness, innovative talents, creative talents, and cognitive self-efficacy. These dimensions reveal the complexity of cognitive styles among respondents and highlight the presence of traits beneficial for creative work.

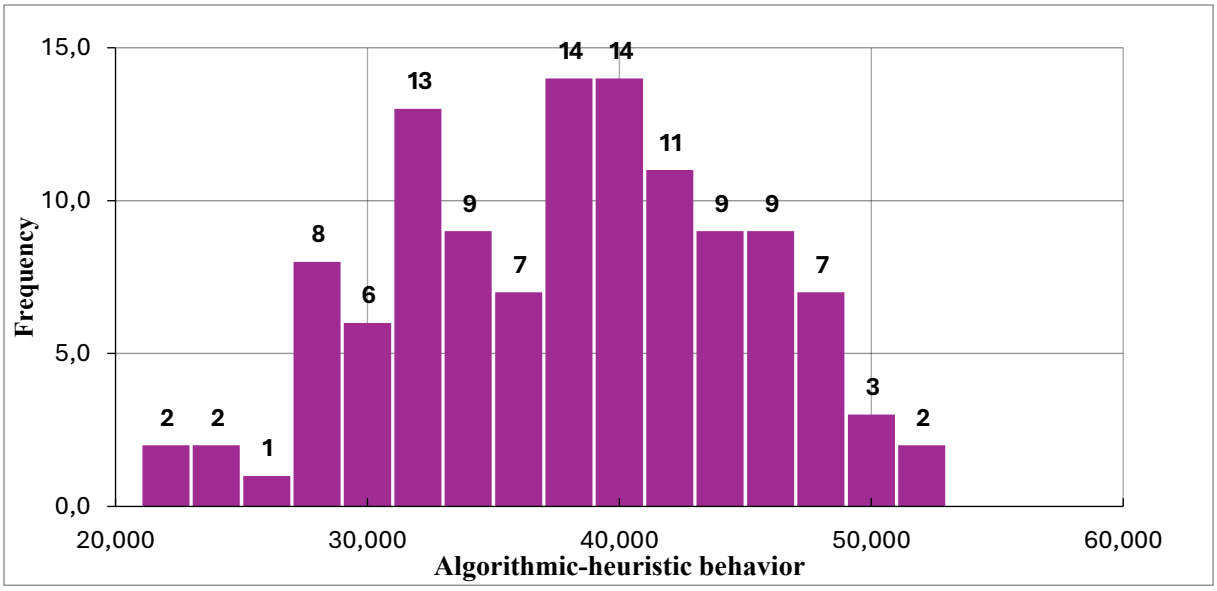


Figure 2. Results of the Algorithmic-Heuristic Behavior scale for a sample of the creative sector in the West Pomeranian region
Source: own elaboration.

Table 7. Scale factors for assessing the algorithmic-heuristic behavior of the studied sample of the creative sector of the West Pomeranian region

Factor I – reflexive openness		
Heuristic behavior	The number of the statement in the form	Algorithmic behavior
Cognitive activity	21	Cognitive passivity
Learning through understanding	8	Learning through understanding
Divergent thinking	14	Convergent thinking
High reflectivity	3	Little reflexivity
Independent observation	13	Perceptive leadership
Intellectual independence	6	„Implementing yourself.”
Factor II – innovative talents		
Heuristic behavior	The number of the statement in the form	Algorithmic behavior
Proficiency and construction skills	17	Low efficiency and construction skills
Technical ingenuity	23	Lack of technical ingenuity
Factor III – creative talents		
Heuristic behavior	The number of the statement in the form	Algorithmic behavior
Artistic talents	10	Lack of artistic talent
Creative imagination	11	Recreative imagination
Verbal Creativity	1	Verbal reproduction
Factor IV – cognitive self-efficacy		
Heuristic behavior	The number of the statement in the form	Algorithmic behavior
Intellectual flexibility	19	Intellectual rigidity
Self-directed learning	15	Targeted learning

Source: own elaboration based on (Bernacka et al., 2016).

The combined scale (K–A + N–H), representing the overall Creative Attitude, yielded an average score of 76.00 with a standard deviation of 12.24. The range of results varied between 33.00 and 101.00.

This places the average respondent within the high creative range (above 7th sten), confirming a strong creative attitude among the employees surveyed. Figure 3 indicates that 4 respondents were classified as having a reproductive attitude, 37 were average, and 73 exhibited a creative attitude.

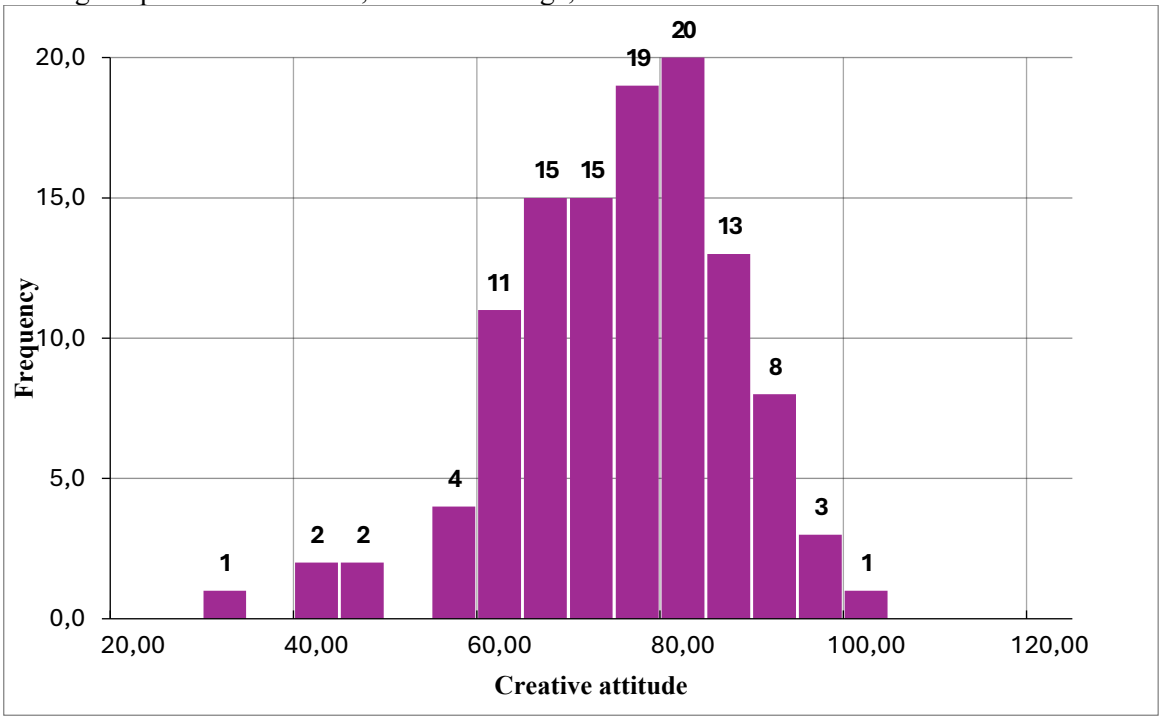


Figure 3. Results of the Creative Attitude scale for the surveyed sample of the creative sector of the West Pomeranian region
Source: own elaboration.

The findings confirmed that the majority of respondents demonstrated a nonconformist attitude, heuristic cognitive style, and a strong creative profile – indicating a high level of creative potential across the sample.

5. DISCUSSION

The results of the study confirmed a high level of creativity among employees working in the creative sector in the West Pomeranian region. Most respondents exhibited nonconformist attitudes, heuristic cognitive styles, and an overall creative approach – traits that are essential for innovation in knowledge-based economies. The dominance of these characteristics supports the assumption made in the introduction: that creativity is a key factor in shaping the competitive advantage of organizations in creative industries.

In particular, the findings emphasize that individuals employed in this sector not only tend to think independently and seek unconventional solutions but also function well in environments requiring adaptability and innovation. These results are consistent with prior research which highlights the relationship between creative potential and nonconformist, heuristic tendencies.

Moreover, the study confirms the relevance of using intelligent management approaches – such as Design Thinking, Agile frameworks, and AI-supported tools – in fostering and sustaining creativity at the organizational level. The alignment between high levels of creativity and work environments that implement intelligent management methods suggests a positive correlation. As employees demonstrate creative behaviors, organizations that reinforce such potential with modern managerial support systems are more likely to thrive in dynamic markets.

Although this study did not test the direct impact of intelligent management tools, the surveyed enterprises are known to implement modern practices such as digital prototyping, real-time collaboration platforms, and AI-enhanced problem-solving environments. Therefore, the high creative scores observed may be at least partially attributed to the stimulating conditions shaped by these tools and approaches.

These results also underscore the need for continued research into the interaction between creative potential and specific technological or managerial interventions. Future studies could empirically test whether and how different AI-based systems or innovation management practices affect measurable creativity outcomes.

Additionally, artificial intelligence offers promising solutions for creativity assessment. Methods for AI-supported creativity diagnostics are rapidly evolving and can complement traditional psychometric tools. Examples include the use of natural language processing (NLP) to evaluate the originality of employee-generated content, AI-supported psychometric testing that adapts in real time, and generative systems capable of evaluating the innovativeness and feasibility of ideas. Tools such as idea management platforms or intelligent collaborative systems (e.g., Slack with integrated AI modules) can also be used to track team-level creative dynamics. These approaches not only increase the objectivity of creativity assessments but also enable scalable, data-informed decisions about talent development and innovation strategies. Future implementations of AI-based creativity assessment tools could offer even more objective and scalable evaluation frameworks.

In practical terms, the findings offer valuable insights for leaders and HR professionals in the creative sector. Diagnosing the level of creative potential within teams allows for more targeted deployment of AI tools and intelligent management strategies. This ensures that such technologies are used not only as efficiency boosters, but also as creativity enablers—strengthening organizational innovation capacity through human–technology synergy.

6. CONCLUSION

The conducted research enabled the assessment of the creativity level among employees in the creative sector of the West Pomeranian region, providing meaningful insights into their creative potential. The results revealed that the surveyed sample was dominated by individuals demonstrating nonconformist attitudes, heuristic cognitive styles, and highly creative approaches. These characteristics are essential in the creative sector, where innovation and unconventional thinking are foundational to business operations. Only a small fraction of respondents showed conformist or algorithmic tendencies, indicating that the sector attracts individuals with a higher-than-average creative profile.

The findings support the assumption that creativity is a critical driver of success in the creative sector, where the ability to generate new ideas, develop innovative solutions, and adapt to a rapidly evolving market environment is indispensable. Employees with a high level of creative attitude are more likely to respond effectively to the challenges of the knowledge-based economy and contribute to organizational innovation.

The results confirmed the initial hypothesis regarding the high level of creativity in this sector. This suggests a natural selection mechanism – organizations in creative industries tend to attract and retain individuals with strong innovative capabilities. At the same time, the variability in creativity levels among respondents highlights the role of both internal and external factors in shaping creative potential. Key determinants include the work environment, access to development opportunities, leadership style, and exposure to intellectual stimuli.

Given these observations, companies in the creative sector should actively foster conditions that support creative thinking. This includes open innovation cultures, freedom to experiment, support for employee initiative, and implementation of intelligent management tools – such as AI-based platforms and collaborative technologies – that can further amplify creativity.

Additionally, AI-supported tools offer new opportunities for assessing and enhancing creativity in the workplace. These include advanced psychometric tests supported by machine learning, natural language processing techniques for idea analysis, and AI-powered systems capable of recognizing creative potential. Such tools can serve as valuable complements to traditional diagnostics like the KANH-III questionnaire, offering scalable, data-driven insights for talent management and innovation strategies.

In summary, this study confirms that creativity is not solely an individual trait but also a function of the environment and organizational strategies. The insights gained here lay the groundwork for further theoretical and applied research, as well as the development of practical tools for fostering and managing creativity in modern, innovation-driven organizations. These findings reinforce the view that creativity

is shaped not only by individual predispositions, but also by systemic organizational efforts. Integrating intelligent management practices—including AI-driven tools—may further enhance creative performance and should be considered as part of long-term innovation strategies in the creative sector.

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Appendix 1

Please respond to the statements included in the questionnaire.

The **KANH-III questionnaire** consists of statements related to various human activities performed in the learning process. Indicate to what extent the statements in the table reflect your behaviors, preferences, characteristics, or beliefs by marking the appropriate letter. **Do not skip any statements.**

No.	Statement	A – Yes	B – Rather Yes	C – No Opinion	D – Rather No	E – No
1	I enjoy creating written statements.	A	B	C	D	E
2	I quickly adapt to new places and situations.	A	B	C	D	E
3	I am inquisitive about new information or phenomena I encounter.	A	B	C	D	E
4	I like leading people and taking control of situations.	A	B	C	D	E
5	I believe that others have the right to their own views, opinions, or beliefs, even if I disagree with them.	A	B	C	D	E
6	I solve problems independently without following others.	A	B	C	D	E
7	In new or difficult situations, I function best when acting independently.	A	B	C	D	E
8	When I study, I always strive to understand the subject matter.	A	B	C	D	E
9	I attach great importance to performing tasks differently than my peers.	A	B	C	D	E
10	I am artistically gifted.	A	B	C	D	E
11	I like to fantasize and have many unconventional ideas.	A	B	C	D	E
12	I usually make decisions independently, without being influenced by others.	A	B	C	D	E
13	I am curious about everything around me.	A	B	C	D	E
14	I approach problem-solving from various angles.	A	B	C	D	E
15	I like it when someone gives me guidance on how to study.	A	B	C	D	E
16	I am an advocate of all kinds of innovations.	A	B	C	D	E
17	I construct and improve devices I use in my surroundings.	A	B	C	D	E
18	I achieve set goals despite difficulties.	A	B	C	D	E
19	New convincing arguments usually make me change my previous point of view.	A	B	C	D	E
20	I persistently complete difficult or tedious tasks with enthusiasm and to the end.	A	B	C	D	E
21	I enjoy expanding my knowledge without external encouragement.	A	B	C	D	E
22	I like taking initiative and undertaking actions.	A	B	C	D	E
23	I enjoy coming up with various improvements in my surroundings.	A	B	C	D	E
24	I am cautious when expressing opinions because I fear ridicule.	A	B	C	D	E

25	Before following orders or regulations, I analyze their rationale.	A	B	C	D	E
26	I have the impression that I am better than others, which gives me confidence in my actions.	A	B	C	D	E

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EMPLOYEE SILENCE AND ORGANIZATIONAL TRUST – THE CONTEXT OF ARTIFICIAL INTELLIGENCE

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ABSTRACT

Purpose: *The aim of the work is to analyze the relationship between employee silence and organizational trust, taking into account the differentiation of motives for silence in the organization in the context of the development of artificial intelligence.*

Need for the study: *Previous studies focus on the analyzed relationship between general constructs, and studies consider internal divisions of employee silence from selected motives. The authors focus on the classic triad van Dyne, Ang & Botero (2003) proposed. However, the category of opportunistic silence is not taken into account. The literature also lacks works combining the conducted considerations with the problems of artificial intelligence applications (in the context of employee silence and trust in the organization). This work can, therefore, be considered pioneering in both areas.*

Methodology: *The analyzed empirical material comes from research on the issue of employee silence conducted on a sample of 426 respondents from the West Pomeranian Voivodeship. Single-variable regression instruments were used to analyze the studied relationships. A total of 5 econometric models were estimated. Individual constructs were synthesized by averaging partial indications of respondents in response to questions formulated in the survey copy relating to the considered constructs.*

Findings: *Other studies' findings on the relationship's negative nature were confirmed. The presented studies also deepened the ambiguity of the conclusions regarding the studied relationship at the level of constructs reflecting silence from selected motives. A negative, statistically significant relationship was identified between prosocial and opportunistic silence (categories practically absent in the literature in the aforementioned context). These categories should focus on building trust in the organization and implementing artificial intelligence solutions. The paper indicates practical implications in this area. This issue has not been exposed in the literature so far.*

Practical Implications: *The work identifies areas for possible action in building trust in the organization and reducing organizational silence. In this context, the challenges and prospects of artificial intelligence development are discussed.*

Keywords: employee silence, organizational trust, trust in the leader, artificial intelligence, AI, econometric models.

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1. INTRODUCTION

The aim of the study was to analyze the relationship between employee silence and organizational trust, taking into account the differentiation of motives for silence in the organization in the context of the development of artificial intelligence.

Organisational relationships are established based on trust, which is a prerequisite for communication and cooperation. People working in environments with high levels of trust in the organisation, leaders, and co-workers feel more comfortable communicating their thoughts and feelings. Trust, therefore, reduces the risk of an employee speaking up.

Hence, the studies cited later in the work observe a negative relationship between employee silence and trust in the organisation. In an environment filled with mutual trust, along with the decreasing risk accompanying employees speaking out, the intensity of silence in the organisation decreases (therefore, the cause-effect relationship is negative). Most of the studies cited later in the work confirm such a relationship.

The research is conducted considering the internal divisions of the studied constructs. The research examines silence revealed as a result of the impact of specific motives (defensive, permissive and prosocial silence – in the triad proposed by van Dyne, Ang & Botero (2003) and later extended to include opportunistic silence by Knoll & van Dick (2013). The category of trust in an organisation can also be described as heterogeneous. Apart from the above-mentioned general organisational level, the research references to trust in the leader (manager) or co-workers. The variables considered in the work that create the studied relationship are also included in the analyses, considering the third variable (mediator, moderator). Such studies are also cited in the theoretical part of this work.

Previous studies took into account the classic triad. The presented studies, filling the emerging research gap, also include the category of opportunistic silence in the analyses of the relationships with trust in the organisation.

It is worth emphasising that the identified relationships can be bilateral. Trust in the organisation reduces the intensity of silence. By reducing silence through the impact of other instruments, we also influence organisational trust, also in the context of artificial intelligence solutions.

These considerations are conducted when applying artificial intelligence and intelligent management. The fourth industrial revolution, along with the progress in artificial intelligence, is causing and will cause significant transformations in many industry and services sectors. Chui et al. (2015) specify that artificial intelligence and robotics can replace 45% of tasks previously performed by humans. AI awareness may raise concerns among employees whether artificial intelligence will not replace them in a particular time perspective. Such a state may translate into an extension of the range of silence (practically for any reason), fearing for their future. An alternative path of dealing with fears can also be indicated, in which the consequence of transformation is an extension of the range of voice behaviors in the organization. Employees, treating change as an opportunity, can demonstrate their professional competencies and contribution to the organization through voice behaviors. Trust in the organization is a factor that additionally induces employee voice.

The literature in the mentioned area (employee silence/voice, communication, or trust in the organization) is currently feeble (more in the literature review); hence, placing the considerations in the context of artificial intelligence can be treated as a pioneering task.

In the structure of the work, in the first part, the literature review presents two constructs considered in the analyses (silence in the organisation and trust in the organisation). Then, a review of studies focusing on analysing the relationships between both variables (in many dimensions, e.g. internal classification divisions) is presented. The next part presents the methodological aspects of the research presented in the work and their results. The work ends with a point presenting a discussion of the presented research results, where the issue of implementing artificial intelligence solutions in the context of building trust in the organisation and reducing silence in the organisation is also addressed.

2. SILENCE IN THE ORGANISATION

The issue of voice/silence was introduced to organisational science by Hirshman (1970). The author indicated four alternative forms of response from dissatisfied employees and customers of the organisation (exit, voice, loyalty, and silence). In this approach, building mechanisms for reporting

work-related problems into the organisational system (voice mechanisms) allows employees to express their concerns and solve problems in a dialogue with management instead of reacting by leaving (Perlow & Repenning, 2009). Hence, the initial focus in organisational literature was on employees' voice behaviour (Withey & Cooper, 1989; Folger, 1977; Kunasz, 2022a). The issue of voice/silence was also present in psychological, political science, sociological, and anthropological literature in other contexts (bottom-up communication, whistleblowing, research on the MUM effect, spiral of silence, self-censorship, procedural justice, issue selling, social ostracism or deaf ear syndrome (Rosen & Tesser, 1970; Noelle-Neumann, 1974; Roberts & O'Reilly, 1974; Thibaut & Walker, 1975; Miceli & Near, 1992; Dutton & Ashford, 1993; Williams & Sommer, 1997; Peirce, Smolinski & Rosen, 1998).

The issue of silence/stillness has been taken up in the literature on the subject only since the turn of the century. The pioneering work in this area was Milliken & Morrison (2000). They treated organisational silence as a collective phenomenon in opposition to the considerations on speaking up by employees conducted so far (Kunasz, 2022b). These focused on the individual decisions of employees to speak up in a given situation. When there is silence in an organisation, it is not the result of unrelated decisions of employees but rather the product of specific forces in the organisation reinforcing organisational silence (Kunasz, 2024a). The key in this respect is the hidden beliefs of managers and the fear of feedback. They determine the creation of organisational structures and the implementation of management practices that support the creation of a climate of silence (the belief shared by employees that speaking up will not contribute to change and, on the contrary, may be met with specific consequences for those speaking up). When such a climate exists, silence, not voice, dominates in the organisation.

In opposition to this thinking pattern, works have appeared in the literature emphasising the individual dimension of employees' decisions to remain silent. In this context, we can speak of employee silence (Pinder & Harlos, 2001). In this approach, employee silence may result from different motives because it is not treated as a monolith as in the original approach (Kunasz, 2024b). The first attempts to categorise the types of employee silence appeared on this basis. van Dyne, Ang & Botero (2003) distinguished three motivations of employees in an organisation: resignation, fear and orientation towards others, distinguishing adequately permissive silence (voice will not change much), defensive silence (fear of the consequences related to speaking out), prosocial silence (voice activity may harm good cooperation between employees).

Knoll & van Dick (2013) extended the original typology of employee silence by adding a fourth category – opportunistic silence. The motive for silence in such a case is the calculation of the benefits and disadvantages associated with voice activity. Perceived disadvantages inhibit voice.

There is currently a consensus in the literature on etymologising the motives for silence (including employees' silence from four motives). However, some Authors (for example, in the case of the studies by other Authors presented below) refer to the 'classic' triad. In this respect, the author's research presented in the further part of the work (also focusing on opportunistic silence) will bring added value to the literature.

We can also speak of consensus in terms of measurement methodology. This instrument was proposed in the context of the considerations on the fourth motive of employee silence by Knoll & van Dick (2013). This instrument will be presented in more detail in the methodological part of the work.

In the above-described context, one should distinguish organisational silence (treated as a uniform construct conditioned by the climate of silence in the organisation) from employee silence (individual decisions induced by a diverse spectrum of motives). Hence, the author uses the analytical category of silence in the organisation of this work. So far, It has not been decided whether voice and silence should be treated as opposite ends of a continuum (Milliken & Lam, 2009) or as separate constructs (Kish-Gephart et al., 2009). In this context, numerous postulates exist to integrate the literature on voice and silence in organisations (Morrison, 2011).

3. TRUST IN THE ORGANISATION

Trust should be defined as a psychological state that includes the intuition to accept vulnerability based on positive expectations about the intentions or behaviours of another person (Rouseau et al., 1998). This positive expectation is rooted in the knowledge and skills of the other party needed to obtain desired

outcomes and in their ethical motivation (Mayer, Davis & Schoorman, 1995). Trusting another party, individuals are more willing to take risks that can bring positive outcomes such as higher levels of task performance, prosocial behaviour, job satisfaction, or reduced turnover intentions (Mayer & Gavin, 2005; Zhu & Akhtar, 2014).

Trust should, therefore, be viewed as a positive psychological process (Turner, Barling & Zacharatos, 2002). Trust reduces the perception of future risk by fostering positive expectations and belief in a specific goal. Destructive relationships are associated with distrust because they induce negative feelings and perceptions of the environment and other organisation members (Lazarus, 1995).

Trust or organisational trust is not a homogeneous category. In various analyses, the research authors refer to different conceptual categories that are actually connected by the term in question. There are also different ways of isolating the components of organisational trust.

Following Mayer, Davis & Schoorman (1995), a distinction should be made between interpersonal and institutional trust. Interpersonal trust is further divided into horizontal and vertical trust.

Horizontal trust is defined as the trust that employees have in each other (trust in co-workers), and vertical trust is the trust between employees and managers (leaders) in the organisation (Ellonen, Blomqvist & Puumalainen, 2008). When employees are treated fairly by a leader they trust, they are likely to think of their relationship with the leader in terms of social exchange rather than economic exchange (Walumbwa & Schaubroeck, 2009). According to social exchange theory, the relationship-based perspective assumes that followers will reciprocate the relationship (leader) (Dirks & Ferrin, 2002).

Institutional trust refers to an employee's belief in the position of institutional structures in achieving success and shaping their own future (Mcknight, Cummings & Chervany, 1998). This type of organisational trust focuses on the organisation as a whole, reflecting an individual's confidence that the organisation will act in their favour or at least will not act in a way that will harm them (Saglam, 2016).

The aforementioned areas of building organisational trust are intertwined. Trust in co-workers or managers builds organisational trust and commitment (Kim et al., 2019). When employees trust the leader, this trust is reflected in the entire organisation because they see the leader as a representative of the organisation. Therefore, the leader plays a decisive role in creating trust in the organisation.

4. STUDY ON THE RELATIONSHIP BETWEEN EMPLOYEE SILENCE AND TRUST IN THE ORGANISATION

The subjects of numerous studies are analysing the literature on the subject and identifying the relationship between organisational silence/employee silence and trust in the leader or organisation. In most cases, a negative relationship is identified. Therefore, an increase in trust in the leader or organisation is a factor that reduces organisational silence or employee silence and vice versa.

Interestingly, many studies indicate a moderate strength of the negative relationship. All of them were conducted using samples from different educational market segments. This strength of the relationship is indicated by meta-analyses conducted in educational organisations by Akar (2018a) (the study examined trust in the manager) and Akar (2018b) (the study examined organisational trust). Also, at work (Cekinberg, Dede, Yilmaz, 2014), an adequate moderate relationship was identified (organisational trust was examined) on a sample of academic employees at work (Demet & Cevat, 2017) and on a sample of primary and secondary school teachers (trust in the supervisor was examined). A negative relationship in the analysed relationship was also identified in the studies presented in the works (Fard & Karimi, 2015) (organisational trust was examined – a statistically significant relationship); (Jurek, 2019) (trust in the supervisor was examined, the only study known to the author in this area conducted on a Polish sample of employees of enterprises from various industries) and (Karabay, Sener & Tezergil, 2018) (trust in the leader was also examined).

An exception in this respect is the work (Saglam, 2016). The author identified a positive statistically significant relationship between organisational silence and organisational trust in a sample of vocational schoolteachers in Turkey.

In the selected works, the studied relationship was analysed, taking into account data reflecting constructs reflecting silence undertaken concerning a diverse spectrum of motives (concerning the

previously discussed ways of categorising the types of organisational silence. The presented studies indicate the existence of the studied relationships in the context of defensive and permissive silence.

Dedahanov & Rhee (2015) conducted analyses on a sample of highly qualified employees separately for the constructs of trust in the organisation and trust in the supervisor. Trust in the organisation in these studies is associated with permissive silence, while trust in the supervisor is also associated with defensive silence. In turn, the relationship between trust in the supervisor and defensive silence in the studies (Ozen Kutanis et al., 2014) is not statistically significant. Schlosser & Zolin (2012), in turn, indicate that defensive silence is reduced by trust in employees.

It is also worth paying attention to the previously cited studies (Saglam, 2016), in which a statistically significant relationship (also positive, as in the case of the synthetic construct) was identified only in the analyses of prosocial silence. For the remaining components considered (permissive and defensive silence), the direction of the relationship was negative, but these relationships cannot be described as statistically significant.

To summarise this part of the discussion, the conclusions from the cited studies regarding the constructs reflecting silence for selected motives are quite ambiguous. In the literature on the subject, the relationships in the analysed scope for prosocial silence (introduced to the classification of silence for various motives by Knoll & van Dick (2013)) have not been studied.

The constructs constituting the analysed relationship were considered in the third variable analysis:

The ethical climate was considered a mediator of the analysed relationship (trust in the leader was examined) in the research (Karabay, Sener & Tezergil, 2018) carried out on a sample of insurance company employees.

Trust in the leader mediated the relationship between employee silence and the leader's destructive personality in a study of a sample of superior-subordinate dyads (Song et al., 2017).

Organisational silence, in turn, was considered in Bourantas, Nikolaou & Vakola's (2011) work as a mediator of the relationship between trust and attitudes towards mergers (using two case studies of companies undergoing a merger).

Trust was included as a moderator in the following studies on the relationship between employee silence:

- with the perceived organisational politics in the research conducted by Jaweria & Jaleel (2016) on a sample of academic staff (the construct of trust in the superior was analysed),
- with the perceived stress in the study by Chung & Dong (2021) conducted on a sample of white-collar workers (the construct of interpersonal trust was analysed),
- with value co-creation in the research by Boadi et al. (2022) conducted on a sample of front-line hotel employees (the construct of organisational trust was analysed, only defensive silence was focused).

The work also focused on the examined relationship with the extension of aspects complementing the current state of knowledge.

5. THE CONTEXT OF ARTIFICIAL INTELLIGENCE

The underlying relationship in the work was analyzed in the context of challenges and prospects for the development of artificial intelligence. In the Ebsco database, one work (newly published) was found focusing on the issue of employee silence and AI awareness among employees (Cheng, Zhang & Wang, 2025). Another work (Lin & He, 2024) indexed in the database in a similar context focuses on voice behavior (a path of voice activity in the organization independent of silence, although these constructs are related). Few works refer to the issue of communication in the organization[1] (including the issue of silence as an element of communication in the organization more broadly) in the context of using artificial intelligence solutions (without references to the issue of employee silence, however) – for example (Yue et al., 2024; Van Quaquebeke & Gerpott, 2024; Koponen et al., 2025). In the Ebsco database, no work focused on the issue of trust in the organization, leader, or co-workers in the context of artificial intelligence applications[2].

[1] We did not analyze work carried out in communication sciences or work focusing on communication issues between artificial intelligence agents or humans and artificial intelligence.

[2] Works focusing on the issue of trust in artificial intelligence were not analyzed.

Using AI solutions in organizations may lead employees to have concerns about their career prospects. There is a fear that AI will replace their work. As a result, employees may reduce their voice activity due to fear of being fired (Cheng, Zhang & Wang, 2025) – they may remain silent for virtually any reason (fear, opportunism, pro-social approach or, to the least extent, lack of prospects – permissive silence).

However, in the aforementioned context, it is worth presenting the opposing idea that AI awareness can motivate employees, as its effect may be the motivation to formulate appropriate strategies to alleviate such fears (Liang et al., 2022). In such a scenario, employees perceive emerging stress as an opportunity to adapt to the evolving landscape of the workplace. This state of affairs may encourage employees to engage in behaviors that prevent the negative impact of introducing AI solutions in the organization. Voice behavior is one of the strategies for coping and career development of employees in the face of crises at work (Lin & He, 2024).

By articulating their proposals for solutions or improvements, employees can demonstrate their professional competencies and contribution to the organization to their superiors. This approach helps employees create a positive and credible image of themselves in the organization, creating favorable conditions for career development (Whiting et al., 2012). Employee voice is crucial for organizational effectiveness. Employees not only express dissatisfaction with work-related problems but also present many valuable observations aimed at progress, supporting the organization's long-term development (Lin, 2023). As previously mentioned, in an environment of mutual trust, voice dominates, not silence.

The above mechanisms can be included in the COR theory, which often defines the management research framework (Hobfol, 1989). In the context of this theory, vocal expression is a way to secure additional resources in stressful conditions. Employees may perceive the introduction of artificial intelligence solutions in the workplace as a source of work-related stress, contributing to resource depletion (Teng et al., 2023). Voice behavior allows for securing resources that fill this gap.

6. METHODOLOGY

The analysed empirical material comes from research on the issue of employee silence (research subject). It was collected in September-October 2021 (research time frame) via a paper questionnaire from respondents from the West Pomeranian Voivodeship (research spatial scope). The research sample includes 426 respondents who completed the survey forms.

In analyses taking into account the typology of employee silence, a commonly used tool is the set of instruments proposed in the work (Knoll & van Dick, 2013). These authors based their analytical concept on other works (Milliken, Morrison & Hewlin, 2003; van Dyne, Ang & Botero, 2003; Brinsfield, 2009). For example, the cited instruments were used in the works (Adamska, 2015; Knoll, Neves, Schyns & Meyer, 2021) and in this work.

The questionnaire includes 20 statements beginning with a common root: "I am silent at work...". Based on confirmatory factor analysis, the authors of the concept indicated questions that can be used in the research context for each of the four types of silence in the organisation discussed in the work. In each area, three statements were indicated. Hence, in the analyses presented in this work, the declarations of respondents who responded to 12 questions from the measurement scale within the five-factor Likert scale (where 1 meant complete disagreement with the statement, and 5 - entire agreement with the statement) were taken into account. However, all 20 questions were included in the research survey.

A synthetic construct was also constructed based on the respondents' indications in response to all 12 questions. The variable constructed in this way reflected one of the constructs of silence taken into account in the analyses of the relationships considered—the silence of employees in general.

Organisational trust was surveyed among respondents using a six-item measurement scale.

Table 1 presents the specification of statements based on which synthetic measures (constructs) were constructed.

Table 1. Specification of statements used to construct synthetic measures (constructs)

Construct	Question
SILENCE (I keep silent at work...) - explained variables	
defensive silence	due to fear of negative consequences
	to avoid being criticised by colleagues or superiors
	because I am afraid of the damage associated with speaking out
opportunistic silence	for fear that others might take advantage of my ideas
	so as not to give up the advantage of knowledge
	because it would mean having to do additional and avoidable work
prosocial silence	because I do not want others to have problems because of me
	because I do not want to hurt the feelings of my colleagues or superiors
	because I do not want to embarrass others
acquiescent silence	because my superiors are not open to suggestions or solutions
	because nothing will change anyway
	because my opinions will not fall on fertile ground anyway
TRUST IN ORGANIZATION - explanatory variable	
trust in organisation	I believe that my employer is highly honest
	I fully trust my employer
	My employer is open and honest with me
	I can expect my employer to treat me consistently and predictably.
	My employer is always honest and truthful
	Overall, my employer's motives and intentions are good.

Source: own study based on the conducted research.

When creating a synthetic measure reflecting a given construct (e.g. defensive silence), the average value of the respondents' indications was calculated based on the statements constituting it. There was no need for corrections to the reverse for selected statements.

Table 2 presents selected statistical descriptions and reliability analysis measures for the studied constructs.

Table 2. Selected measures of statistical description and reliability analysis for the analysed constructs

measures / variables	silence					trust in organi-sation
	defensive	prosocial	opportunistic	acquiescent	all positions (12)	
DESCRIPTIVE STATISTICS						
median	2,00	2,33	2,00	2,00	2,17	3,17
variance	0,98	1,21	0,87	1,14	0,50	1,12
standard deviation	0,99	1,10	0,93	1,07	0,71	1,06
skewness	0,83	0,47	0,60	0,63	0,07	–0,02
kurtosis	–0,08	–0,45	–0,29	–0,47	–0,71	–0,68
RELIABILITY ANALYSIS						
Cronbach's alfa	0,599	0,699	0,595	0,735	0,833	0,668

Source: own study based on the conducted research.

The distributions of the variables for the constructs reflecting the analysed categories of silence are asymmetric on the right side – the positive values of skewness evidence this. The most extraordinary asymmetry in the group can be noted in the case of defensive silence, and the smallest is for prosocial silence. Therefore, respondents relatively more often chose to disagree with the statement referring to the state of silence in the organisation. Such asymmetry is not revealed for the synthetic variable covering all items of the measurement scale of silence in the organisation. Also, it is impossible to identify asymmetry for the synthetic measure reflecting the trust in organisation construct (skewness close to zero).

All distributions for the analysed constructs are platykurtic, as evidenced by negative kurtosis values. Therefore, in these distributions, the variable values are clustered closer to the central measure (than in the normal distribution), and the tails are less developed. The lowest kurtosis value was noted

for defensive silence, while the highest was for the construct reflecting silence in the organisation based on all questions that make up the measurement scale. The lowest variance was noted for this variable (the smallest differentiation of the variable). The highest variance was noted for prosocial silence (variances are comparable due to the standard range of possible variants of the formation of variables on a scale from 1 to 5).

Cronbach's alpha was calculated for each construct. The values of this measure generally fall within the norm (> 0.6). For defensive and opportunistic silence, Cronbach's alpha balances on the border of the norm. It can, therefore, be assumed that the scales are reliable.

The single-variable regression instrument was used in the analyses of the studied compounds. Five econometric models were estimated, and model parameters were estimated using the classical least squares method. To assess the quality of the model fit, the following were calculated for each: R^2, the sum of squared residuals, and the logarithm of likelihood.

Like any other research, this one also has its limitations. The research is partial and not complete. It is important to note the subjective nature of respondents' declarations in response to survey questions. The spatial scope of the research limits it to the regional dimension (West Pomeranian Voivodeship) and not the national one. The research presents a static image of reality. The dynamics of change could be reflected in longitudinal research.

7. RESEARCH RESULTS

The research estimated five single-variable regression models. In each case, the explanatory variable was trust in the organisation. The explanatory variables were constructs reflecting the four types of employee silence discussed in the literature review (permissive, defensive, prosocial, and opportunistic) and a construct reflecting the category of silence in general (the average of the respondent's responses to all 12 questions from the questionnaire differentiating the individual types of employee silence in the organisation). The relevant data are included in Table 3.

Table 3. Model estimation results

Variable	Coefficient	Standard error	t	p-value
model 1 - silence generally				
const	2,76938	0,165132	16,77	<0,0001***
trust	–0,170294	0,0488454	–3,486	0,0006***
model 2 – acquiescent silence				
const	2,39607	0,238362	10,05	<0,0001***
trust	−0,105646	0,0705068	−1,498	0,1358
model 3 - defensive silence				
const	2,61928	0,265775	9,855	<0,0001***
trust	−0,0371445	0,0786155	−0,4725	0,6372
model 4 - prosocial silence				
const	2,82228	0,219411	12,86	<0,0001***
trust	−0,205345	0,0649010	−3,164	0,0018***
model 5 - opportunistic silence				
const	3,23990	0,243180	13,32	<0,0001***
trust	−0,333039	0,0719318	−4,630	<0,0001***

Source: own study based on the conducted research.

A negative relationship between the analysed variables, known from the literature, was identified in all cases. Thus, an increase in the mean measure of trust in the organisation translated into a decrease in the mean measure describing a given category of employee silence. It, therefore, contributed to reduced employee silence (and, of course, vice versa). For example, in the model with a dependent variable reflecting silence in general, a decrease in the mean measure of trust by 0.17 should be associated with an increase in the mean measure of silence (within the measurement scale) by one unit.

In models 2 and 3, in which the explained variable in a given relationship was respectively acquiescent and defensive silence, no statistically significant dependencies were noted (p-value

adequately 0.136 and 0.637 – in the second case, a very high level of this measure). In the case of the other two constructs referring to the typology of division of employee silence, however, statistically significant dependencies were noted. The lowest negative value of the estimated parameter was noted for the construct of opportunistic silence (–0.333, the lowest p-value). It should also be noted that the model reflects the construct of employee silence in general in relation to organisational trust (synthetic measure – negative relationship).

To assess each model's modelling quality, three measures – R square, the sum of squared residuals, and the logarithm of likelihood - were calculated. The relevant data are included in Table 4.

Table 4. Modelling quality assessment measures

model	R^2	sum of squared residuals	logarithm of likelihood
model 1	0,065294	81,6497	–182,145
model 2	0,012739	170,1255	246,746
model 3	0,001281	211,5064	–265,905
model 4	0,054403	144,1487	–232,165
model 5	0,109684	177,0717	–250,267

Source: own study based on the conducted research.

Considering the essential measure of econometric model assessment, i.e. R square, it should be noted that the indicator value is relatively low (models of one variable were studied, and other factors probably influence the explained variable simultaneously). This fact should be noted as a limitation of the research. The highest score in this respect should be assigned to model 5, where the most substantial relationship was noted. Models in which a statistically significant relationship was identified between the studied variables (models 1 and 4, respectively) can be rated relatively high.

The situation is similar for the next measure of fit used. The lowest sum of squared residuals (the model that best fits the actual measures) was observed for models 1, 4, and 5. The log-likelihood analyses partly confirm this pattern of data. The exception here is model 5, which can be assessed in this context as slightly worse in terms of fit than model 2.

8. DISCUSSION

The paper examines the causal relationship between employee silence and organisational trust (interpersonal and institutional trust). The findings from other studies on the negative nature of such a relationship were confirmed (Cakinberg, Dede & Yilmaz, 2014; Fard & Karimi, 2015; Demet & Cevat, 2017; Jurek, 2019). Thus, increasing trust in the organisation reduces employee silence (and vice versa). However, the relationships may be two-sided - actions to reduce silence in the organisation may also build trust in the organisation, including trust in artificial intelligence.

The examined relationship at the level of silence is statistically significant (p-value for the variable trust in the organisation $p = 0.0006$). The literature on the strength of the examined relationship is not unambiguous. The prevailing view is that this relationship has moderate strength (Akar, 2018a; Akar, 2018b).

Also, at the level of constructs reflecting silence from selected motives, conclusions from the literature on the subject are ambiguous. Usually, two categories of employee silence are indicated in the aforementioned context (permissive and defensive silence) (Schloser & Zolin, 2012; Ozen Kutanis et al., 2014; Dedahanov & Rhee). For prosocial silence, the studies cited in the literature review indicate a statistically significant, although positive, relationship with organisational trust (Saglam, 2016).

The presented research deepened the previously mentioned ambiguity of conclusions resulting from analyses of the literature on the subject. No statistically significant relationships were identified in relation to organisational trust between permissive and defensive silence. However, in this context, they were identified for the practically absent categories of prosocial and opportunistic silence. In both cases, a statistically significant negative relationship was identified with organisational trust, with a significantly greater strength of this relationship noted for the category of opportunistic silence.

Therefore, it is necessary to focus on the role of the mentioned generic categories of employee silence (with particular emphasis on opportunistic silence) in the context of building trust in the organisation, including building trust in the context of implementing artificial intelligence solutions.

In this context, it is worth paying attention to the following aspects:

- Artificial intelligence significantly increases the possibilities of personalising communication – support in formulating messages tailored (not only in terms of content but, for example, presented in the right tone) to the individual preferences of individual employees (taking into account, for example, their gender, age, position or functional area). This can strengthen employee engagement and motivation to speak up in the form of, for example, feedback.
- Employees may find communicating with artificial intelligence (bots) easier than with humans. This may reduce the overall level of silence in the organisation. Of course, building trust in this form of communication and constantly improving its quality (compared to communication with humans) may play an important role here. Of course, the problem may be that the communicator may not be sure whether they are talking to artificial intelligence or a human (when it will become increasingly difficult to distinguish these forms of communication with progress).
- It is worth paying attention to the risk of misunderstandings in bot-human communication. The imperfection of solutions can be downright irritating, which by limiting trust in this form of communication can discourage communication in general in this form and parallel in other forms, increasing the space of silence. The aforementioned risk will be limited with the progress of technological solutions.
- One of the important threads raised in the discussion of employee silence is the issue of hiding mistakes as part of professional solidarity (e.g. in medicine). This is the primary motive for prosocial silence (a statistically significant relationship was observed for silence based on this motive in the studied relationship - high trust in the organisation can reduce this type of silence, but there will always be a margin of acceptance for this type of behaviour in the organisation due to pure professional loyalty towards co-workers). Errors and their negative consequences may appear in the case of artificial intelligence algorithms. Employees can hide them in the same way as in the case of behaviour towards their co-workers. This is a very interesting context for further research on employee silence (how they will approach errors made by artificial intelligence).
- Processing a huge amount of data allows managers to better identify and understand key problems that appear in employee feedback practically in real-time (reaction time is, therefore, shorter) and to react quickly in real-time. Such actions, such as increasing trust in the management staff/organisation that recognises the problems of lower-level staff and responds to them, can significantly reduce the space of employee silence (by increasing trust in the management staff).
- For example, the possibility of analysing emotions revealed in opinions or sentiments in social media provides a rich arsenal of adequate instruments for resolving and de-escalating conflicts adjusted to their current source, which, by influencing a positive assessment of the actions of managers (who correctly identify sources of conflicts) in response to employee opinions, also increases trust in the manager.
- The growing possibilities in data processing speed and the emergence of modern technological solutions allow for increased communication effectiveness related to the automation of responses (e.g. e-mail) in contact with employees. Such solutions can bring savings in time or human resources, which translates into financial efficiency, but also allows managers and employees to focus on more complex non-routine tasks, in which artificial intelligence cannot replace them or recognise key employee needs, responding to them in order to increase engagement and trust in the organisation.

It is worth remembering, however, that the effectiveness of the above-mentioned tools depends on the staff's openness to new technologies and willingness to use them in everyday life. Introducing AI to interpersonal relationships can bring many benefits but will not replace authenticity and empathy in interpersonal relationships. Artificial intelligence should be a tool that supports and does not replace human interaction. It is worth finding a balance between automation and the human aspect of communication so as not to dehumanise interactions, which will limit trust in artificial intelligence and managers or organisations. It is also worth remembering this in the context of reducing employee silence.

The aspects outlined above may become the subject of further research.

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A MODEL APPROACH TO THE RELATIONSHIP BETWEEN EMPLOYEE RELATIONS, AGILITY, AND INNOVATION IN A SMARTLY MANAGED ORGANIZATION BASED ON RESEARCH

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ABSTRACT

Purpose: *In an organisation managed based on artificial intelligence, innovation plays a key role in building an effective operating model. On the other hand, developing interpersonal relationships and agile behaviours is desirable in response to the growing demands of a turbulent environment.*

Need for the study: *There are relatively few studies dedicated to understanding how interpersonal relationships and agility affect the generation and diffusion of new solutions. Therefore, these processes are still insufficiently explored.*

Methodology: *Using diagnostic survey methods and structural equation modelling, the authors conducted a study to discover whether there are relationships between relationships, agility, and innovation in the organization. The research sample consisted of two hundred and fifty-four managers representing the economic sector. A model of the interdependence of the above-mentioned features was proposed.*

Findings: *Based on the research, it was found that the type of relationships between organisational members and the organisation's innovation are correlated. The analysis also indicates that innovative behaviours are easier in agile organisations and that agility influences the relationship between interpersonal connections and innovation. The discussed results and their conclusions can be viewed as a contribution to the existing body of knowledge, which should continue to be expanded.*

Practical Implications: *The authors recognise an opportunity to add new constructs to the analysed model, which will become the subject of research in their next phase.*

Keywords: intelligent management, smart organization, relationships, innovation, agility, model approach

Jel codes: C1, M12

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1. INTRODUCTION

Intelligent organisational management aims to automate management decisions and is related to the design of management behaviours. (Lv& Li, 2021). The main substrate for the creation of enterprise intellectualisation mechanisms is artificial elements (complex computer systems, local networks, etc.). However, the natural intelligence of employees also plays an important role. It is supported by their professional development aimed at competence formation through training in knowledge, skills and abilities (Odrekhivskyi et al., 2023). It results both from the serious limitations of contemporary artificial intelligence systems, which, among other things, are unable to generalize (von der Malsburg et al., 2022), and from the fact that interactions with AI systems force solving ethical, social and environmental problems (Kumar, 2023, 18).

Many researchers point out that artificial neural networks support creative and innovative behaviours (e.g. Clegg et al., 2022; Siemion, 2022). Innovation is a key feature of organizations in the era of constantly changing environment and related constant challenges, as well as intensifying competitive struggle. The founder of the concept of innovation, J. Schumpeter, understood it as the creation of new combinations of existing resources,-however, in more modern times this concept is also defined in other ways. Innovation can also be perceived as a process that integrates science, technology, economics, and management, aiming to achieve novelty and extending from the emergence of an idea to its commercialization, or as new knowledge introduced into products, services, and processes (Kogabayev&Maziliauskas, 2017; Mazur-Wierzbicka, 2018, 2019). Some additionally highlight creativity as a particularly important element of innovation. For example, Cropley et al. (2011) note, following other authors, that creativity was previously considered the first stage of innovation, followed by the application of ideas resulting from creativity. However, in more recent theories, the interdependence of these two features is not viewed as sequential, although creativity still always precedes the implementation of innovation. A similar position is represented by Meutia et al. (2018), who write, among other things, that creativity is the initial phase of innovation. Also in works such as Roy & Mohapatra (2023), Ek Styv'en et al. (2022) or Rzepka & Sabat (2022) far-reaching relationships are noted between being creative and innovative.

The turbulent conditions in which organizations currently operate increasingly force them to adopt flexible behaviours. This issue has become particularly apparent in recent years, as the COVID-19 pandemic, followed by the outbreak of the war in Ukraine and the resulting energy crisis, have highlighted the necessity of rapid adaptation to change (Jojczuk et al., 2023). The agility of organizations and the adaptation of leaders to these conditions began to be discussed in the 1980s and 1990s. In the early 1980s, agility began to be defined as the ability to respond quickly to changes in the environment, but a certain group of researchers believe that the term has its roots in the context of production and is related to the need to find a new production system that responds to new factors of production in the manufacturing industry (Desalegn et al., 2024). However, this topic, along with the factors or dimensions of its occurrence, was addressed in a more structured manner only in the first decade of the 21st century. The dominant dimensions of organizational agility include, among others: business, markets, strategy, and process (Silva & Oliveira, 2023). Some authors emphasize the important role of leadership in an organization, noting that building trust in employee teams fosters the creation of flexible leaders. Tyagi et al. (2022) wśród czynników determinujących efektywność i zaangażowanie członków zwinnych zespołów wymieniają między innymi obecność liderów, którzy wykazują służebną postawę wobec współpracowników oraz skłonnych do dzielenia się swoją wiedzą i umiejętnościami, jak również promujących refleksyjność, co dodatkowo zachęca do innowacyjności. Trzeciak & Banasiak (2022) also mention solutions naturally related to the human factor in the organization, such as a transparent and appropriate evaluation system, defining planned employee development, and team atmosphere. It is also worth noting the agile mindset, which is attributed a key role in the process of effectively introducing flexibility (e.g., Eilers et al., 2022; Asseraf&Gnizy, 2022). Organizational agility, like innovation, should also be considered in the broader context of intelligent management. Research results published in works such as Gonçalves et al. (2022), Saputra et al. (2023), and Wang et al. (2022) clearly indicate the positive impact of using AI tools on decision-making processes, including their speed and the accompanying proper judgment of managers.

Employee relations are a very important element of every organization (Mazur-Wierzbicka & Cierniak-Emerych, 2024). As an intangible value, they are often included in the broadly understood

organizational capital of a given entity, understood as a set of intellectual property assets of the organization, its processes and methods, as well as communication and information infrastructure (Chmielewiec, 2019). Enterprises more heavily based on human capital (Rzepka & Witkowski, 2024) have greater ease in obtaining external financial resources for their activities, as in the assessment of the holders of these resources, they represent greater creditworthiness (Honjo et al., 2022). At the same time, they widely use motivational compensation systems and various non-monetary benefits to retain the most important talents from the perspective of their operations (Hasan & Uddin, 2022). The increasing importance of interpersonal relationships in organizational activities is also evidenced by the presence of the concept of relational capital in the literature. This capital can be defined in various ways: for example, as an expression of the value of relationships that an enterprise maintains with all entities in its environment (Garcia-Merino et al., 2014), as knowledge acquired and obtained from these relationships, or as resources created based on personal relationships, such as trust, norms, commitments, reputation, and identity (Sanchez-Famoso et al., 2020). However, it is worth mentioning that in the context of using tools based on artificial intelligence, at least some of these values may be diminished. As noted by Ojo &Afolaranmi (2024), AI technologies lack the nuanced emotional understanding necessary for true intimacy, and they do not foster the building of authentic trust and achieving significant relational depth.

Based on the above, both agility and the relationships between an organisation's employees should be considered as very important factors affecting the way it operates. They should be considered in the context of innovation as one of the most important dimensions of an organisation's functioning.

2. LITERATURE REVIEW

The issue of innovation has been present in the literature for a long time, and authors of various publications, in search of key determinants for introducing innovative solutions, point to different types of investments that should be made to more effectively utilize the potential of innovation. El-Bar (2021) distinguishes two types of such investments, one of which enables the creation and promotion of knowledge, while the other translates knowledge into specific innovative solutions. Some researchers focus primarily on assets that foster innovation, which are based on material values. This can include the broadly understood area of R&D or the development of information and communication technologies (El-Bar, 2021; Czerwińska et al., 2023), as well as certain business activities related to tangible asset transfer. For example, one of the more recent studies highlights innovation based on foreign trade exchange, where the import of high-quality semi-finished products leads to an increased number of patents (Zhong, 2023).

In many works, intangible values are seen as a crucial stimulator of innovative capabilities. Innovation is relatively often associated with the organizational culture of a company. As Salilew (2019) writes, a strong organizational culture allows for the effective use of employees' capabilities and improvement of their performance. Rodriguez-Gonzalez et al. (2023) and Rzepka (2023) argue that the impact of organizational culture on a company's performance is largely determined by employees' attitudes toward the implemented innovative changes. They write that particular importance is given to the fuller contact of employees with individual supply chains and the improvement of their perception of organizational innovations. Naveed et al. (2022) and Pedraza-Rodriguez et al. (2023) emphasize the role of organizational members' acceptance of changes made in the workplace. In another study, it is noted that shared values, mutual relationships, adopted patterns of thinking and behaviour, as well as methods of cooperation, have a significant impact on organizational effectiveness (Domańska-Szaruga & Knap-Stefaniuk, 2022). A relatively new research topic is the impact of family ties between employees on the functioning of a company, as discussed by Memili et al. (2020) and Chrisman et al. (2021). In the first case, researchers focus on the management problems of companies owned by several families. They propose certain mechanisms to limit the potential negative impact of divergent non-economic goals related, among other things, to family altruism and transgenerational succession. In the second case, the authors conclude, based on examples from companies in the hotel industry and healthcare sector, that small and medium-sized family businesses can achieve transgenerational sustainability and success if they leverage their strong non-financial aspects while simultaneously minimizing the impact of family-focused goals on the company's performance. In small family businesses, owners prefer intuitive,

informal decision-making and exercising control over every important aspect of the operation, which includes unwillingness to delegate certain functions to third parties. However, it is uncertain whether this unwillingness is primarily due to the nature of such enterprises or their size (Rieg et al., 2022). Family relationships among employees influence organizational psychological capital, which Fischer-Kreer et al. (2021) view as an essential resource for family businesses during times of stress. However, such relationships are not limited to family businesses. As Obiekwe et al. (2019) argue, fostering close bonds between coworkers, even when they are not related, generates greater engagement, increases attachment to the employer, and contributes to greater empowerment in teamwork. From an economic perspective, such a network of connections allows the participating entities to operate with low transaction costs (Ramirez-Sólis et al., 2022).

The scientific literature addresses the mutual relationship between agility and innovation. Many studies emphasize the positive connection between these two aspects of organizational functioning, generally attributing a key role to flexible behaviours in innovation processes. For example, Sjödin et al. (2020) propose a model illustrating an alternative approach to microservice innovation based on rapid, iterative development and adapted to changing innovation requirements, which brings more flexibility to the innovation process. In turn, Alamsjah (2022), examining supply chains, finds, among others, that open innovation practices improve companies' agility capabilities, which is also confirmed by the research results presented in another work (Arsawan et al., 2022) Bellis et al. (2024) examine the correlation between agility and innovation through the lens of leadership. They conclude, among other things, that the development of innovative activities requires leaders to become ambidextrous, agilely adapting to different environments and adjusting their behaviours and styles while maintaining consistency in values and norms. However, Annosi et al. (2022) seem to take a different stance on this matter, concluding, based on the example of a large telecommunications company, that actions aimed at developing agility may have an adverse impact on employees' pro-innovation attitudes. If it is assumed that direct management interventions limit the agile behaviours of organizational members, a similar view to that of Annosi et al. (2022) is in fact represented by Lill & Wald (2021), who, based on their own research, surprisingly state that such top-down interactive controls can positively impact employees and their creative abilities. The issue of agility and innovation can also be considered on a regional scale, as exemplified by the work of Andriyani et al. (2024), which identifies important aspects and common practices between agility and open innovation concepts. According to the authors, the adaptation of innovation in the region should focus on critical aspects such as collaboration, prototyping, adaptability, feedback loops, experimentation, risk management, ecosystem development, and data-driven development.

The relationship between agility, innovation and the use of artificial intelligence technologies is also increasingly being studied. For example, based on a study conducted on a group of companies in Slovenia, it is clearly stated that the implementation of AI tools allows for a faster increase in profitability and innovation by providing accurate data and information, facilitating quick and informed decision-making, which ultimately leads to successful results in which products or services meet customer expectations (Rozman et al., 2023, 32-33). Similar conclusions were also drawn from the analysis described in the work of Noronha et al. (2023). However, not all studies confirm the positive correlation of the use of artificial intelligence and agility. As an example, we can mention the analysis conducted by Romanian researchers, which leads them to the conclusion that the use of this advanced technology can have a significantly negative impact on the agility of the internal processes of the organization and agility in relation to changes in the external environment (Stefan et al., 2024, 414).

In summary of the above literature review, it can be stated that scholars recognize the relationships between the interactions among organizational members, its agility, and innovation. At the same time, there is a lack of research that provides an answer to the question of whether organizational agility should be viewed not only as a direct determinant of innovation but also as a crucial element determining how the type of interactions between employees influences the ability to create and implement new solutions.

3. METHODOLOGY AND MATERIALS

Based on the literature on personal relationships within organizations, its agility, and innovation, a model of the interrelationships between these components was developed (Fig. 1). The model includes the following research hypotheses:

- Hypothesis 1 [H1]: There is dependence between the relationships among employees within the organization and its innovation (A1).
- Hypothesis 2 [H2]: The more agile the organization, the more innovative it is (A2).
- Hypothesis 3 [H3]: Dependence between relationships and innovation is mediated by agility (A3xA2).

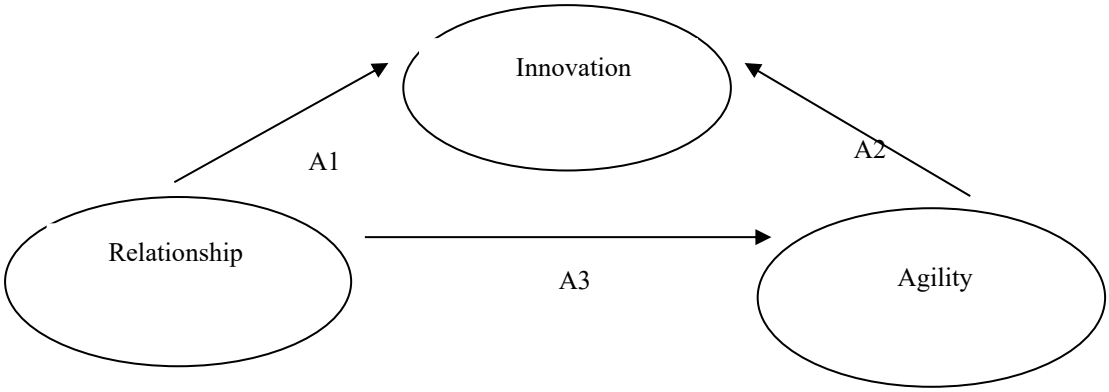


Figure 1. Model of the relationships between internal organizational relationships, agility, and innovation
Source: own elaboration.

To achieve the research objective of verifying the hypotheses and thus checking whether the proposed model of interdependencies is correct and corresponds to the collected data, the diagnostic survey method and the structural equation modeling (SEM) method in the form of GSCA (Generalized Structured Component Analysis) were used. GSCA represents a component-based approach to structural equation modeling (SEM), which defines a latent variable as a component or weighted composite of indicators. The GSCA method also allows users to obtain general and local model fit measures, parameter estimates with bootstrapped standard errors and confidence intervals, as well as total and indirect effects of latent variables and indicators.

The measurement data were obtained through a survey conducted in 2023 via one of the national research panels and were part of the international project "Teal Organizations in Economy 4.0" carried out in Poland, England, Hungary, Ukraine, the Czech Republic, Spain, Georgia, and the USA (Rzepka, 2023). A survey was conducted with 254 individuals representing the management staff of enterprises in Poland. The tool used was a proprietary questionnaire, distributed according to the standards of the CAWI technique, and consisting of thematic blocks related to the leader in the organization, innovations and technologies used in the company, prevailing relationships, agility and creativity, social capital, knowledge and information, trust, and organizational structure and culture. The questionnaire consisted of 5 parts, each containing 5-7 closed-ended questions focusing on various topics. The study was conducted in accordance with the recommendations developed by OECD-DAL. For the purposes of inference in this paper, 6 questions from the following thematic blocks were used: innovations and technologies (2 questions), relationships (2 questions), agility and creativity (2 questions). This selection allowed for the examination of the interrelationships between three aspects of an organization's functioning. It provided insight into the dependence of an organization's innovation level on both employee attitudes, particularly openness to mutual collaboration and partnership in pursuit of goals, as

well as on agile behaviours within the organization, based on creativity. The full list of questions (formulated as declarative sentences) along with their assignment to the components of the analyzed model is presented in Table 1.

Table 1. Components and questions (indicators) used in the study

Component	Indicator	
	Symbol	**Question**
Relationships	REL1	We all strive to achieve a common goal
	REL2	Competition has been replaced in our company by partnership and cooperation.
Component	**Indicator**	
	Symbol	**Question**
Agility	AGIL1	In our company, employees quickly adapt to the requirements of new equipment.
	AGIL2	In our company, a lot of space is left for creative and innovative activities.
Innovation	INNO1	We strive to ensure that all processes conducted in our company are characterized by innovation.
	INNO2	I have the opportunity to continue my education and development at work.

Source: own elaboration.

The entities represented by the respondents show significant diversity in terms of the type of their business activities, their geographical scope, size, and industries, as presented in Table 2.

Table 2. Characteristics of the structure of enterprises represented by the respondents

Type of activity (%)		**geographical scope (%)**		**Number of employees (%)**		**Industry (%)**	
commercial	16.6	local	9.4	0-9	3.3	aviaton	5.3
manufacturing	28.0	Regional	27.3	10-49	55.1	Fuel industry	4.0
service	55.4	domestic	22.0	50-249	16.6	Automotive industry	3.8
		international	41.3	250-999	16.6	IT	11.4
				1000 and more	8.4	Education	3.8
						Research and Development (R&D)	4.0
						Gastronomy	5.2
						Construction industry	5.3
						Trade	3.4
						Banking sector	10.0

Source: own elaboration.

To verify the correctness of the proposed dependency model, the structural equation modeling (SEM) method in the form of GSCA was used. The use of this method is justified when examining the relationships between different constructs in order to detect mutual dependencies. This type of modeling is also used in the case of analyses including variables such as: innovation, agility and interpersonal relations (e.g.: Homayoun et al., 2024; Arsawan et al., 2022; Dabic et al., 2021). In particular, the following elements were used to validate the data and the model:

- model fit indices such as: FIT, AFIT, FITs, FITm, GFI, SRMR, OPE, OPEs, OPEm,

- estimated component weights and component loadings of indicators on the component, bootstrap standard errors (SE), and bootstrap 95% confidence intervals to determine the statistical significance of the model,
- path coefficient estimates and their bootstrap standard errors (SE), as well as 95% confidence intervals to verify the statistical significance of the mentioned coefficients at the 5% confidence level,
- correlation coefficients between the components of the model,
- quality indicators of the model constructs: PVE, Cronbach's alpha, Rho (Dillon-Goldstein's rho), Dimensionality to determine whether the model correctly reflects the assumed hypothesis connections and to check the reliability level of the model,
- Fornell-Larcker criterion to assess discriminant validity in the model,
- R2 values concerning both indicators in the measurement model (to identify the level of model fit to the measurement data) and components of the structural model (to determine what portion of the variability of a given component is explained by other components in the model,
- variance inflation factor (VIF), whose value helps identify whether the independent variables in the model are highly correlated (multicollinearity),
- The F-squared value for each predictive component to determine their mutual influence on each other,
- Mean values of unscaled components on the same scales as their original indicators to determine the most frequently chosen responses,
- correlation coefficients between all indicators to determine the strength of their mutual relationship, as well as between indicators and components (correlations of each indicator with all components).

4. RESULTS

The first stage of model verification was the analysis of indicators showing the degree of its fit to empirical data. The study used fit indices such as: FIT, AFIT, FITs, FITm, GFI, SRMR, OPE, OPEs, OPEm. Table 3 presents their values for the examined model. The FIT parameter indicates the total variance of all variables (indicators and components) explained by a specific model specification and, in the case of the constructed model, reflects 64.7% of the variables. AFIT (Adjusted FIT) is similar to FIT but takes into account the complexity of the model. Like the adjusted R-square in linear regression, AFIT cannot be interpreted in the same way as FIT (i.e., the percentage of total explained variance). Instead, it can only be used to compare competing models. Among the competing models, the one with the highest AFIT value can be selected. FITs indicates the total variance of all components explained by a specific structural model specification. FITs values range from 0 to 1. The higher this value, the greater the variance in the components accounted for by the specified structural model. For the analyzed model, this parameter is equal to 0.336. FITm indicates the total variance of all indicators explained by a specific measurement model specification. FITm values range from 0 to 1. The higher this value, the greater the variance of indicators accounted for by the specified measurement model. In the analyzed model, it is 0.802. The GFI (goodness-of-fit index) and SRMR (standardized root mean squared residual) measures are proportional to the difference between sample covariances and covariances reproduced by GSCA parameter estimates. A recent study suggested the following cutoff criteria for GFI and SRMR in GSCA (Cho et al., 2020):

- When the sample size = 100, GFI ≥ 0.89 and SRMR ≤ 0.09 indicate acceptable fit. Although both indices can be used to assess model fit, using SRMR with the above cutoff value may be better than using GFI with the suggested cutoff value. Additionally, if SRMR ≤ 0.09, then a GFI cutoff value ≥ 0.85 may still indicate acceptable fit.
- When the sample size > 100, GFI ≥ 0.93 or SRMR ≤ 0.08 indicates acceptable fit. In this case, there is no preference for one index over the other or for using a combination of indices instead of using them separately. The suggested cutoff value for each index can be used independently to assess model fit.

In the case of the constructed model, the GFI index equals 0.996, while the SRMR is 0.038, indicating a good model fit.

Table 3. Model fit indices

FIT	AFIT	FITs	FITm	GFI	SRMR	OPE	OPEs	OPEm
0.647	0.643	0.336	0.802	0.996	0.038	0.357	0.674	0.198

Source: own elaboration.

Table 4 presents the estimated component weights and component loadings of indicators on the component (Estimates). It also shows the bootstrap standard errors (SE) and bootstrap 95% confidence intervals (95% CI) of the weight and loading estimates. The 95% confidence intervals can be used to test the significance of the estimate (i.e., the estimate can be considered statistically significant at the 0.05 level if its confidence interval does not include 0). When a component is specified as a canonical component, the loadings of its indicators will not be shown. In the case of the constructed model, all model parameters are statistically significant at the 0.05 level, and the 95% CI intervals do not contain the value 0, indicating a good model fit.

Table 4. Component Weights and Loadings for the Examined Model

	Estimate	SE	95%CI	
		Weights		
REL1	0.555	0.03	0.504	0.62
REL2	0.557	0.027	0.501	0.608
AGIL1	0.445	0.031	0.387	0.505
AGIL2	0.668	0.039	0.597	0.738
INNO1	0.565	0.028	0.504	0.619
INNO2	0.549	0.028	0.504	0.601
		Loadings		
REL1	0.899	0.017	0.863	0.928
REL2	0.9	0.02	0.859	0.932
AGIL1	0.844	0.037	0.772	0.9
AGIL2	0.934	0.01	0.917	0.952
INNO1	0.901	0.017	0.865	0.929
INNO2	0.895	0.018	0.852	0.927

Source: own elaboration.

In the next table (Table 5), estimates of path coefficients (Estimate) and their bootstrap standard errors (SE) as well as 95% confidence intervals (95% CI) are included. None of the confidence intervals contain 0, so the values of the path coefficients are statistically significant at the 5% confidence level.

Table 5. Path Coefficients

	Estimate	SE	95%CI	
Relationship→Agility	0.676	0.037	0.6	0.742
Relationship→Innovation	0.33	0.063	0.225	0.467
Agility→Innovation	0.477	0.07	0.322	0.594

Source: own elaboration.

The correlation coefficients between the individual components of the model indicate a strong relationship (Table 6). Values in the range of 0.5 – 0.7 indicate a strong correlation, while values in the range of 0.7 – 1 indicate a very strong correlation. The strongest correlation is between Agility and

Innovation, while there is a strong relationship between Relationships and Agility, as well as Relationships and Innovation.

Table 6. Correlation Coefficients of Components

	Relationship	**Agility**	**Innovation**
Relationship	1.0	0.676	0.653
Agility	0.676	1.0	0.701
Innovation	0.653	0.701	1.0

Source: own elaboration.

Table 7 provides information on the quality of the model's construction. It includes four indicators:

- PVE (Proportion of Variance Explained): The average amount of variance explained by the indicators through their corresponding components. A value above 70% may indicate unidimensionality.
- Alpha (Cronbach's alpha): A measure of internal reliability for the sum of indicators, assuming equal covariances.
- Rho (Dillon-Goldstein's rho): Composite reliability, more appropriate than alpha in the context of GSCA.
- Dimensionality: The number of eigenvalues greater than 1 for the set of indicators.

The value of Cronbach's alpha, which is a measure of internal reliability, should be at least 0.7 to indicate an acceptable level of reliability. Higher values, such as above 0.8, suggest good reliability, and values above 0.9 indicate very high reliability. However, it is worth noting that a value too high (close to 1) may indicate redundancy of indicators, meaning they measure very similar aspects of the same construct. The value of Dillon-Goldstein's rho (also known as composite reliability) should be at least 0.7 to indicate an acceptable level of model reliability. Values above 0.8 are considered good, and values above 0.9 are very high. Compared to Cronbach's alpha, Rho is more appropriate for assessing reliability in the context of GSCA, as it does not assume equal covariances between indicators. The Dimensionality parameter refers to the number of eigenvalues greater than 1 for the set of indicators assigned to a given component. If Dimensionality is 1, it suggests that the indicators are unidimensional, meaning they measure one common factor. When this value exceeds 1, it suggests the possibility of more than one factor, which may require considering a more complex model, such as with a greater number of components for the given set of indicators. From the analysis of the data values in the table, we can conclude that the model's indicators are unidimensional (PVE > 70% and Dimensionality = 1), thus the model correctly reflects the assumed hypothesis connections. Additionally, Dillon-Goldstein's rho greater than 0.8 indicates that the model's reliability level is good.

Table 7. Model Construction Quality Indicators

	Relationship	**Agility**	**Innovation**
PVE	0.809	0.792	0.806
Alpha	0.764	0.747	0.759
Rho	0.895	0.884	0.892
Dimensionality	1.0	1.0	1.0

Source: own elaboration.

The values of the Fornell-Larcker criterion are used to assess discriminant reliability in structural models. According to the Fornell-Larcker criterion, the average variance extracted (AVE) for each construct should be greater than its highest squared correlation with any other construct in the model. This means that constructs should explain the variance of their indicators better than they share variance with other constructs, ensuring that constructs are discriminant, i.e., different from each other. Discriminant reliability in structural models refers to the model's ability to distinguish between different constructs (latent variables). This means that each construct in the model should explain the variance of its indicators better than the variance of indicators of other constructs. If the model has good discriminant reliability, it means that the constructs are clearly different from each other and do not overlap in terms

of what they measure. From the analysis of the values in Table 8, we conclude that each construct in the model explains the variance of its indicators better, indicating proper discriminant reliability.

Table 8. Fornell-Larcker Criterion Values

	Relationship	**Agility**	**Innovation**
Relationship	0.9		
Agility	0.676	0.89	
Innovation	0.653	0.701	0.898

Source: own elaboration.

To identify the level of fit of the model to the measurement data, R-squared (R^2) coefficients were used for the indicators in the measurement model. Table 9 presents the amount of variance of each indicator explained by its assigned component in the measurement model. R^2 values indicate how well the component explains the given indicator. A higher R^2 value (close to 1) means that a larger portion of the indicator's variance is explained by the component, suggesting a stronger relationship between the indicator and the component. These values help assess the quality of fit of the measurement model to the data. When a canonical component is chosen for a set of indicators, R^2 values for the indicators are not provided. R^2 values should be higher than 0.7. Analyzing the values from the table, we can say that the model is well-fitted to the measurement data.

Table 9. R-squared Values

INNO1	**INNO2**	**REL1**	**REL2**	**AGIL1**	**AGIL2**
0.811	0.8	0.809	0.81	0,712	0.872

Source: own elaboration.

Additionally, R^2 values were determined for individual components in the structural model. The R^2 coefficient in this case indicates what portion of the variability of a given component is explained by other components in the model. $R^2 > 0.90$ for constructs measuring perceptions, attitudes, or intentions indicates potential misfit. In the considered model, the R^2 value for the Agility component is 0.457, while for Innovation it is 0.55. This means that both constructs are explained by approximately 46% and 55%, respectively, which is correct. At the same time, the canonical component (no R^2 value) is the Relationships component.

The Variance Inflation Factor (VIF) helps identify whether independent variables in the model are highly correlated (multicollinearity), which can lead to less reliable estimates of path coefficients. VIF values below 3 suggest that multicollinearity is not a serious problem. Higher values may indicate the need for further analysis or model modification, while low values indicate good model quality, where independent variables are not excessively correlated. Interpreting the values from Table 10, it can be concluded that multicollinearity does not occur, and there is no need for changes in the model.

Table 10. Variance Inflation Factor (VIF)

	Relationship	**Agility**	**Innovation**
Relationship	0	0	1.841
Agility	0	0	1.841
Innovation	0	0	0

Source: own elaboration.

Table 11 presents the values of the f^2 indicator, which is a measure of effect size for each predictor in the structural model. It indicates how much impact a given predictor has on the dependent variable. According to general guidelines, f^2 values of 0.02, 0.15, and 0.35 can be considered small, medium, and large effect sizes, respectively (Cohen, 1988). From the analysis of the table, it can be concluded that

the predictor Agility has a very large impact on Relationships, while the predictor Innovation has a medium impact on Relationships and Agility.

Table 11. f^2 Indicator Values for the Model

	Relationship	Agility	Innovation
Relationship		0.841	0.123
Agility			0.295
Innovation			

Source: own elaboration.

The average values of unscaled components and their variances were also analyzed (Table 12). Considering that the responses to all questions forming the basis for the verified model were presented on a five-point Likert scale and rounding the values listed in the summary, it should be stated that the most frequently given response for each of the three components was 4 – rather agree.

Table 12. Average Values of Unscaled Components and Their Variances

	Relationship	Agility	Innovation
Average values	4.015	3.851	3.699
Variations	0.598	0.656	0.785

Source: own elaboration.

Table 13 contains the correlation values between individual indicators of the model (lower diagonal) and the differences between sample correlations and model correlations (upper diagonal). The correlation values indicate that all indicators are either strongly (value range 0.5 – 1.0) or moderately related (value range 0.3 – 0.5). The data show that the strongest relationship is between AGIL2 and INNO1 and INNO2, which are indicators reflecting agility and innovation, respectively. Additionally, significant mutual relationships are shown between indicators of agility and employee relations (AGIL2 and REL1 and REL2). All indicators are strongly correlated with all components (Table 14).

Table 13. Correlations Between Indicators and Residual Correlations

	INNO1	INNO2	REL1	REL2	AGIL1	AGIL2
INNO1	0.0	-0.194	-0.007	0.007	0.012	-0.008
INNO2	0.611	0.0	0.007	-0.007	-0.013	0.008
REL1	0.558	0.54	0.0	-0.191	0.028	-0.019
REL2	0.528	0.482	0.618	0.0	-0.028	0.019
AGIL1	0.454	0.431	0.497	0.469	0.0	-0.192
AGIL2	0.637	0.655	0.554	0.622	0.596	0.0

Source: own elaboration.

Table 14. Correlations Between Indicators and Components

	Relationship	Agility	Innovation
INNO1	0.604	0.628	0.901
INNO2	0.568	0.63	0.895
REL1	0.899	0.591	0.612
REL2	0.9	0.625	0.563
AGIL1	0.537	0.844	0.493
AGIL2	0.654	0.934	0.719

Source: own elaboration.

5. DISCUSSION AND CONCLUSION

Based on the research results discussed above, it can be concluded that the proposed model of interdependencies between employee relationships, agility, and innovation within the organization has been positively verified. Consequently, all three previously formulated research hypotheses have been confirmed as true.

The positive verification of hypothesis [H1] means that organizations where types of personal relationships based on cooperation and common goal pursuit prevail also have greater capabilities in introducing innovative solutions. This can be linked to the community of behaviours, values, and norms, as well as acceptance of changes, which some authors discuss in the context of improving operational efficiency and innovation (e.g., Rodriguez-Gonzalez et al., 2023; Naveed et al., 2022; Pedraza-Rodriguez et al., 2023; Domańska-Szaruga& Knap-Stefaniuk, 2022). Proper employee selection can also play an important role here. When companies use creative abilities and innovative traits as hiring and selection criteria, their employees are likely to generate diversity of ideas and engage in more innovative behaviours (Maier et al., 2023, 646). On the other hand, enterprises should develop performance management plans with their employees, taking into account their goals and actual needs (Jia, 2023, 5). Innovation can also come from the relationships of new firm founders with their parent companies. Such a collaborative network can be an important source of information. If venture founders do not have connections with innovative co-inventors, they may do well by focusing more actively on forming alliances or hiring technology personnel from other firms (Boeker et al., 2019).

Regarding agility and the role it can play in the process of creating and transferring new solutions (which hypothesis [H2] addressed), the conclusions from the analysis support the claims of researchers who emphasize that the ability of organization members to respond quickly and flexibly to changes positively impacts the level of innovation (e.g., Sjödin et al., 2020; Alamsjah, 2022). Innovation is characterized by uncertainty. The increasing dynamism of markets and growing customer demands, as well as the demand for personalized products, are challenging organizations to shorter innovation cycles. Agile methods and processes can serve as a way to deal with these uncertainties in the context of the product development process (Schock et al. 2023, 431). A fundamental characteristic of agile workers is the ability to transfer abstract ideas and technologies to a concrete product, and this is something that, together with openness to new technologies, appears to drive innovation (Brand et al., 2019, 181). However, on the other hand, these conclusions somewhat contradict the observations of authors such as Annosi et al. (2022) and Lill & Wald (2021), who see a ‘dark side’ of agility. The study also confirmed the strong relationship between being creative and the ability to create and implement innovative solutions, which is mentioned in several previously cited publications (Cropley et al., 2011; Meutia et al., 2018; Rzepka & Sabat, 2022; Roy & Mohapatra, 2023; Ek Styvén et al., 2022).

The study also confirmed hypothesis [H3], which posits the mediating effect of agility on the relationship between employee relationships and innovation. The openness of organizational members to interactions with colleagues can facilitate more effective responses in crisis situations or those requiring adaptation, thereby enhancing organizational agility. This agility fosters the development of informal or even familial bonds, whose importance for organizations is increasingly recognized in the literature. At the same time, these relationships can positively impact creativity, which is crucial for innovation. As noted by Rzepka & Sabat (2022), the willingness to implement new, creative solutions determines the effectiveness of utilizing acquired knowledge, which is of primary importance for introducing innovative practices. On the other hand, a turbulent environment can initiate new, previously non-existent types of internal relationships that play a critical role in innovation processes (James et al., 2022). Strong internal relationships may stem from knowledge-based agility and managerial decisions regarding whether to act on new opportunities. As Hutton et al. (2024) point out, organizations can develop their ability to respond to various situations (agility) through personnel rotation, which enhances the skills of selected individuals and contributes to the creation of open innovations.

The positive verification of the hypotheses adopted in the study leads to the conclusion that both interpersonal relationships and agility, by influencing innovation, also impact the possibilities of implementing intelligent management methods in the organization. As mentioned earlier, many researchers point to the close interdependence between the use of AI tools in management processes and the generation and implementation of new solutions. However, it is also true that the processes of adapting modern digital technologies in an innovative environment are still not fully understood, as is

the role of the human factor in them (Haefner et al., 2021). As noted by Gama &Magistretti (2023) based on their literature review, the relationships between AI, innovation management, and capabilities are characterized by a high degree of complexity, and as such, they will require further, in-depth analyses in the coming years.

Continuing research on the issues of interest in this study, it is reasonable to include an additional research thread in the form of leadership. Many authors recognize that leadership styles significantly impact the above-discussed areas of organizational functioning. For example, Gren & Ralph (2022) and Reunamäki& Fey (2022) believe that leaders in organizations can negatively affect the agile thinking and behaviours of the teams they lead if they themselves, instead of developing agility, represent more traditional leadership styles based on supervision and control. A leader who wants to develop and empower others to reach their highest potential should possess leadership qualities such as listening, empathy, awareness, persuasion, conceptualization, foresight, commitment to the growth of people, stewardship, and building community (Knoll, 2019). It is worth noting that this empowerment is also of great importance for innovation and creativity.

6. PRACTICAL IMPLICATIONS

The conducted study indicates that to enhance the innovativeness of an organization, management should ensure a proper atmosphere within the internal environment. This particularly involves abandoning behaviour models that promote competition in favor of those that ensure cooperation and focus on jointly chosen and subsequently set goals. At the same time, members of the organization should be encouraged to be more independent by creating a broader scope for taking grassroots initiatives in response to ongoing changes in the organization's environment.

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METHODOLOGICAL FRAMEWORK FOR TEACHING HUMAN RESOURCE MANAGEMENT IN GASTRONOMY: A CRITICAL ANALYSIS OF PROJECT ASSUMPTIONS AND OUTCOME

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ABSTRACT

Purpose: *This article attempts to critically analyse the solutions, methods and tools used in the project entitled 'Methodology of teaching human resource management to current and future catering employees' for the development of students and employees in the field of human resource management.*

Need for the study: *Drawing attention to employee development, and more specifically to the methods and tools used to teach human resource management issues, is particularly important given the target group identified in the project. The absence of human resource management in curricula seems to be a cognitive gap.*

Methodology: *The critical analysis used in the project concerns two methods. The first is the project itself, and the second is a set of teaching methods applied directly to employee development.*

Findings: *The results of the analysis can be used by employee development specialists.*

Practical Implications: The results of the analysis may be useful in the selection and use of methods and tools in the employee development process.

Keywords: Human Resources Management, Gastronomy, Project, employee development

Jel codes: M10, B 40, O3

1. INTRODUCTION

The human resource management process provides a basis for various research and design activities undertaken by both theorists and practitioners. The same applies to the individual stages of this process. Regardless of whether one considers human resource planning, employee motivation, periodic employee evaluation, or the process of employee departure, these issues are of great analytical interest to specialists in various fields. The same is true for employee development. Improving professional qualifications is a controversial issue for both employers and employees. The former – employees – generally expect their employers to systematically improve their professional qualifications, while the

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latter are aware of the need to invest in their human resources, but tend to limit themselves to mandatory health and safety training and induction training, which is compulsory for all new employees.

They usually include only general and on-the-job training. Periodic training can also be mentioned here. These training courses are necessary to refresh knowledge and must be repeated at specific intervals, which depend on the position. Therefore, there is a certain misunderstanding between employers and employees. In Poland, the law imposes an obligation on employers to improve qualifications, and on employees to improve their qualifications with the employer's consent, which entitles them to certain privileges. However, this is not the only area of discourse in the field of employee development; other issues concern the most effective training methods and tools, as well as ways of applying the knowledge gained in training during professional work.

The European Community has certainly enriched the issue of improving qualifications by creating opportunities to obtain funding for training, postgraduate studies and other forms of improving qualifications. These funds can be obtained through regional programmes or the Erasmus Plus programme.

It was this programme that was used to create the project entitled ‘Methodology of teaching human resource management for current and future catering employees’. The authors of this project undertook the task of creating a curriculum, developing lesson plans and preparing criteria for assessing progress in the acquisition of knowledge in the field of human resource management. The project is aimed at students and graduates of catering schools in three countries: Poland, Germany and Italy.

The aim of the article is to critically analyse primarily the human resource management issues that have been introduced into the curriculum. It then focuses on the methods and tools developed to transfer knowledge. Finally, attention is drawn to the very concept of the project's assumptions from the point of view of the employer-employee relationship, and it should also be added here that the student may undergo professional training. First, a review of the literature on human resource management, employee development methods and tools, as well as the structure of the project itself, will be conducted. In the next part, attention will be focused on analysing the solutions proposed in the project in order to critically consider the possibilities of achieving success in the project, but above all in the process of developing employees in the catering industry.

2. LITERATURE REVIEW

In order to properly grasp the essence of the article and thoroughly analyse the solutions, methods and tools for the development of students and employees in the field of human resource management used in the project ‘Methodology of teaching human resource management for current and future catering employees’, it is necessary to begin with a review of the literature. The main issue, a kind of guiding principle of the project, is human resource management, which is a complex issue. Human resource management is a process consisting of the stages of planning, recruitment, selection, training, motivation and retention of employees, aimed at achieving the strategic goals of the company (Armstrong, 2014). Similarly, S. Snell and G. Bohlander draw attention to human resource management as a process, which they consider to be strategic and operational activities aimed at the effective management of people in an organisation, including recruitment, training, assessment and motivation of employees (Snell, Bohlander, 2013). Perhaps the composition of the process in question is shown slightly differently, but nevertheless, it can be seen that it constitutes a complex sequence of activities. Edwin Flippo takes a similar view, defining human resource management as ‘planning, organising, directing, and controlling the supply, development, compensation, integration, retention, and distribution of human resources to achieve individual, organisational, and societal goals’ (Flippo, 1984). J. Stoner, R. Freeman and D. Gilbert also deal with the same concept of human resource management as a process. For them, human resource management is an organisational function that aims to recruit and retain suitable employees and create conditions conducive to their effective work (Stoner, Freeman, Gilbert, 2001). For H. Król and A. Ludwiczyński, human resource management is a process that includes activities related to planning, organising, directing and controlling employment in an organisation (Król, Ludwiczyński, 2006). It is worth mentioning other researchers in the field of human resource management, including G. Dessler, who claims that, Human Resource Management is the process of acquiring, training, appraising, and compensating employees, and attending to their labor relations, health and safety, and fairness concerns (Dessler, 2017), D. Urlich describes human resource

management as follows: human resource management is not just about managing people, it is a process that helps organizations deliver value through people by aligning HR practices with business strategy (Urlich, 1997). John Storey writes, that human resource management is a distinctive approach to employment management which seeks to achieve competitive advantage through the strategic deployment of a highly committed and capable workforce, using an array of cultural, structural and personnel techniques (Storey, 1995), a P. Boxall and J. Purcell say that human resource management includes all those activities associated with the management of work and people in organisations. It is a process that shapes how work and people are managed to serve organisational goals (Boxall, Purcell, 2016). The authors cited above view human resource management as a process of shaping work and relationships with people in order to implement the organisation's strategy. J. Storey, quoted above, sees the strategic and multidimensional nature of human resource management, which encompasses organisational culture, structure and specific people management techniques. Dessler defines human resource management as the process of managing the employee life cycle – from recruitment to departure – and as a function that supports fairness and good working conditions. D. Ulrich views human resource management as a strategic process that integrates personnel practices with business objectives. He points out that human resource management must deliver organisational value. In conclusion, it is worth quoting M. Armstrong, who presents human resource management as a strategic process of the company (Kozłowski, 2018) and an integrated one, covering all activities related to employees – from recruitment, through development, to assessment and motivation. Therefore, ultimately referring to M. Armstrong, it should be pointed out that the human resource management process consists of the following seven elements: employment planning, recruitment and selection, training and development, performance appraisal, motivation and remuneration, employee relations management, and compliance with regulations and ethics. All of the stages mentioned above focus on human resources, so it is worth taking a moment to consider this concept – human resources. First and foremost, it should be emphasised that people are not resources, but rather possess resources at their disposal. These resources are the characteristics and qualities embodied in them, which enable them to perform various roles within an organisation. The most important elements of human resources include: knowledge, abilities, skills, health, attitudes and values, and motivation. Additionally, it should be remembered that the owner of human resources is the employee, and it is they who ultimately decide on the degree of commitment of these resources during work (Pocztowski, 2003). Other authors have a similar view of human resources. For example, W. F. Cascio describes human resources as human capital – the unique characteristics of employees, such as knowledge, skills and learning ability, which contribute to organisational value (Cascio, 2021). He emphasises the link between human resource management and efficiency, quality of life at work and profitability. A contemporary, systemic view of human resource management as an investment rather than a cost. This approach can be found in Raymond A. Noe (Raymond A. Noe et al., 2021), J. Bratton & J. Gold (Batton, Gold, 2017).

A review of selected definitions of human resource management and a clarification of the meaning of resources reveals two important directions. The first treats people as one of the key resources of an organisation, alongside capital, technology and structure. It also emphasises that human resource management is a deliberate effort to maximise their contribution (Daft, 2018). The second shows the strategic importance of the human resource management process. Therefore, human resource management should not be overlooked in the context of an organisation's objectives. n the context of this article, it should be emphasised that each of the authors cited here highlights employee development as one of the elements of human resource management. Development is related to employee competencies. It can be assumed that competence is the ability to perform specific activities and tasks (actions that each person can undertake and perform appropriately, as well as roles that they can play), as well as a set of characteristics and behaviours necessary to perform a specific job (Whiddett, Hollyforde, 2003). It is worth noting that competencies are not static (Górska-Rożej, 2014) and are subject to change under the influence of various factors (Załoga, 2019). Assuming that competencies are knowledge, skills and attitudes (Filipowicz, 2004), it is these three areas that need to be influenced. Factors influencing changes in employees' competencies cause their development. One element of this development is improving qualifications. Examples of methods for improving employee qualifications, and thus employee development (Borkowska, 2005), include lectures, training courses, postgraduate studies, conferences, seminars, case studies, assigning tasks, participation in project work, modelling, mentoring, coaching, gamification, industry meetings, e-learning and LMS (Learning Management

System) platforms. Other methods can be found elsewhere, including lectures, reading, the use of audiovisual aids, graphic presentations, group discussions, educational games, role-playing, drama, simulation, practical activities, case studies, projects, and teaching others.

Training is considered to be the most popular form of development (Król, Ludwiczyński, 2007). H. Król defines training as a set of activities (usually organised outside school) concerning employees of an organisation and (to a lesser extent) unemployed persons, providing an opportunity to broaden and deepen specific elements of individual human capital, as well as equipping it with new elements useful now or in the future (Król, Ludwiczyński, 2007). Z. Pawlaka, on the other hand, clarifies the concept of vocational training. He defines it as preparation for a specific job, in a specific position and in a specific company, which is mainly carried out in extracurricular forms and covers people who are working and who are candidates for a specific position (Król, Ludwiczyński, 2007). It must be admitted that training provides many benefits for the trainee, but also for the organisation in which they work. Training can contribute to a change in thinking, attitude and behaviour. In addition, training allows pioneering concepts and assumptions to be analysed and tested in a safe manner, without the risk of failure, enabling the exchange of experiences between participants and, consequently, promoting the sharing of knowledge, which is used by learning organisations. They provide new, more effective tools to achieve set goals, allow for greater independence in planning and management, and give participants the opportunity to compare new content with their own experiences, which can be a motivating factor for employees if participation in training is presented as an investment in the individual. They help to integrate and build cooperation within the company, and the interactive methods used during the training contribute to greater involvement of participants and identification with the conclusions or results achieved (Sołtysińska, Żywiec-Dąbrowska, 2001). Training guarantees that organisations and individuals move from the so-called current state to the desired state. This is accompanied by a qualitative change. The current state is the situation in which we currently find ourselves. Everyone has their goals, organisations too – this is what is called the desired state. By its very nature, the desired state must be better and more beneficial than the current state. Training is one of the most effective ways to develop an organisation and improve the competence of the entire company by investing in employees (Lanz, 2004).

It can be assumed that there are many methods of employee development and improving qualifications, but the literature emphasises that motivation is an important factor in development, improving qualifications and transferring knowledge. According to M.S. Knowles, the main motivation for adults is internal motivation. External punishments and rewards are of little significance. (Knowles, 1972). In addition, research on motivation clearly indicates that it can be stimulated by the teacher. As part of the content they teach, they can create conditions in which trainees are ready to improve their individual skills and maintain them at the highest possible level. This does not mean, however, that external rewards (e.g. a pay rise or promotion) are irrelevant. On the contrary, they are extremely important motivators. Nevertheless, a stronger motivating factor is certainly the satisfaction of a person's internal needs, such as the desire to achieve greater satisfaction from their work, increasing self-esteem, quality of life, etc. M.S. Knwles believes that motivation to learn depends on four factors (Knowles, Holton III and Swanson, 2009):

- success – adults want to be successful in learning,
- will – adults want to feel that they have an influence on their learning,
- value – adults want to be convinced that they are learning something valuable,
- enjoyment – adults want to enjoy learning.

It is therefore important to obtain these four elements in the employee development process in order to make the learning process more effective.

The literature on the subject emphasises that effective human resource management in the catering industry has a direct impact on the quality of services provided, customer satisfaction and the competitiveness of businesses (Nowak, 2019). The difficulties in recruiting qualified staff and the need to continuously improve employee qualifications in the face of changing culinary and technological trends are not without significance (Jankowska, 2020). In turn, scientific literature increasingly emphasises the importance of education and training for the development of catering staff competencies. For example, research conducted by Kowalski showed that training programmes aimed at students and graduates of catering schools significantly improve their preparation for work in the industry and increase their motivation and willingness to work.

At the end of the literature review, attention should be paid to the term "project", as it is the project that provides the framework for the measures taken to improve human resource management skills, which will be the subject of analysis. Specialists define a project as a temporary endeavour aimed at creating a unique product, service or result, carried out in accordance with specific objectives, a schedule and a budget, using available resources and management methods (PMI, 2021). The definition quoted above focuses on the results of a project. For K. Schwalbe, a project is a temporary endeavour undertaken to create a unique product or service, with clearly defined objectives and constraints (Schwalbe, 2015). H. Kerzner, on the other hand, proposes a different approach, arguing that a project is an organised set of activities aimed at achieving specific results within specific time, financial and resource constraints (Kerzner, 2013). The available time, financial and resource constraints provide a certain framework that guides the project in a specific way. This allows us to focus on the essence of the project. Adding to this the thesis that a project is a unique undertaking that requires planning, coordination and control to achieve its objectives within a specified time and budget (Meredith & Mantel, 2014), it therefore has a specific procedure for action. It can be assumed that this is a process with a specific structure that ensures a certain degree of success based on the achievement of the desired goal. This is all the more important from the point of view of the catering industry. The specific nature of human resource management in the catering industry is characterised by unique challenges and needs resulting from the specific nature of the sector. First and foremost, this industry is characterised by high seasonality of employment, which requires flexibility in employment planning and a quick response to changing needs (Kozłowski, 2018).

The combination of human resource management issues with the catering industry and the recognition of the need to support current and future managers working in catering organisations was the impetus for the project.

3. METHODOLOGY

3.1. Participants

The project 'Methodology of teaching human resource management for current and future catering employees' was addressed to a wide range of people associated with the catering industry. The participants were mainly students and graduates of catering courses and further training courses, both those already working as chefs and those just planning to take up work in this field. The project was also joined by students and graduates from Poland, Italy and Germany, where the project was implemented. In addition, Ukrainian citizens were invited to participate in the project. This was due to the geopolitical situation. Many Ukrainian citizens reside in Poland. They study and work in Polish schools and workplaces. In order not to discriminate against anyone, they were also invited to participate in the project.

Young chefs graduating from catering schools and courses have high professional qualifications, but are often not prepared to lead a task force. On the other hand, vocational school teachers, masters and trainers in chambers and craft guilds, as well as trainers in extracurricular institutions, do not have sufficient tools, programmes or modern – including digital – methods to support teaching in the field of human resource managementThe project also indirectly covered vocational schools offering catering courses, institutions and entrepreneurs providing dual education, chambers of crafts and training institutions operating outside the school system. All these entities struggle with a lack of knowledge, teaching materials and suitably trained staff in the area of personnel management education.

More than 200 people took part in the project, including all target groups, experts and multipliers.

3.2. Research Protocol and Stimuli

The project was implemented in response to specific needs that had emerged during earlier initiatives, such as the organisation of internships and work placements for catering school students. It was then that it was observed that young people, despite their very good professional preparation, have serious deficits in soft skills – especially those related to teamwork, effective communication, problem solving and dealing with misunderstandings and conflict. It can be seen that the characteristics of Generation Z in the labour market are also reflected among students and young employees in the catering industry (Gajda, 2017).

During conversations with chefs, it also turned out that the recruitment process for catering teams was often random. New employees were sometimes hired on the basis of a short, superficial interview, without analysing their professional CV or actually checking their skills and competences. Many chefs, despite being excellent craftsmen in their field, lacked knowledge and tools in the area of personnel management. Their approach to working with the team was based mainly on intuition and personal experience, which often led to organisational problems and unsatisfactory results. The most frequently mentioned shortcomings were difficulties in motivating employees, resolving conflicts and establishing effective communication in the kitchen.

In order to better understand the needs of the industry, a survey was conducted among students and teachers of catering professions in Poland, Italy and Germany. A total of 172 respondents took part in the survey. The results confirmed the previously identified problems and clearly indicated that interpersonal skills are just as important as professional skills. In addition, individual interviews were conducted with chefs, in which they emphasised that they did not feel confident enough in communicating with their teams, which often led to tensions and hindered their daily work.

On this basis, the main objective of the project was formulated: to strengthen interpersonal skills in the area of human resource management among students and graduates of vocational schools and people learning the profession of chef in the craft system, as well as to improve their digital skills in parallel.

Specific objectives were also set as part of the project activities, which included:

1. Improving the digital and methodological competences of vocational instructors, teachers and trainers providing education in vocational and industry schools.
2. Increasing access to modern, practical knowledge on human resource management in the catering industry.
3. Improving the chances of catering school graduates and students on the labour market by expanding the educational offer to include issues related to social and digital competences.
4. Providing schools, educational institutions and industry organisations with innovative methods and curricula for teaching personnel management in the catering industry.

The project was implemented as an international partnership involving institutions from Poland, Italy and Germany. Representatives of vocational education, craft chambers and research institutions participated in the work, which allowed the problem to be viewed from many perspectives and solutions to be developed that respond to the needs of different environments. Thanks to international cooperation, it was also possible to compare practices and challenges in the three countries, which significantly enriched the results of the project and gave them a universal character.

Thus, the project not only contributed to improving the quality of vocational education in catering, but also helped to raise working standards in the industry by offering both students and teaching staff specific tools for better human resource management.

3.3. Research Apparatus

When analysing the research method, it should be noted that in this case, two types of methods can be applied at two levels. The first method used is the project. It was used to achieve the objective that was implemented as part of the Erasmus+ programme entitled: ‘Methodology of teaching human resource management for current and future catering employees’, No. 2023-1-PL01-KA220-VET-000167215. When describing the project method, it should be mentioned that it included various activities. These included surveys as well as individual in-depth interviews. The survey questionnaire and interview questionnaire tools were used to diagnose the level of knowledge and needs of catering school students and graduates in terms of human resource management knowledge and skills. In addition, study visits to individual project partner institutions were organised as part of the project. The topics focused, among other things, on the opportunities, procedures and legal regulations in force in their countries in the field of vocational education. The aim was to ensure that the materials developed were universal in nature and could be used in various formal or informal education systems. In addition, methods and tools related to the development of educational materials were discussed. The project involved the implementation of work packages in partnership, thanks to which all project partners were involved in the work. The packages formed a logical whole. Not all packages will be discussed here, but the focus will be on educational materials. These materials include, first and foremost, a human resource management curriculum based on five modules: employee selection, team building, task delegation, conflict resolution, motivation and lesson plans. Each of the developed products was

prepared in Polish, English, German and Italian. The project provided for the development of a research tool to verify the knowledge of those participating in human resource management classes. The programmes and lesson plans for students include various teaching methods and toolsD. Kolb believes that learning is a process of constantly modifying previous experience through subsequent experience. New ideas are not written down like marks on a 'clean, white sheet of paper' in the learner's mind, but interact with ideas that the learner already had. According to the author, the educational process takes place primarily in interaction with the environment, and knowledge is acquired through the transformation of experience - thanks to the opportunity to experience different situations and exchange experiences with other participants in the educational process, one can learn most effectively. This is because successive experiences enrich and cause new information to be assimilated more quickly than is the case, for example, when acquiring knowledge through passive listening. D. Kolb proposed that the learning process should be viewed as a cycle in which the main function is performed by the individual's experience and its analysis. This cycle is extremely complex, but the author has identified four stages in the process of learning through experience:

1. concrete experience, consistent with the learner's views, in which the learning process
1. begins;
2. reflective observation, when the experience is analysed and viewed
3. from different perspectives;
4. abstract conceptualisation, when the learner continues to analyse the data and begins to
5. draw conclusions from the experience in which they participated;
5. active experimentation – the final stage, which begins when learners change theirbehaviour and start experimenting with new knowledge to see if their newly developed theories are useful in solving problems and making decisions.

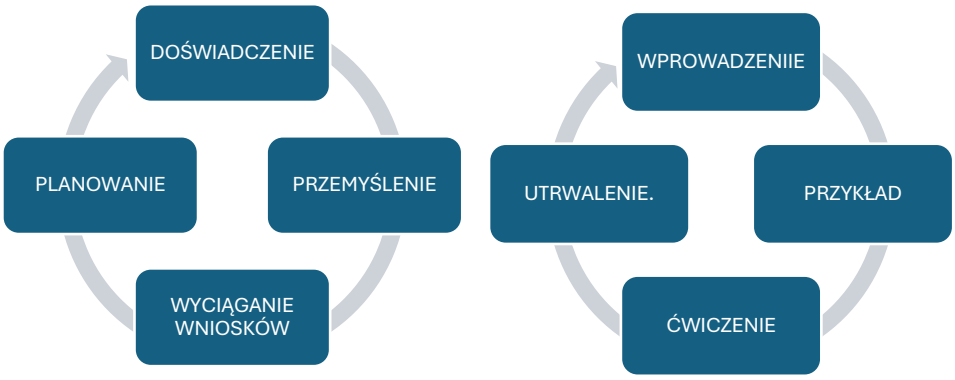


Figure 1. Kolb's cycle
Source: own study based on D. Kolb, op. cit.

When considering this model for training, we must reject the traditional approach to teaching, which presumes that a certain theory must be presented first, and only once learners have mastered it can they move on to practical exercises. D. Kolb's concept presents the exact opposite. Learners can generalize observed patterns to other situations and relate experiences to broader theoretical concepts, allowing them to better understand them. This means that theoretical knowledge is neither distant from personal experience nor alien, and therefore less acceptable. Furthermore, each subsequent experience can provide the learner with an opportunity to draw conclusions and can initiate the next learning cycle.

The developed materials utilize D. Kolb's teaching method. The second method employed in developing the educational materials is the use of ICT. The development of digital technologies and mobile tools is playing an increasingly important and supportive role in the adult learning process, as they allow them to access knowledge at a convenient time and place, and also allow for the individualization of their learning path. The project leveraged this potential by creating a set of educational videos that students can independently watch on computers, tablets, or smartphones – both during and outside of classes. This type of solution not only promotes knowledge retention but also

allows for repeated re-reading of the material, which is particularly important for learners who learn at different paces.

The educational film development process was enhanced by the use of artificial intelligence-based tools, which supported content creation, development of teaching scenarios, and adaptation of the material to the audience's needs. As a result, the educational films are characterized by a modern format, visually appealing content presentation, and a high level of substantive content, which increases their educational effectiveness and motivates students to independently deepen their knowledge. Selected photos from the developed educational films are presented below.



Figure 1. Photo from an educational film on human resources management
Source: 'Methodology of teaching human resource management to current and future catering employees', no 2023-1-PL01-KA220-VET-000167215.

Educational films feature a narrator who discusses a human resources management topic. In addition to presenting theory, the video depicts a real-life "kitchen" scene where the discussed topic might be applied or encountered. The educational films also presents a best practice—a solution that can be applied in similar situations.



Figure 2. Photo from an educational film on human resources management
Source: 'Methodology of teaching human resource management to current and future catering employees', no 2023-1-PL01-KA220-VET-000167215.

The solution proposed in the project – educational videos using artificial intelligence – offers the opportunity to increase the attractiveness of classes, but also to encourage independent learning and, above all, the introduction of digital solutions.

It is important to note that preparing teachers to impart knowledge and use educational materials based on artificial intelligence requires them to acquire skills in this area. By using such materials, teachers disseminate knowledge among their students about how to use AI tools and the benefits of its application.

The methods used seem to guarantee educational success.

3.4. Analysis of Measurement Data

Taking into account the analysis of the educational materials developed for the project, attention will be focused on the curricula and their substantive content, and on the sample lesson plan.

As mentioned earlier, the human resources management course curriculum covers five topics: 1. employee selection, 2. team building, 3. delegation, 4. conflict resolution, and 5. motivation. Each of these topics consists of three lessons. The human resources management (HRM) curriculum was developed based on the needs of the restaurant industry and provides a practical tool for developing interpersonal, managerial, and digital skills among students, graduates, and teaching staff. The program is structured around several thematic blocks that logically introduce participants to the concepts of personnel management.

The first module focuses on workforce planning within organizations. It discusses the principles of selecting employees for task and project teams, demonstrating how thoughtful planning impacts work efficiency. Participants acquire knowledge and practical skills in workforce planning and become aware of the consequences of personnel decisions.

The next part of the program is dedicated to employee recruitment and selection. Participants learn the essence and process of recruitment, learn how to construct job advertisements – both internal and external – and analyze common mistakes and their consequences. They then move on to topics related to candidate selection, including conducting interviews. Particular emphasis is placed on the ability to ask questions, interpret answers, and make informed choices.

The second part of the program covers team building. Participants learn the differences between a group and a team, types of teams, and the characteristics of a good team from the perspective of the organization, the employee, and the manager. The stages of team development according to B. Tuckman and team roles according to M. Belbin are analyzed. Developing managerial attitudes appropriate for different stages of team development and developing communication skills are also important. Principles of formulating messages, providing feedback, and conducting constructive conversations and employee severance packages are discussed.

The third block focuses on task delegation. Participants learn what delegation is, its benefits and principles, and how to properly select employees to carry out tasks. Both concerns about delegation—on the part of both the supervisor and the employee – are analyzed, as well as ways to overcome them. A strong emphasis is placed on proper communication during the delegation process and avoiding common mistakes.

The final block of the program covers issues related to employee motivation. Definitions of motivation and motivation, types of motivation, and various approaches to building motivational systems are discussed, including Maslow's hierarchy of needs and the importance of salary and non-salary motivators. Particular attention is paid to conducting motivational interviews – their structure, stages, and practical techniques for supporting effectiveness.

As a result of the program, participants gain comprehensive knowledge of human resources management in the restaurant industry, develop practical skills in planning, recruitment, selection, team building, delegating tasks, and motivating employees, and understand the consequences of personnel decisions. The program was designed to meet the real needs of the industry and prepare students for the role of team leader in a dynamically changing work environment.

The second material analyzed in the project is the lesson plan. It is a detailed plan of educational activities that precisely defines the objectives, content, working methods, teaching materials, and methods for monitoring and assessing student progress. Unlike an outline, a lesson plan is a more flexible document – it allows for changes to be made during the course of the lesson, and its main function is to plan the course of each activity step by step.

The scenario includes a detailed time schedule, including the start and end times of individual tasks (e.g., 8:00 AM–8:03 AM, 8:03 AM–8:08 AM) as well as the duration of each activity (e.g., 3 minutes, 5 minutes). Each activity also has a specific goal – for example, explaining the workshop rules or familiarizing participants with the rules for constructing feedback.

The work methods and teaching materials that should be used at a given point in the session are also a crucial element of the scenario. For example, the instructor writes proposed rules on a flipchart and gives them a title, which they then place on the wall in the form of graphics, such as icons, for everyone to see. Similarly, participants write their expectations on sticky notes, which are then collected and discussed. Another example is an individual presentation by the instructor combined with a multimedia presentation – slide 1 presents the training title, and slide 2 presents its objectives.

Instructor notes, providing practical tips for the instructor, are also a key element of the scenario.

These might include, for example, emphasizing practical skills for training purposes, and only then emphasizing cognitive values (knowledge). The instructor is also responsible for monitoring time and informing participants that a detailed discussion of the content of individual modules will occur within subsequent sessions.

Thanks to this structure, the lesson plan becomes not only a planning tool but also a practical support for conducting classes. It allows the instructor to maintain the dynamics of the work, better organize their time, and adapt teaching methods to the learning objectives, while ensuring clarity and active participation in the learning process for participants.

4. RESULTS

Based on the above considerations, two types of results can be identified – positive and negative. First, we will focus on the positive outcomes. These include:

- Improving the interpersonal and managerial skills of students, graduates, and employees in the food service industry.

This is a crucial outcome, as the food service industry requires not only technical skills but, above all, teamwork. Increasing interpersonal skills strengthens the ability to collaborate and positively impacts the workplace atmosphere.

- Developing digital skills through the use of modern tools, including educational videos and artificial intelligence.

The introduction of technology into the learning process responds to the needs of the modern labor market. Participants gained the opportunity to learn in a flexible manner, which increases the accessibility of knowledge and facilitates self-education.

- Development and implementation of a human resources management curriculum.
- The program systematizes knowledge and provides practical tools for personnel management. It is the first material of its kind aimed directly at students and teachers in vocational education in the catering industry.
- Creation of detailed lesson plans.
- These lesson plans support teachers and trainers, structure the teaching process, and enable the use of proven methods. This increases the effectiveness of classes and provides instructors with a sense of methodological certainty.
- Increased teaching competences of teachers, trainers, and masters of the profession.

Thanks to the project, educational staff have enriched their work with new tools. This facilitates the transfer of knowledge in a modern and engaging way for young people.

- Improved quality of vocational education in culinary schools in Poland, Italy, and Germany.

This result underscores the international nature of the project. The exchange of experiences between countries has enabled the development of universal solutions and raised standards of vocational education.

- Increased opportunities for graduates in the labor market thanks to the acquisition of team management skills.

This is a practical result – graduates are more competitive and better prepared to enter the job market, especially in industries with high employee turnover.

- Equipping schools and educational institutions with programs, tools, and teaching materials on human resources management.

The facilities received specific, ready-to-use resources. This increases the sustainability of the project's results and allows for their continued use after its completion.

- Strengthening management staff in the catering industry.

Chefs, often excellent professionals, gained knowledge and tools in personnel management, which positively impacts the functioning of entire teams.

- Involvement of over 200 participants from various countries.

Such a large number of participants allowed not only for the verification of prepared materials but also for the exchange of good practices and the building of a network of international cooperation.

- Involvement of Ukrainian citizens in project activities.

The integration of refugees within the project provides added value – it supports their professional development and facilitates their adaptation to a new cultural environment.

Among the negative outcomes that also pose challenges are:

- Lack of prior programs and teaching tools for teaching HR management.

This posed a significant obstacle during the preparatory phase, but it also demonstrated that the project filled a real educational gap.

- Teachers and trainers lacked sufficient competencies in teaching personnel management.

This challenge necessitated intensive staff support and the creation of additional support materials. This, however, made the project even more valuable.

- Limited readiness of some participants to work with modern digital tools.

Additional instruction and exercises were necessary. However, as a result, participants overcame barriers and acquired new competencies.

- Differing levels of knowledge and experience among participants.
- This challenge hindered the delivery of consistent classes and required individualized work, but this allowed the materials to be tested across different target groups.
- Additional time and resources were required to prepare the materials.

While this extended the implementation process, it also allowed for the refinement of the content and ensured its high quality.

- Language and cultural barriers.

These were a challenge, especially during international collaboration, but ultimately strengthened the project team's communication skills.

- Difficulties in ensuring a consistent level of quality in program implementation.

Differences in education systems between countries led to uneven implementation but also provided an opportunity to adapt materials to different realities.

5. DISCUSSION

The "Methodology of Teaching Human Resources Management to Current and Future Catering Employees" project, implemented as part of the Erasmus Plus program, is an example of an effective response to the real needs of the catering industry, which requires employees to possess not only high technical skills but also well-developed soft and managerial competencies. The competency gap identified in the diagnosis – particularly in teamwork, communication, and conflict resolution – was confirmed by both practical observations and empirical research. Data triangulation (interviews, surveys, observations) strengthens the reliability of the findings and ensures that the project is based on real needs, not merely on the assumptions of its authors.

At the methodological level, the project utilized two complementary approaches: a project-based approach (typical of Erasmus+ programs) and research methods based on surveys and interviews. Another valuable element is the use of Kolb's experiential learning cycle. His choice aligns with current trends in vocational education, which are moving away from traditional teaching models in favor of more interactive, engaging, and practical forms of work. This is particularly important in the catering industry, where experience, observation, and experimentation are the foundation of the learning process. Combining this model with ICT tools, including artificial intelligence-assisted educational videos, gave

the project a modern and engaging dimension for participants. It's worth noting that such solutions not only enable individualized learning paths but also increase the accessibility of knowledge across time and space, which is crucial for young people accustomed to flexible learning methods.

However, the effectiveness of this approach requires reflection. On the one hand, incorporating active and digital methods increases participant motivation and addresses the needs of Generation Z. On the other hand, the difficulties some participants have encountered in using modern technologies demonstrate that the process of digitalizing vocational education is not uniform. It requires additional training and support to equalize competency levels. This problem, if not properly addressed, can lead to digital exclusion.

Another aspect worth emphasizing is the international nature of the project. The partnership between institutions from Poland, Germany, and Italy enabled the exchange of experiences and comparison of education systems and personnel management practices. This undoubtedly added value, giving the developed teaching materials a more universal and transnational character. On the other hand, systemic differences and linguistic and cultural barriers posed a significant challenge that could have limited the effectiveness of the collaboration. Although participants declared that these barriers were overcome, it is worth asking to what extent they influenced the uniformity of the program's implementation across countries. The diversity of educational systems can lead to discrepancies in the interpretation and application of materials, limiting the full consistency of results.

When analyzing the results, it's important to emphasize their multidimensionality. The project contributed to the development of participants' interpersonal and digital skills, as well as to enriching the teaching skills of teachers and professional mentors. The curriculum, encompassing five key modules (employee selection, team building, task delegation, conflict resolution, and motivation), provides a valuable tool for systematizing knowledge and practical skills. Lesson plans and other teaching materials support teachers in organizing the educational process and facilitate the introduction of modern working methods. Another significant achievement is the creation of the first comprehensive human resources management curriculum in this industry, aimed directly at vocational schools. This increases the sustainability of the results and allows for their continued use after the project's conclusion.

At the same time, it's important to emphasize that the project faced challenges typical of this type of initiative. The lack of prior teaching materials on human resources management in the restaurant industry, varying levels of participants, and the need for additional time and resources to develop the materials were factors that could have delayed implementation. On the other hand, such difficulties point to the project's feasibility and authenticity – it filled a real educational gap.

The study sample is also worth noting – 172 respondents in three countries constitute a relatively small number, limiting the possibility of broadly generalizing the results. The results provide a picture of needs and problems, but their representativeness should be considered with caution. In the longer term, research involving a broader group of students, teachers, and employers is needed.

The project also brought a social dimension – the inclusion of Ukrainian citizens in educational activities fostered their professional and cultural integration. This is an example of how educational initiatives can simultaneously support social goals and address current social and demographic challenges.

In summary, the project should be assessed as innovative and valuable in both its educational and practical dimensions. Its main strengths include: a reliable needs assessment, the use of modern methods (Kolb, ICT), the universality of the materials, the international dimension, and the multiplicity of the target audience (students, teachers, and masters of the profession). Limitations primarily concern the scale of the research, digital and cultural barriers, difficulties in implementation, and the lack of previous models. Nevertheless, the project represents an important step towards the professionalization of vocational education in the catering industry and can be a starting point for further research on the effectiveness of the methods used, the updating of teaching materials, and the expansion of their application to other professional sectors.

It should be noted that the project's results clearly indicate that all assumptions have been met, and the intended goals – both general and specific – have been achieved. This is undoubtedly a success, especially given the project's international nature. International projects bring together diverse institutions and professional communities, which is particularly important, as it demonstrates the high quality of partner collaboration and effective management of the implementation process.

Looking further, we see many opportunities for further development and practical application of the project's results. The developed products have real potential to become a permanent element of the educational offerings of schools and catering facilities. The interest they generated, both during the project's implementation and its dissemination, suggests that in the long term, they could be permanently incorporated into everyday teaching practices. International cooperation is also a significant advantage, as it can serve as a foundation for future initiatives, foster the exchange of experiences, and contribute to further improving the quality of vocational education in Europe. Furthermore, the growing demand for innovative solutions in education – particularly in the catering and hotel sectors – creates favorable conditions for implementing the developed materials and tools.

However, potential threats cannot be ignored. The most serious of these is the risk of failure to implement the results in practice, stemming from the reserve and caution of some recipients. If educational institutions and industry decide not to implement new solutions, there is a risk that they will remain merely theoretical proposals. Furthermore, changing socio-economic conditions, reforms to the education system, and the emergence of competing educational initiatives may weaken the relevance and significance of the achieved results.

In summary, the project can be considered a success, with high educational and social value. Its greatest strengths include the extensive network of collaborations, international reach, and the variety of dissemination tools used. Identified weaknesses—such as the lack of immediate acceptance by all recipients or difficulties in measuring effectiveness—do not negate the success achieved, but rather point to areas requiring further work.

Long-term success will depend primarily on the willingness of institutions and the industry to accept and consistently apply the results. Therefore, it is recommended to undertake additional measures to support the adaptation process, such as organizing implementation training, presenting examples of good practices, and building trust among teachers, trainers, and representatives of the catering sector. These actions may determine the sustainability and full utilization of the project's results in the future.

6. CONCLUSION

The completed project confirmed the importance of a reliable diagnosis of educational needs as a foundation for creating innovative solutions in vocational education. Addressing identified deficits in soft and managerial skills in the catering industry, the project provided teaching materials that not only fill the gaps in curricula but also introduce new standards in vocational education. The results indicate that incorporating engaging methods, experiential learning (Kolb's cycle), and ICT tools can significantly increase the effectiveness of the teaching process, particularly in sectors requiring intensive professional practice.

The project’s products – the curriculum, lesson plans, AI-powered teaching videos, and a package of materials for teachers and masters of the profession – have the potential to become a permanent element of the educational offerings of vocational schools and catering establishments. Their attractiveness and practical usefulness were confirmed by participants during pilot and dissemination activities. In the long term, they may contribute to the standardization of education in the field of human resources management in the catering industry and serve as inspiration for other service sectors.

The project’s international dimension is also noteworthy. Collaboration between institutions from Poland, Germany, and Italy enabled the comparison of different educational systems and organizational practices, which translated into the development of transnational solutions. This gave the project's results a broader universality, and the initiative itself laid the foundation for subsequent programs and long-term activities aimed at improving the quality of vocational education in Europe.

Despite the successes achieved, potential threats related to the sustainability of the results must be considered. The greatest risk is the lack of implementation of the developed tools into educational practice, resulting from caution or a lack of trust on the part of some institutions. The volatility of the socio-economic environment, dynamic reforms of education systems, and the emergence of alternative initiatives may further limit the relevance and attractiveness of the results. Therefore, it is necessary to strengthen the processes supporting the adaptation of the project's products – through implementation training, creating a space for teachers to exchange experiences, and presenting best practices that build trust and facilitate implementation.

The practical implications stem primarily from the potential use of the developed materials in the daily work of teachers and trainers, as well as their potential to improve the quality of educational services in catering schools. They can facilitate the process of preparing students for leadership roles, support the development of interpersonal skills, and increase the attractiveness of the educational offer for future employees in the sector. Furthermore, the project contributed to the integration of Ukrainian citizens, demonstrating that educational initiatives can also fulfill a significant social function.

Theoretical implications, in turn, support the effectiveness of activating and digital methods in vocational education and demonstrate that their implementation requires systemic institutional support. The project demonstrates that international cooperation and the transfer of best practices foster the creation of solutions applicable in diverse cultural and educational contexts. It thus makes a significant contribution to the discussion on the role of teaching innovations and ICT tools in modernizing vocational education.

In summary, the project should be viewed as a model initiative that has made a significant contribution to the development of vocational education in the catering industry and opened new perspectives for further research. It demonstrates that combining needs assessment, innovative teaching methods, and transnational cooperation constitutes an effective strategy for addressing the challenges of the contemporary labor market. Further research should focus on analyzing the effectiveness of implementing the developed tools in various educational contexts, assessing their long-term impact on the development of professional competencies, and exploring mechanisms that promote the sustainability and widespread dissemination of results.

It is worth adding that the presented example of good practice will be available after the completion of the project 'Methodology of teaching human resources management for current and future catering employees', no. 2023-1-PL01-KA220-VET-000167215, which is implemented under the ERASMUS plus program, on the website of the Erasmus + Project Results Platform: https://erasmusplus.org.pl/platforma-rezultatow-projektow-erasmus.

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MIXED-METHODS OF USER EXPERIENCE EVALUATION OF EDUCATIONAL BOARD GAMES DESIGNED WITH 3D PRINTINGTECHNOLOGY

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ABSTRACT

Purpose: *The study aimed to evaluate Adventure Seekers, an educational board game designed with the support of 3D printing and artificial intelligence–assisted prototyping tools. Its primary goal was to assess how children experience the game cognitively, emotionally, and socially, and to determine how AI-supported design can enhance inclusivity and engagement in game-based learning.*

Need for the study: *Although board games are widely recognized as effective educational tools, few studies have examined how user experience (UX) evaluation and AI-assisted design processes influence children's learning engagement. By integrating UX assessment with AI-driven prototyping, this research addresses the growing need for inclusive, data-informed, and technologically enhanced learning environments.*

Methodology: *A mixed-methods approach was employed, combining post-game surveys (quantitative data) with in-situ and post-session interviews (qualitative data). The study involved 81 participants aged 10–13, tested in real-world educational settings such as schools and scouting centers. Game components were modeled with Meshy.ai and ChatGPT to accelerate prototyping and adapt designs based on user feedback.*

Findings: *The results indicate a highly positive user experience. Ninety-three percent of participants found the game visually appealing, 88% rated the rules as easy to understand, and 90% expressed a willingness to play again. Statistical analysis (Cronbach's $\alpha = 0.87$; logistic regression $R^2 = 0.42$) showed that visual appeal and curiosity were the strongest predictors of replay intention. Interview data confirmed strong emotional engagement, cooperation, and enjoyment, with minor improvement suggestions related to component size and game variety.*

Practical Implications: *The study demonstrates that combining 3D printing and AI-assisted design supports faster iteration, personalization, and inclusive usability in educational games. It also provides a methodological model for integrating UX research into the development of pedagogical tools. These findings highlight how AI can function as a creative partner in designing learning materials that are not only functional but emotionally resonant and engaging for young learners.*

Keywords: Educational board games, User Experience (UX), 3D printing, Mixed-methods research, Game-based learning, Cognitive development, AI in 3D design process

Jel codes: A29, O33, C93

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1. INTRODUCTION

Modern education increasingly turns toward engaging, experience-based methods that respond to the cognitive and emotional diversity of learners. Among such approaches, board games stand out as particularly effective tools that merge entertainment with learning. They foster not only knowledge acquisition but also executive functions such as planning, inhibition, and cognitive flexibility (Diamond 2013). Moreover, research has consistently shown that gameplay stimulates linguistic, mathematical, and social competencies while creating a cooperative atmosphere conducive to emotional development (Prensky 2001; Gee 2004). In both school and out-of-school contexts, educational games have thus become a bridge between structured learning and playful exploration – a space where motivation, curiosity, and challenge naturally coexist.

Recent technological advances – especially in additive manufacturing and artificial intelligence–assisted design – have opened new opportunities for personalized learning tools. 3D printing allows educators and designers to produce physical components tailored to children's needs, including those with sensory or motor challenges (Pantazis and Priavolou 2017; Kwon et al. 2020; Jorge et al. 2021). When paired with AI-based design support systems such as Meshy.ai or text-driven modeling tools, it becomes possible to iterate prototypes rapidly and adjust them according to user feedback. By combining ergonomics, aesthetics, and safety, these technologies extend accessibility and usability while nurturing creativity among young learners.

Parallel to these technological shifts, education research increasingly emphasizes user-centered design—commonly referred to as User Experience (UX). In game-based learning, UX evaluation goes beyond verifying knowledge outcomes; it examines how aesthetic pleasure, emotional engagement, and functional fluency influence cognitive effort and motivation (Norman 2013; Kim and Pekrun 2014). Emotions play a vital role in learning: positive affect supports curiosity and persistence, while frustration, when balanced, fosters resilience (Immordino-Yang and Damasio 2007). For this reason, understanding how young players perceive and feel the game – both during and after play – is essential for designing truly inclusive and effective educational experiences.

The present study aimed to conduct a multidimensional evaluation of *Adventure Seekers*, an educational board game developed through a design process integrating 3D printing and AI-assisted modeling tools. The evaluation focused on how children aged 10–13 perceived and interacted with the game within authentic educational contexts – scouting meetings and school activities. A mixed-methods design was applied, combining quantitative measures (post-game surveys) with qualitative exploration (in-situ and retrospective interviews). This combination made it possible to capture both numerical patterns and nuanced interpretations of player experience, including aesthetic appreciation, emotional engagement, ergonomic comfort, and perceived educational value (Morville 2004; Vermeeren et al. 2010).

2. LITERATURE REVIEW

Modern pedagogy increasingly embraces active learning methods that encourage students to become co-creators of knowledge rather than passive recipients. Board games fit naturally into this constructivist paradigm, as they combine play, exploration, and social interaction – key components of experiential learning. Dewey's concept of *learning by doing* (Dewey 1938) underscores that knowledge arises from meaningful experience, while Piaget and Vygotsky (Vygotsky 1980; Piaget 1999; Ültanır 2012) emphasized the importance of social dialogue and hands-on discovery in cognitive growth. These ideas remain central to game-based learning today, where play becomes a structured yet flexible framework for building understanding through participation, collaboration, and reflection.

Empirical research confirms that regular engagement with board games enhances key executive functions – cognitive control, planning, and mental flexibility – by placing learners in situations that demand rapid decision-making and adaptive thinking (Diamond 2013). Structured gameplay also reinforces mathematical reasoning, language skills, and logical problem-solving (Sarı and Szczygieł 2023). Beyond cognition, the social dimension of games cultivates empathy, cooperation, and fairness, helping children learn to navigate competition, handle setbacks, and celebrate collective success. Such emotional and interpersonal learning outcomes make board games especially valuable in both inclusive and mainstream education contexts (Garris et al. 2002).

From a didactic perspective, educational board games perform several interconnected functions – motivational, diagnostic, and reinforcing. Their interactive nature sustains learner engagement and curiosity, while also offering teachers a unique observational window into students' problem-solving approaches and group dynamics. When used thoughtfully, games become informal yet powerful assessment tools, revealing both strengths and areas for further development (Alotaibi 2024). This dual role – as both learning medium and diagnostic instrument – illustrates why games are increasingly seen not merely as entertainment but as structured learning environments that generate authentic data about cognitive and social processes (Hamari et al. 2016).

Games also hold diagnostic potential by reproducing real-world decision-making within a safe, low-pressure environment (Howard-Jones and Demetriou 2008). They enable educators to observe how learners plan, negotiate, and adapt – behaviors that reveal individual cognitive styles and social strategies. Such contexts allow informal yet meaningful assessment of both academic progress and interpersonal skills. Moreover, repetition and feedback loops embedded in gameplay support knowledge consolidation without inducing test-related anxiety (Howard-Jones and Demetriou 2008; Ilić Rajković et al. 2020; Sun et al. 2023). In this sense, games act as living laboratories for studying learning in action.

Because of their inherently social structure, board games promote cooperation, negotiation, and perspective-taking – skills that directly contribute to prosocial behavior and empathy (Papoutsi and Drigas 2016; Stubbs and Sorensen 2025). The cooperative or semi-competitive format also encourages students to communicate effectively and appreciate diverse viewpoints. These characteristics make educational board games highly compatible with inclusive teaching practices, providing a shared space where learners with different abilities can participate meaningfully and learn from one another

Within inclusive education, board games offer remarkable flexibility. Their modular structure and adjustable difficulty levels allow learners with disabilities to engage at an appropriate pace while still participating fully in group activities. Such inclusiveness reduces social distance, normalizes diversity, and reinforces the sense of belonging (Cezarotto et al. 2022; Cezarotto and Armstrong 2023). Because the motivation arises from play rather than obligation, students are more likely to stay engaged and retain what they learn. This combination of accessibility, autonomy, and motivation positions games as powerful instruments for inclusive pedagogy.

From a design standpoint, an educational board game evolves through three complementary phases: defining goals, constructing the system of play, and evaluating user experience (Salen Tekinbaş 2011). For the game to be pedagogically effective, each phase must correspond to the learner's perceptual, cognitive, and motor capacities. Personalization plays a key role in this alignment. The introduction of 3D printing and AI-assisted design tools has expanded what can be customized—from component size and texture to ergonomics and symbolic meaning. This integration allows designers to create inclusive learning environments where visual, tactile, and functional accessibility are embedded directly into the design process (Bicer et al. 2017; Jorge et al. 2021).

3D-printed components can be readily adjusted in size, texture, or form, which enhances both usability and aesthetic appeal. Beyond practical benefits, the process itself encourages creativity and iterative thinking – learners and designers alike engage in cycles of testing, reflection, and refinement (Bicer et al., 2017; Kwon et al., 2020). In educational settings, this mindset aligns closely with constructivist and design-thinking approaches, where making becomes a way of understanding.

3. METHODOLOGY

3.1. Aim of the study

The main goal of this study was to conduct a multidimensional user experience (UX) evaluation of Adventure Seekers – an educational board game developed through a design process that integrated 3D printing and AI-assisted prototyping. The research aimed to assess how children perceived the game's visual appeal, usability, and educational relevance in authentic learning environments. Equal emphasis was placed on subjective impressions and measurable indicators of engagement.

The methodological foundation of the study followed a mixed-methods approach, combining quantitative tools (a structured post-game survey) with qualitative methods (semi-structured in-game and post-game interviews)(Bernstein and Nunnaly 1995; Johnson and Onwuegbuzie 2004; Bryman

2006; Creswell et al. 2018). This combination allowed for both statistical comparison and interpretative depth.

The study also sought to identify which design features required further optimization and how AI-supported design and 3D printing could enhance inclusivity and personalization in educational game development. The 3D elements – such as pawns, tokens, and tiles – were generated using Meshy.ai, an artificial intelligence platform that produces 3D models from textual and visual prompts. Generated models – The generated models were checked and, where necessary, corrected in the Blender modelling program. Early concept descriptions were refined with ChatGPT, enabling iterative improvements to rules and component ergonomics. Physical prototypes were printed using a Prusa MK4 with PLA filament, chosen for its safety, low environmental footprint, and tactile comfort suitable for younger players.

3.2. Participiants

The study included 81 participants aged 10–13 years. This age range aligns with the educational framework of the Polish Scouting Association - ZHP (2009; Bronfenbrenner 2009; Czechowska et al. 2014), where structured play and cooperation-based tasks are central elements of pedagogical practice (Kwon et al., 2020). Participants were recruited from scouting groups and partner schools that regularly incorporate board games into educational activities. Conducting the study in these familiar settings ensured ecological validity and reduced experimental stress(Bronfenbrenner 2009; Cohen 2018).

In accordance with the "small group" system used in scouting, participants played in teams of six. The sample was predominantly female (74%, n = 60), with 13 boys (16%) and 8 participants (10%) who preferred not to disclose gender. While the sample provided valuable insights into this demographic, it was not intended to represent the entire school-age population. Instead, the focus was on exploring authentic user experiences within a specific and naturally cohesive educational community.

All participants took part voluntarily, with informed consent obtained from parents or legal guardians. Data were collected anonymously, following institutional ethical guidelines.

3.3. Research methods and tools

A mixed-methods design was adopted, combining quantitative and qualitative approaches to achieve both breadth and depth of analysis. Three complementary tools were used:

- Post-game survey – to quantify player satisfaction and evaluate key UX dimensions (aesthetics, ergonomics, comprehensibility, and emotional engagement).
- In-game interviews – short moderator-led interactions during gameplay to capture spontaneous impressions and behaviors.
- Post-game interviews – semi-structured individual or small-group discussions to collect reflective feedback after play sessions.

The survey contained 18 items: 12 closed-ended Likert-scale statements (1 = strongly disagree, 5 = strongly agree), 4 single-choice questions, and 2 open-ended questions. Example items included:

- "The rules were clear and easy to remember."
- "The 3D-printed pieces were comfortable to handle."
- "I felt excited while playing the game."

The structure of the questionnaire was inspired by UX research frameworks (Morville 2004; Vermeeren et al. 2010; DeVellis 2017; Lazar and Feng 2017) and adapted to children's cognitive and linguistic abilities. Open-ended questions allowed participants to elaborate freely, offering insights that complemented the quantitative data.

3.4. Research process

The study was carried out in natural learning environments – schools and scouting centers – where participants regularly engaged in cooperative tasks. This choice ensured ecological validity and authentic social interaction. The procedure consisted of three stages(Nicolini 2013; Cohen 2018; Patton 2025):

- Introduction and briefing. Participants were introduced to the research aims and trained in the game rules through a short demonstration.

- Gameplay and in-situ interviews. Children played Adventure Seekers in teams of six, while the facilitator observed behaviors and conducted brief, non-intrusive interviews to record immediate reactions.
- Post-game debriefing. After gameplay, participants completed the questionnaire and took part in follow-up interviews focusing on overall impressions, emotions, and perceived educational value.

Sessions were conducted in familiar, friendly settings typical for scouting meetings – shared tables, group discussions, background chatter. This everyday atmosphere encouraged authentic behavior and emotional expression, minimizing performance bias often seen in formal classroom experiments.

3.5. Technologies and materials used

All physical components were produced using a Prusa MK4 3D printer and PLA filament – a material known for durability, safety, and environmental friendliness. The design prioritized child ergonomics: pieces were proportioned for small hands, with rounded edges to enhance comfort and safety.

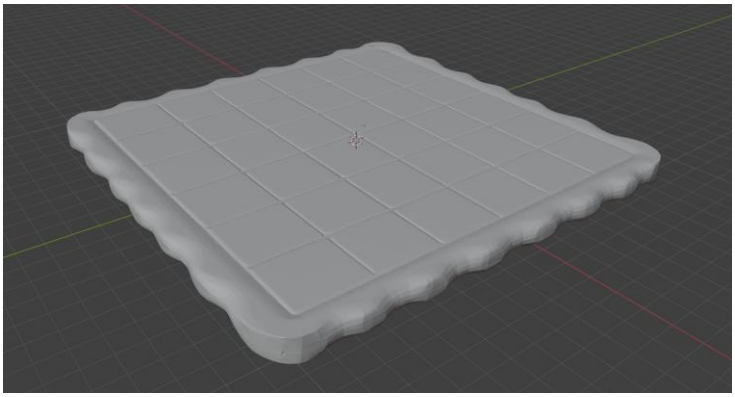


Figure 1. Photo of the game board model used in the game. Screenshot from Blender.
Source: own elaboration

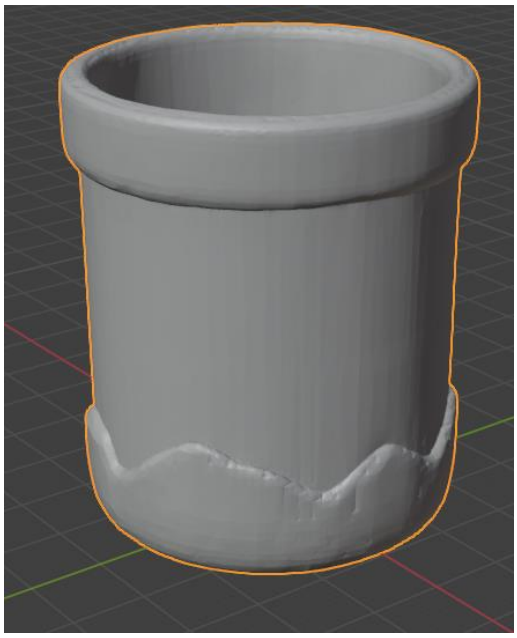


Figure 2. Photo of the basket model for other figurines used in the game. Screenshot from Blender.
Source: own elaboration



Figure 3. Photo of the board game used in the study during gameplay.
Source: own elaboration

Artificial intelligence tools supported the iterative design process. Meshy.ai was used to generate 3D component concepts from textual descriptions and sketches, while ChatGPT assisted in rewording and refining game instructions to match the cognitive level of younger users. This AI-supported workflow accelerated prototyping and made it easier to incorporate real user feedback after each testing phase (Poleac 2024; Olmanson et al. 2025). Through this combination of AI assistance and physical prototyping, the development process mirrored modern iterative UX design cycles, bridging technology, pedagogy, and creativity.

4. RESULTS

4.1. Survey results

The results indicate that Adventure Seekers was enthusiastically received by the participants. Both quantitative data and qualitative remarks suggest that the game effectively fulfilled its dual purpose—as an educational tool and a playful, emotionally engaging activity.

Aesthetic and ergonomic appeal. A large majority of players (93%) found the game visually attractive, highlighting the colorful board and tactile 3D-printed pieces. Almost all respondents (95%) described the components as durable and pleasant to handle. Three out of four participants (74%) noted that the shapes and colors improved clarity and made it easier to follow the gameplay. One 12-year-old girl said, “I liked that every token had a different shape – it helped me remember what was mine.”

Rule clarity and gameplay dynamics. Most players (88%) reported that the rules were easy to understand, and 91% said that learning them took only a few minutes. The gameplay was described as interesting by 89% of respondents, although some mentioned that sessions lasting over 40 minutes could become repetitive.

Usability and component design. About 77% of players found the pieces comfortable to move and the board easy to navigate. Around one-fourth suggested small improvements, such as enlarging the pawns or slightly extending the play area. A 10-year-old participant commented, "Sometimes the pieces bumped into each other – we could make the board a bit bigger."

Overall experience and motivation to replay. Ninety percent of respondents expressed willingness to play again, describing the game as cooperative and exciting. Children frequently emphasized the balance between competition and teamwork, noting that the group tasks created a sense of fairness. One boy (age 11) summarized: "It felt fair because everyone had a turn to do something important."

Statistical validation. The internal consistency of the questionnaire was assessed using Cronbach's alpha, which reached $\alpha = 0.87$, indicating high reliability (Nunnally & Bernstein, 1994). The coefficient was based on 12 Likert-scale items covering aesthetics, ergonomics, clarity of rules, and emotional response.

A Mann–Whitney U test was conducted to compare responses between genders, accounting for unequal sample sizes. None of the differences were statistically significant (all $p > 0.05$), though a small effect size was observed for visual preference ($r = 0.18$).

A binary logistic regression model was used to identify predictors of willingness to replay the game. The strongest predictor was visual appeal ($\beta = 1.38$, OR = 3.97, $p = .01$), followed by gameplay curiosity ($\beta = 0.52$, OR = 1.68, $p = .04$) and ease of rule comprehension ($\beta = 0.33$, OR = 1.40, $p = .05$). Model fit was satisfactory (Nagelkerke $R^2 = 0.42$), and no multicollinearity was detected (all VIF < 2). These findings indicate that positive aesthetic impressions and intellectual curiosity were the most influential factors motivating replay intentions.

Collectively, the results show that children valued Adventure Seekers for its vivid aesthetics, clear rules, and cooperative nature. While a few ergonomic adjustments were suggested, the overall UX indicators confirm that the game achieved a strong balance between enjoyment and educational value.

4.2. Interviews

The qualitative interviews complemented the survey results, offering a deeper understanding of how children experienced *Adventure Seekers* emotionally and socially.

Aesthetics and craftsmanship. Across almost all groups, participants praised the bright colors and fine details of the board and tokens. As one 11-year-old girl explained, *"It looks like something you'd buy in a real store, not something made in class."* A few children mentioned minor imperfections, such as uneven paint or small scratches on the pawns, but these remarks were isolated.

Usability and clarity. Most participants found the pieces easy to hold and move, and the instructions clear. Out of 14 groups, 13 reported no issues in understanding the rules. Observations during play showed that children quickly internalized the game flow and helped peers who were less confident.

Emotional engagement. Nine groups explicitly expressed excitement or curiosity during play. A 12-year-old boy noted, *"I like that we don't just answer questions—we have to think together."* Another participant added, *"It's fun when something unexpected happens, like a surprise card."* Such reactions illustrate how design elements that balance challenge and reward sustain motivation and collective focus.

Perceived fairness and willingness to replay. All groups described the game as fair, emphasizing that each player had meaningful participation. Nearly every group (14/14) expressed enthusiasm to play again. One facilitator observed, *"Children immediately asked if we could keep the game for next week."* This strong replay intention aligns with the quantitative findings, reinforcing that perceived fairness and aesthetic appeal contribute significantly to overall satisfaction.

Suggestions for improvement. In six groups, children suggested enlarging certain components or adding new challenge cards to make future rounds more varied. Rather than expressing dissatisfaction, these suggestions reflected engagement and ownership—the players were already imagining how the game could evolve.

5. CONCLUSSIONS

The findings of this study demonstrate that Adventure Seekers – an educational board game designed through the combined use of 3D printing and AI-supported prototyping – offers considerable educational and experiential value for children aged 10–13. By integrating post-game surveys with in-

situ and retrospective interviews, the research captured not only what children thought about the game but also how they felt while playing it. This emotional and cognitive duality is central to understanding how playful learning environments shape motivation, cooperation, and memory.

Participants consistently emphasized the aesthetic appeal, clarity of rules, and cooperative nature of the game. The 3D-printed components were described as durable and satisfying to handle, while the visual design encouraged engagement from the start. Importantly, the clear mechanics reduced cognitive overload, allowing children to focus on collaboration and problem-solving – skills directly linked to executive functioning and socio-emotional learning.

Several constructive suggestions emerged. Some children proposed larger pieces for better visibility, while others wanted more diverse challenge cards or multiple difficulty levels. These comments, while minor, reflected genuine engagement and ownership – traits that indicate intrinsic motivation and long-term learning potential.

The integration of AI tools such as Meshy.ai and ChatGPT proved especially beneficial during the prototyping phase. Meshy.ai allowed rapid generation and scaling of component models, while ChatGPT was used to refine rule explanations and adjust language for younger audiences. This workflow reduced design time and supported a more iterative, user-centered process – demonstrating how AI can complement human creativity rather than replace it. Such hybrid workflows exemplify the emerging paradigm of AI-augmented design thinking in education.

A key strength of this study lies in its ecological validity. Conducting tests in natural learning environments – schools and scouting centers – allowed participants to behave spontaneously and provided authentic feedback rooted in real social contexts. However, this also introduces limitations: the sample, while adequate for exploratory analysis, was not representative of the broader population, being limited to a specific cultural and organizational context (ZHP). Future studies could expand the sample to different age groups, school systems, and cross-cultural settings to explore how context influences gameplay experience and educational outcomes.

Overall, Adventure Seekers illustrates how thoughtful integration of UX research, AI-assisted design, and 3D printing can produce educational tools that are inclusive, customizable, and deeply engaging. Beyond its immediate application, the study demonstrates the methodological value of mixed-methods research for evaluating play-based learning experiences. Future iterations of the game will continue this approach, using user data and AI-assisted prototyping to refine design features and explore new dimensions of engagement and learning.

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CHAPTER 2
Predictive analytics and real-time decision-making with the use of AI and machine learning

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APPLICATION OF GENERATIVE PRE-TRAINED TRANSFORMER AS AN EXPERT SYSTEM RECOMMENDING THE TYPE OF HEATING

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ABSTRACT

Purpose: *The aim of this article is to develop and verify an expert recommendation system based on ChatGPT (Generative Pre-Trained Transformer), which helps in selecting a heat source.*

Need for the study: *With the development of large language models, the capabilities of artificial intelligence to process, interpret and infer from data are growing. These features are used in complex decision-making problems. One of these problems is the selection of a heating system.*

Methodology: *The construction of the system included collecting data and preparing a domain knowledge base, followed by testing and fine-tuning. The verification of the developed system was carried out using case studies, including confirmation of the heat source selected by human experts or selection of a heating system. In addition, the performance and recommendations of the expert system were compared with the performance and recommendations of the original ChatGPT 4o.*

Findings: *The research results indicate that the expert system, unlike the original ChatGPT, provided more precise calculations and more detailed data. Moreover, in the case of incomplete data, the system asked for details, reducing the risk of incorrect recommendations.*

Practical Implications: *This type of ChatGPT-based expert recommendation system can effectively replace domain experts and positively influence the decisions made by individual stakeholders, businesses, and public institutions.*

Keywords: generative artificial intelligence, expert system, large language model, ChatGPT, heating systems, heat sources

Jel codes: C45; C69; C88; Q40

1. INTRODUCTION

In recent years, there has been a dynamic development of LLMs (Large Language Models). Models such as ChatGPT (Generative Pre-Trained Transformer) (Stribling et al., 2024), DeepSeek (Xie et al., 2025), Gemini (Hirosawa et al., 2024), Claude (Caruccio et al., 2024), LLaMA (Large Language Model Meta AI) (Chiu & Hung, 2025) and many others (Kunze et al., 2025) are finding more and more applications in which they replace humans. It is considered that ChatGPT is

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currently the most popular LLM (Zhang et al., 2023). ChatGPT was trained on a large corpus of text data. It uses deep learning algorithms to analyse and interpret natural language and generate text-based responses (Ullah et al., 2024). Unlike classical artificial intelligence methods, which are designed to automate routine and repetitive tasks, ChatGPT can replace highly skilled workers (Dong et al., 2024). In particular, it can fill the gap between complex raw data and meaningful and human-readable observations by answering questions, summarizing and interpreting data, sometimes outperforming human experts (Zagar et al., 2025). The above-mentioned features of ChatGPT are the basis for its use as a domain expert in complex problems requiring data processing and interpretation, as well as reasoning. One of such problems, with a high degree of complexity, is the selection of a heating system for a single-family house. This is a key decision that affects the costs and comfort of living. In turn, the dynamic changes in the EU climate policy in recent years, including ETS (Emissions Trading System), ETS 2, European Green Deal, Fit for 55, etc. (Jorge-Vazquez et al., 2024), make the choice of a heat source a complex decision-making problem (Miranda-Quiñones et al., 2024). The large number of different heating systems available on the market further complicates this problem. Therefore, it is important to propose a useful tool that helps in choosing a heating system. This creates a research gap concerning whether a properly trained LLM like ChatGPT can be used as an expert system to support users in the selection of a heating system. This gap gives rise to research questions about how the model should be constructed and trained, and what kind of results can be expected.

The aim of the article is to develop and verify an expert recommendation system that helps in selecting a heat source. This system will be based on ChatGPT, thanks to which it will communicate with the user using natural language. The system will enable the selection of heating based on the user's individual preferences, housing conditions, infrastructure availability and economics of use.

2. CONSTRUCTION OF AN EXPERT SYSTEM BASED ON CHATGPT

The construction of an expert system for recommending heat sources for a single-family house based on the needs and capabilities of the user began with data collection. The fact that the system will be intended for users in Poland is of crucial importance for the selection of the scope and data sources for the system. Therefore, data on heating costs and available technologies were taken from Polish specialist websites: kb.pl (*Budowa, remont, wykończenie - KB.pl*, 2025), samurio.pl (Maron, 2023), extradom.pl (Kaliska-Borowicz, 2023), mgprojekt.com.pl (*Ogrzewanie domu*, 2025), www.portalsamorzadowy.pl (Krzemiński, 2023), businessinsider.com.pl (*Jak tanio ogrzać dom?*, 2024), rotal.pl (*Jakie ogrzewanie do starego domu wybrać?*, 2024), home.morele.net (Przyborowska, 2022), engocontrols.com (*Which home heating is the most economical*, 2023), muratordom.pl (Kazimierowicz, 2025). Additionally, data published by the Industry Agreement for Energy Efficiency POBE (*Porozumienie Branżowe Na Rzecz Efektywności Energetycznej POBE*, 2022) were used. These data include a heating cost calculator (*Kalkulator POBE – Koszty Ogrzewania w Typowych Budynkach w I Kwartale 2025 r.*, 2025) and information on changes for the construction sector in the scope of the "Fit for 55" package (Wróbel, 2021) in relation to heat sources. The expert system also implemented knowledge related to the 'My Heat' (Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, 2025b) and 'Clean Air' (Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, 2025a) programs.

Data collected from various sources required cleaning and conversion to a uniform knowledge base format. The data processing process included the following elements:

- Removal of unnecessary information, graphics, metadata and advertisements.
- Normalization of values to the ISO 8601 format.
- Segregation of data into separate files containing individual heat sources.
- Removal of data redundancy.
- Merging data into a single knowledge base file.
- Formatting data for more efficient processing by LLM. Formatting included changing the case of letters, removing unnecessary characters, unifying separator characters and rebuilding tables.

Using the capabilities of LLM ChatGPT to work with PDF files, the collected data was transformed and merged into files in this format. The data were segregated, cleaned and reformatted. Incorrect data,

duplicates and unnecessary content were removed in this way. Despite the convenience of working with the PDF format, some content containing tables, charts and sheets may be incorrectly recognized by LLM. Therefore, this type of data was prepared in a structured CSV format. The collected and processed data were added to the LLM ChatGPT knowledge base and used in the expert recommendation system.

Based on the information contained on the previously mentioned subject-related websites (*Budowa, remont, wykończenie - KB.pl*, 2025; *Jak tanio ogrzać dom?*, 2024; *Jakie ogrzewanie do starego domu wybrać?*, 2024; *Kalkulator POBE – Koszty Ogrzewania w Typowych Budynkach w I Kwartale 2025 r.*, 2025; *Ogrzewanie domu*, 2025; *Porozumienie Branżowe Na Rzecz Efektywności Energetycznej POBE*, 2022; *Which home heating is the most economical*, 2023; Kaliska-Borowicz, 2023; Kazimierowicz, 2025; Krzemiński, 2023; Maron, 2023; Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, 2025a, 2025b; Przyborowska, 2022; Wróbel, 2021), the basic data needed to generate recommendations were defined:

- Technical data of the building.
- Preferred type of the heating system.
- Annual indicator of demand for usable energy (*Jak obliczyć zapotrzebowanie energetyczne domu lub mieszkania?*, 2024) or building insulation standard.
- Whether the building is new or modernized.
- Location (voivodeship or municipality) – potential subsidy programs.
- Infrastructure – availability of the media (access to gas or electricity), possibility of installing an LPG tank, heat pump, wood or pellet storage.
- Ecology – does it depend on low CO2 emissions and renewable sources.
- Investment budget – approximate range of funds for investment.
- Operating budget – maximum heating cost per year.
- System operation – preferences for maintenance-free systems (e.g. heat pumps, gas) and manual operation options (e.g. wood).
- Existing or planned installation of PV (photovoltaics) or other renewable sources.
- Is the user interested in solutions that comply with the requirements of TC (Technical Conditions) 2021 (*Jakie normy musi spełniać nowy dom?*, 2021) (e.g. building energy standards) and ETS2 (*ETS 2: będzie opłata emisyjna od węgla, gazu i oleju opałowego*, 2024) (e.g. avoiding fossil fuels).

The expert system expects the above information in order to model the user's preferences and needs. The system processes and classifies this information, and then compares it with the data contained in the knowledge base. Based on the obtained results, LLM generates a recommendation regarding the most suitable heat source. The system also uses algorithms related to supplementing the data, initially provided by the user. If the system is unable to extract the above information or it is ambiguous, the system may ask the user to supplement the data. The expert recommendation system based on ChatGPT conducts reasoning by examining the compatibility of available heat sources with the user's preferences and needs. It takes into account both technical parameters and subjective user expectations. For this purpose, advanced recommendation algorithms are used, such as Content-Based Filtering, Collaborative Filtering, Hybrid Recommendation Systems, etc. (Roy & Dutta, 2022).

The configuration, testing and fine-tuning process began with the validation of data fed into the expert system. Validation was performed using prompts, asking questions about the types of heating systems, their parameters, advantages, disadvantages, additional requirements necessary for their installation and use. The expert system, based on the reasoning process, prepared answers to the questions posed to it. The next step was to check the requirements for houses intended for the installation of a heating system. Prompts were also used to regulate the importance of information influencing the choice of heating and the way of presenting information to the user. During the construction of prompts, methods designed specifically for LMM ChatGPT (Wei et al., 2022) were used.

The flow chart of the expert system construction process is presented in Figure 1.

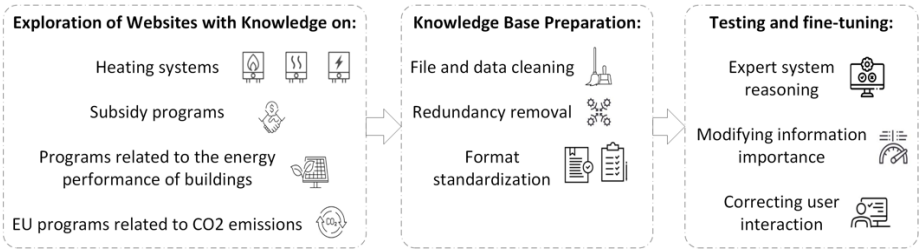


Figure 1. The expert system construction process recommending heat sources
Source: own elaboration.

3. RESULTS

3.1. Case study-based verification of the heat source recommendation system

In order to analyse the recommendation system, a study of four different cases was conducted. These cases differ in terms of the size and purpose of single-family houses, geographical locations and available energy sources. The lifestyle characteristics of families and their motivations, approach to ecology and workload on heating systems are also diverse. The case studies were taken from reality – they were based on real information about users and buildings. Three cases were ex-post – information was available about the type of heating actually chosen, recommended and implemented by industry specialists. In these cases, the expert system was required to confirm or question the heating technology used. The fourth case is ex-ante, and therefore presents a situation in which the user is just making a choice and has not yet consulted experts.

Case 1. A typical single-family house from the 1990s, located in the Łódź-Górna district. Masonry building, partially basement, area of 120 m². Classic layout of rooms: residential ground floor, usable attic. Medium insulation – insulation from a dozen or so years ago (10 cm), double-glazed windows, gravity ventilation. Radiator heating. The house is inhabited by retirees who were looking for a convenient and familiar solution – they decided to replace the old coal boiler with a modern condensing gas boiler. The proximity of the gas network and local subsidies made the decision easier.

- **Lifestyle:**
  - frugal, reluctant to making big changes, but value comfort.
- **Information from the owners:**
  - After retiring, they wanted a warm and safe home without firing the stove every day.
  - They chose a familiar system – gas with the "golden mean" between costs and comfort.
  - They did not use the subsidy, but they used the thermal modernization relief.
- **Building parameters:**
  - Area: 120 m².
  - Standard: good (EUco ~80 kWh/m² per year).
  - Installation: steel radiators, domestic hot water from a boiler.
- **Conditions:**
  - Location: city, access to the gas network.
  - Priorities: comfort, proven technology.
  - Budget: PLN 35,000.

Case 2. A modern, Energy-efficient bungalow with an area of 180 m², located on the outskirts of Gdańsk (Osowa district). The building was built using prefabricated technology, with very good insulation and ventilation with heat recovery. Underfloor heating throughout the house, Smart Home system with energy consumption monitoring. The owners – young professionals from the IT industry – planned a low-energy house with a ground heat pump and PV installation from the very beginning. The ground is conducive to installing vertical probes. High costs are balanced by almost zero bills and high thermal comfort.

- **Lifestyle:**
  - very environmentally conscious, interested in new technologies and investments in RES.

- **Information from the owners:**
  - From the beginning, they wanted to build a house in line with the "house without bills" principle.
  - They had a larger budget and treated the house as a long-term project.
  - They wanted a completely emission-free system that would meet standards for decades.
  - They use smart control, monitoring and automation system.
- **Building parameters:**
  - Area: 180 m².
  - Standard: TC 2021 + recuperation, EUco = 50 kWh/m² per year.
  - Heating system: underfloor heating throughout the house.
- **Conditions:**
  - Location: Gdańsk (mild climate).
  - Access to RES: yes, PV option.
  - Priorities: efficiency and long-term savings.
  - Budget: up to PLN 100,000.

Case 3. A wooden Scandinavian-style recreational house located in the mountain village of Przesieka in the Karkonosze Mountains. Area of 90 m², ground floor with a mezzanine. The building is used mainly in weekends and during holiday periods. Well insulated (graphite polystyrene, mineral wool), natural ventilation, low heat demand. Open interior, no boiler room, with southern exposure. The owners – a couple from Wrocław – value silence and simplicity. Due to the lack of gas and small heating needs, they decided on heating with infrared foils – a maintenance-free, comfortable and aesthetic solution.

- **Lifestyle:**
  - minimalist, they like nature and silence, they don't want to waste time on servicing devices.
- **Information from the owners:**
  - The house is to be a place of rest – the lack of a boiler room and noise was crucial.
  - The heating foils met their aesthetic expectations (invisible, no radiators).
  - Operating costs were secondary, but the lack of the need for servicing was an advantage.
  - They plan to install PV to completely eliminate bills.
- **Building parameters:**
  - Area: 90 m².
  - Standard: good insulation (EUco ~55 kWh/m² per year).
  - Use: seasonal (spring-summer-autumn + winter weekends).
- **Conditions:**
  - Location: mountainous, no gas, low temperatures.
  - Priorities: simplicity, maintenance-free, low investment.
  - Budget: PLN 20,000.

Case 4. A single-family detached house, located in Opole, Opole voivodeship (2nd climate zone). Area of 130 m². The building after thermal modernization in 2023. The owner prefers a maintenance-free heating system.

- **Lifestyle:**
  - comfortable, maintenance-free.
- **Information from the owners:**
  - No maintenance required.
  - Clean and cheap heating.
  - Openness to RES.
  - Willingness to use subsidies – yes ('Clean Air').
- **Building parameters:**
  - Area: 130 m².
  - Standard: thermal modernization in 2023 – insulation of walls (15 cm), attic (20 cm), new triple-glazed windows, gravitational ventilation, low-temperature radiators (after modernization).

- **Conditions:**
  - Location: natural gas – none, Space for fuel – none, electricity – available, 18 kW connection, no restrictions.
  - Budget: up to PLN 30,000.

3.2. Solutions proposed by the expert recommendation system

Case 1. The expert system confirmed that a condensing gas boiler was the best choice for this specific case. The rationale for this choice was supported by the appropriate analysis. The system drew attention to ETS2 (future emission fees) and the direction of changes in the EU related to the planned departure from subsidizing gas boilers. It proposed an alternative in the form of an air-to-water pump with the support of PV and noted a significant increase in the budget and the need to modernize the installation in this case.

Case 2. The system determined the selected solution as the best for the given parameters. It justified this choice and provided estimated annual fees for such an installation. It checked and provided the amounts possible to obtain from the 'My Heat' subsidy. It drew attention to compliance with TC 2021 standards and possible future EU regulations (Fit for 55). The system provided a possible alternative (air-to-water heat pump or hybrid pump with PV and Energy storage) and suggested the selection of a specific ground-source pump, preparation of a cost estimate taking into account subsidies and calculation of annual costs.

Case 3. In this case, the expert system also confirmed the correctness of the heat source selection under the given conditions. The system provided its advantages, estimated installation and operating costs, and compliance with RES. The system suggested extending the heating system with remote control and a heat buffer, as well as the possibility of selecting PV based on energy balance. Alternative heating methods (heat pump, pellet/wood/biomass, LPG/oil) were also discouraged along with the justification.

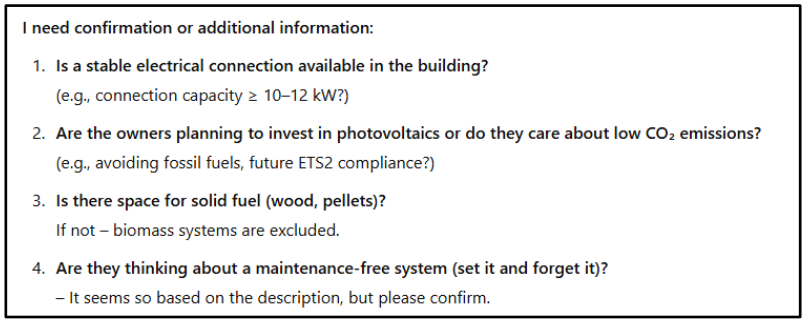
Case 4. Since in this case the owner did not receive a recommendation for the expert – he is open to any solution. The expert system proposed a solution based on heating foils and a PV installation. He justified his choice by indicating the main advantages of this solution in the context of the studied case. Heating foils are maintenance-free – ideal for a user who values comfort. They do not generate CO2 emissions, so they will not be covered by ETS2 fees. The use of heating foils in combination with PV allows to reduce heating costs even to zero. The system considered this solution to be ideal for a well-insulated house after thermal modernization, also indicating the speed of installation without the need to modernize the boiler room or fuel storage. The investment budget, around PLN 28–30,000, can be obtained in its entirety from the 'Clean Air' program. Moreover, in the long term, heating foils are resistant to future EU regulations (no fossil fuels, 100% electric energy sources). All these elements were raised by the expert system, recommending heating foils as the right solution.

4. COMPARISON OF THE OPERATION OF THE DEVELOPED EXPERT SYSTEM WITH THE ORIGINAL VERSION OF CHATGPT 4O

Case 1. Although both the expert system and the original GPT 4o model recommend a condensing gas boiler, there are fundamental differences in their operation. The first difference are the questions in the expert system supplementing knowledge with information concerning:

- availability of an electrical connection with a capacity greater than 10–12 kW,
- planned investments in PV,
- avoidance of fossil fuels in connection with ETS2,
- availability of space for potential storage of solid fuels (wood, pellet).

The above questions are presented in Figure 2.

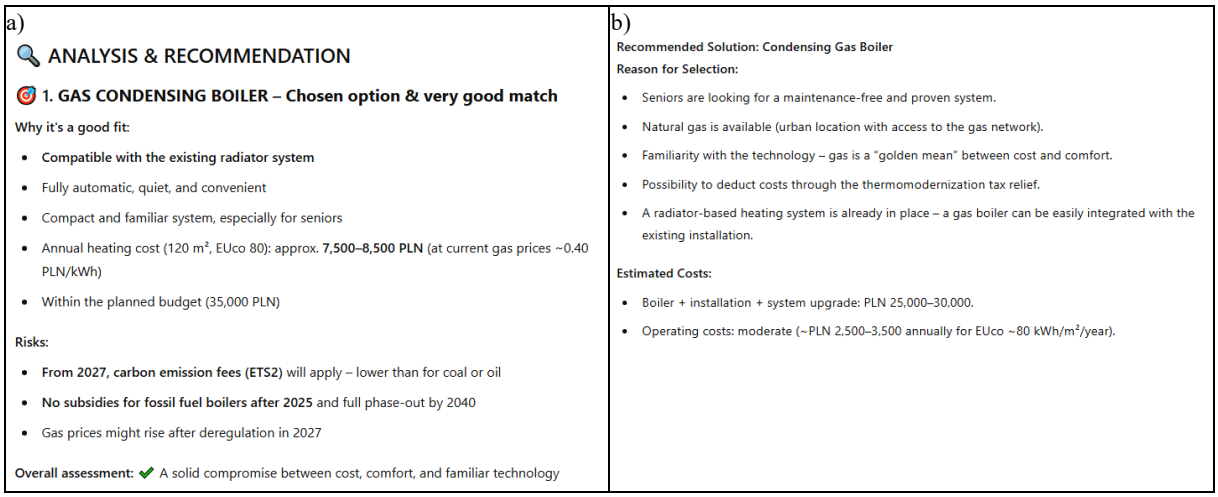

I need confirmation or additional information:

1. **Is a stable electrical connection available in the building?**
   (e.g., connection capacity ≥ 10–12 kW?)
2. **Are the owners planning to invest in photovoltaics or do they care about low CO_2 emissions?**
   (e.g., avoiding fossil fuels, future ETS2 compliance?)
3. **Is there space for solid fuel (wood, pellets)?**
   If not – biomass systems are excluded.
4. **Are they thinking about a maintenance-free system (set it and forget it)?**
   – It seems so based on the description, but please confirm.

Figure 2. Questions employed by the expert system to gather more detailed information – case 1
Source: chatgpt.com.

Further differences occur in the calculated operating costs. The expert system estimates annual heating costs at PLN 7,500 – 8,500 based on the current gas price, while the original ChatGPT 4o reports annual heating costs in the range of PLN 2,500 – 3,500, which is a significant underestimation. The expert system informs about the planned CO2 emission fees from 2027 and about the lack of subsidies for gas boilers from 2025. The original ChatGPT 4o does not take this information into account. The differences between the recommendations are shown in Figure 3.

Both systems provide a heat pump (air-to-water) as an alternative. The original version additionally proposes a pellet boiler (without knowledge of the possibility of storing fuel) and electric heating + PV as an alternative. In turn, the expert system compares the current annual heating and investment costs for natural gas, heat pump and pellet. As the final information, the expert system proposes preparing an application for a thermal modernization allowance, checking the possibility of switching to a hybrid system and simulating costs for the next 10 years in the comparison of gas vs. heat pump. The original ChatGPT 4o only offers a cost summary and an estimated calculation for annual heating costs. These differences are shown in Figure 4.


a)

🔍 ANALYSIS & RECOMMENDATION

🎯 1. GAS CONDENSING BOILER – Chosen option & very good match

Why it's a good fit:

- **Compatible with the existing radiator system**
- Fully automatic, quiet, and convenient
- Compact and familiar system, especially for seniors
- Annual heating cost (120 m², EUco 80): approx. **7,500–8,500 PLN** (at current gas prices ~0.40 PLN/kWh)
- Within the planned budget (35,000 PLN)

Risks:

- **From 2027, carbon emission fees (ETS2)** will apply – lower than for coal or oil
- **No subsidies for fossil fuel boilers after 2025** and full phase-out by 2040
- Gas prices might rise after deregulation in 2027

Overall assessment: ✔ A solid compromise between cost, comfort, and familiar technology

b)

Recommended Solution: Condensing Gas Boiler

Reason for Selection:

- Seniors are looking for a maintenance-free and proven system.
- Natural gas is available (urban location with access to the gas network).
- Familiarity with the technology – gas is a "golden mean" between cost and comfort.
- Possibility to deduct costs through the thermomodernization tax relief.
- A radiator-based heating system is already in place – a gas boiler can be easily integrated with the existing installation.

Estimated Costs:

- Boiler + installation + system upgrade: PLN 25,000–30,000.
- Operating costs: moderate (~PLN 2,500–3,500 annually for EUco ~80 kWh/m²/year).

Figure 3. Recommendations of (a) the expert system and (b) the original ChatGPT 4o – case 1
Source: chatgpt.com.

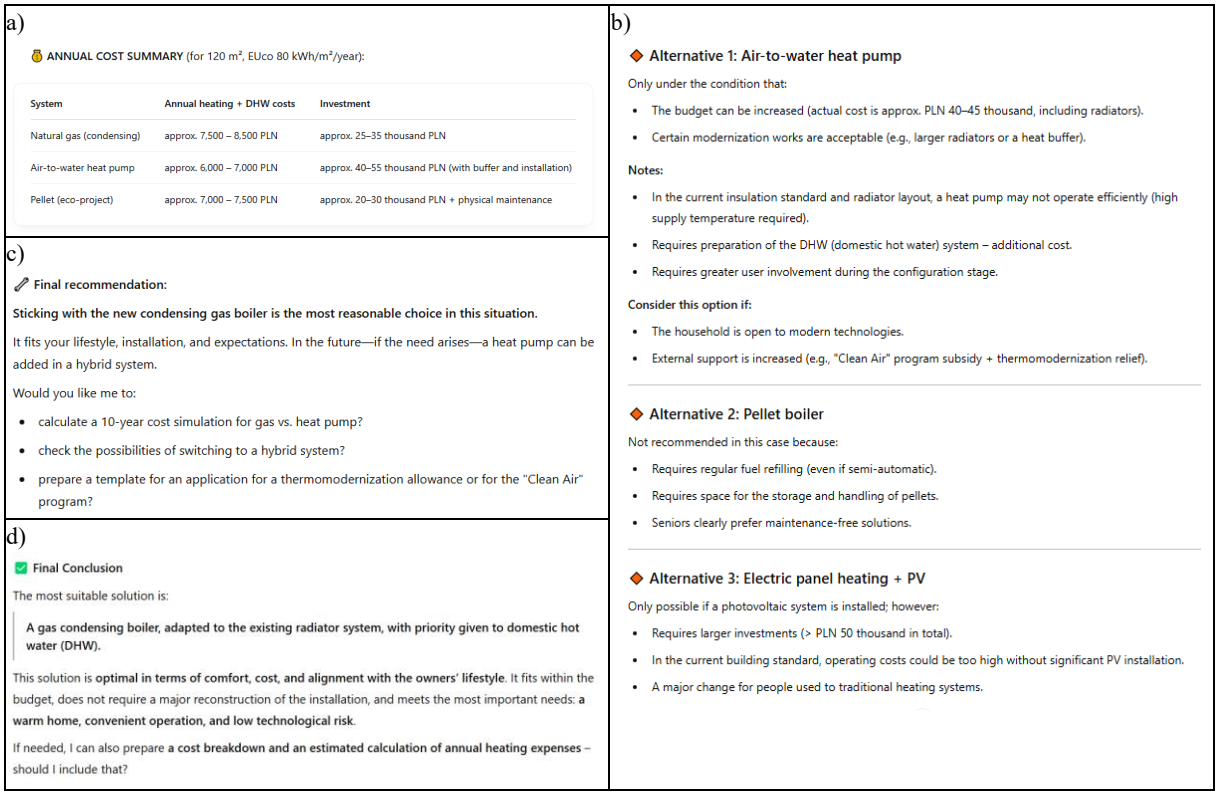
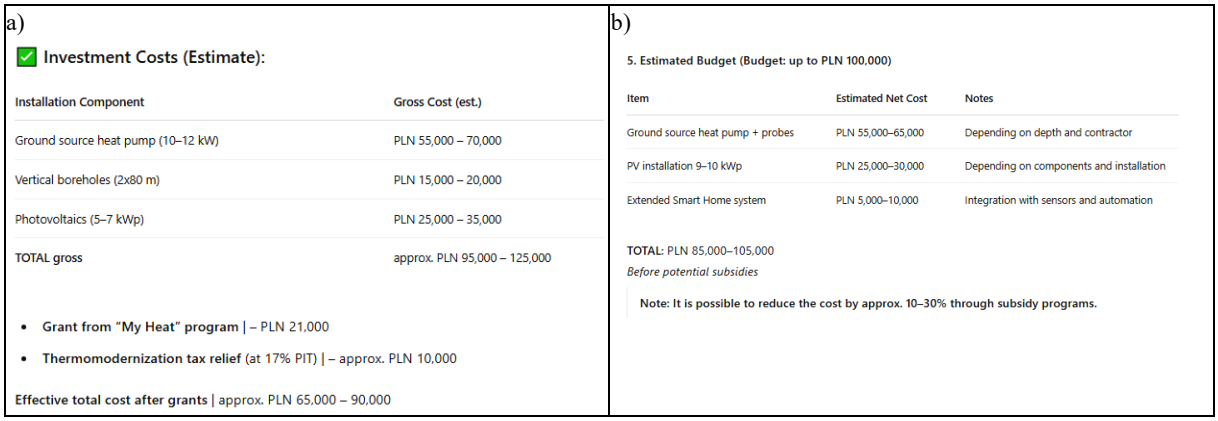


Figure 4. Other differences between the expert system and the original ChatGPT 4o – case 1: (a) costs of alternative heat sources according to the expert system, (b) alternative options suggested by ChatGPT-4o, (c) conclusions of the expert system (d) conclusions of ChatGPT-4o
Source: chatgpt.com.

Case 2. As in the previous case, the expert system asked for the missing information:

- year of construction of the house,
- what is the power connection capacity,
- whether an application for the 'My Heat' program is planned.

Both systems recommended a ground source heat pump with vertical probes and a PV system. In addition, the original ChatGPT 4o model recommended an Energy storage as an additional option (despite exceeding the budget). The original ChatGPT 4o estimated the PV installation power at 9 – 10kWp compared to the power of 7 – 9kWp proposed by the expert system. The original ChatGPT estimated the cost of the entire investment at PLN 85,000 – 105,000 compared to the cost of PLN 95,000 – 125,000 (PLN 65,000-90,000 including the 'My Heat' subsidy) predicted by the expert system. These differences result primarily from differences in the estimated costs of PV and a pump with vertical probes. The original ChatGPT 4o estimated the cost of PV (9 – 10kWp) at PLN 25,000 – 30,000, and the cost of purchasing and installing a pump with probes at PLN 55,000-65,000. In turn, the author's expert system assumed the cost of PV (5 – 7kWp) at the level of PLN 25,000 – 35,000, and the cost of a pump with probes – PLN 70,000 – 90,000. Comparing this to offers on the market, it should be noted that the expert system estimated the costs more accurately. There are also differences in the calculation of the subsidy. The expert system calculated subsidies in the amount of PLN 21,000 ('My Heat' program) and PLN 10,000 of thermal modernization relief. In turn, the original ChatGPT 4o only informed about the possibility of reducing costs by about 10-30%, without providing information about specific aid programs. Figure 5 presents all the differences.


a)

✅ **Investment Costs (Estimate):**

Installation Component	Gross Cost (est.)
Ground source heat pump (10–12 kW)	PLN 55,000 – 70,000
Vertical boreholes (2x80 m)	PLN 15,000 – 20,000
Photovoltaics (5–7 kWp)	PLN 25,000 – 35,000
TOTAL gross	approx. PLN 95,000 – 125,000

- **Grant from "My Heat" program** | – PLN 21,000
- **Thermomodernization tax relief** (at 17% PIT) | – approx. PLN 10,000

Effective total cost after grants | approx. PLN 65,000 – 90,000

b)

5. Estimated Budget (Budget: up to PLN 100,000)

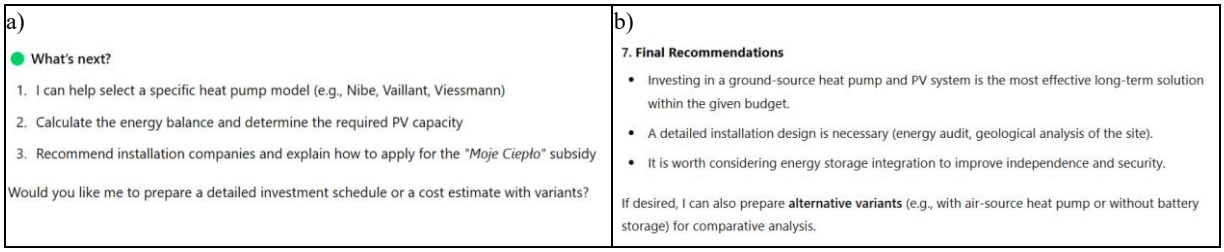
Item	Estimated Net Cost	Notes
Ground source heat pump + probes	PLN 55,000–65,000	Depending on depth and contractor
PV installation 9–10 kWp	PLN 25,000–30,000	Depending on components and installation
Extended Smart Home system	PLN 5,000–10,000	Integration with sensors and automation

TOTAL: PLN 85,000–105,000
Before potential subsidies

Note: It is possible to reduce the cost by approx. 10–30% through subsidy programs.

Figure 5. Recommendations of (a) the expert system and (b) the original ChatGPT 4o – case 2
Source: chatgpt.com.

As the last piece of information, the expert system suggested the selection of specific heat pump + PV sets (specific brands) or calculating after how many years this investment will pay off in relation to, for example, gas heating. Moreover, the system offered assistance with submitting an application for funding under the "My Heat" program. The original ChatGPT 4o suggested comparing the selected heat source to a system with an air-to-water pump or without an energy source. Figure 6 shows the differences between the final conclusions of the expert system and those of the original ChatGPT-4o.


a)

What's next?

1. I can help select a specific heat pump model (e.g., Nibe, Vaillant, Viessmann)
2. Calculate the energy balance and determine the required PV capacity
3. Recommend installation companies and explain how to apply for the *"Moje Ciepło"* subsidy

Would you like me to prepare a detailed investment schedule or a cost estimate with variants?

b)

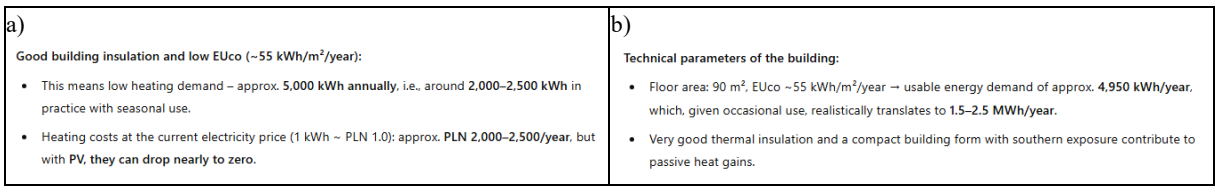
7. Final Recommendations

- Investing in a ground-source heat pump and PV system is the most effective long-term solution within the given budget.
- A detailed installation design is necessary (energy audit, geological analysis of the site).
- It is worth considering energy storage integration to improve independence and security.

If desired, I can also prepare **alternative variants** (e.g., with air-source heat pump or without battery storage) for comparative analysis.

Figure 6. Final conclusions of (a) the expert system and (b) the original ChatGPT 4o – case 2
Source: chatgpt.com.

Case 3. In this case, the expert system had sufficient data and did not ask for additional information. Both systems correctly determined the advantages of the recommended infrared foil heating and correctly calculated the budget. The difference occurred when calculating the seasonal heat demand (2 – 2.5 MWh according to the expert system and 1.5 – 2.5 MWh according to the original ChatGPT 4o). It should be noted here that the expert system's estimate was more precise. Additionally, the expert system determined the annual cost of electricity and suggested using PV to reduce this cost. The indicated differences between the recommendations are shown in Figure 7.


a)

Good building insulation and low EUco (~55 kWh/m²/year):

- This means low heating demand – approx. **5,000 kWh annually**, i.e., around **2,000–2,500 kWh** in practice with seasonal use.
- Heating costs at the current electricity price (1 kWh ~ PLN 1.0): approx. **PLN 2,000–2,500/year**, but with **PV, they can drop nearly to zero.**

b)

Technical parameters of the building:

- Floor area: 90 m², EUco ~55 kWh/m²/year → usable energy demand of approx. **4,950 kWh/year**, which, given occasional use, realistically translates to **1.5–2.5 MWh/year**.
- Very good thermal insulation and a compact building form with southern exposure contribute to passive heat gains.

Figure 7. Recommendations of (a) the expert system and (b) the original ChatGPT 4o – case 3
Source: chatgpt.com.

In addition, the expert system suggested adding heating mats or infrared wall panels to critical points in the house. Both the expert system and ChatGPT 4o suggested calculating the operating costs in the summary (the expert system additionally after the potential installation of PV). In addition, ChatGPT 4o suggested determining the heating power for individual rooms. These options are shown in Figure 8.

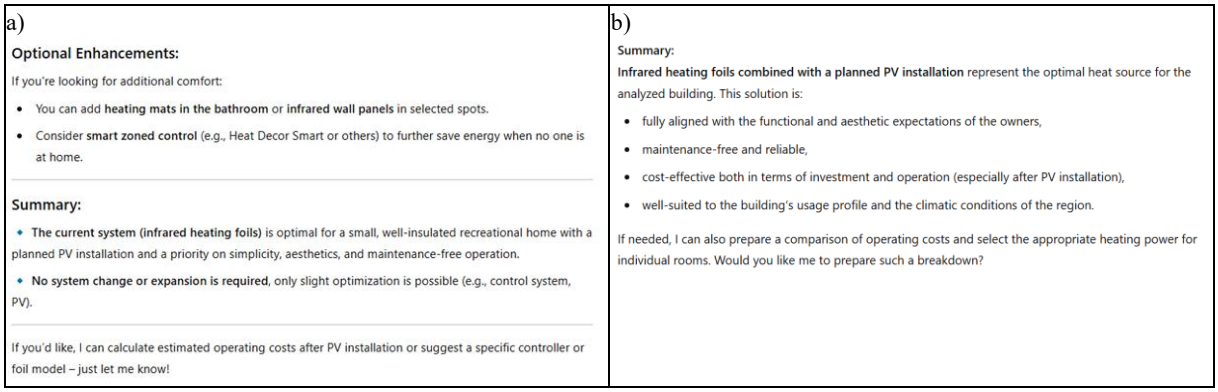


Figure 8. Additional suggestions proposed by the expert system and the original ChatGPT 4o - case 3
Source: chatgpt.com.

Case 4. The biggest differences between the recommendations of the author's expert system and ChatGPT 4o were visible in case 4. The author's system suggested infrared heating foils and a PV installation, while ChatGPT suggested a monoblock air-to-water heat pump. These recommendations are presented in Figure 9.

Analysing expertly case 4 (house after thermal modernization, low-temperature radiators, no natural gas, no space for heating, maximum budget of PLN 30,000), we must note that heating foils + PV are a better solution. They are cheaper to install, less invasive and fully compatible with the owner's lifestyle, and in combination with PV – also cheaper to operate. However, if the initial conditions related to the budget were to be significantly changes (to twice the size), the monoblock heat pump suggested by ChatGPT would be more attractive, especially in combination with PV. However, it is worth noting that when the budget is raised to PLN 60,000, the expert system also recommends a heat pump, optionally combined with PV, as illustrated in Figure 10. However, this is a split pump, technically more advanced than a monoblock pump. This case confirms the advantage of the expert system recommendations over the recommendations of the original ChatGPT 4o.

A comparison of the basic recommendations generated by both systems is presented in Table 1.

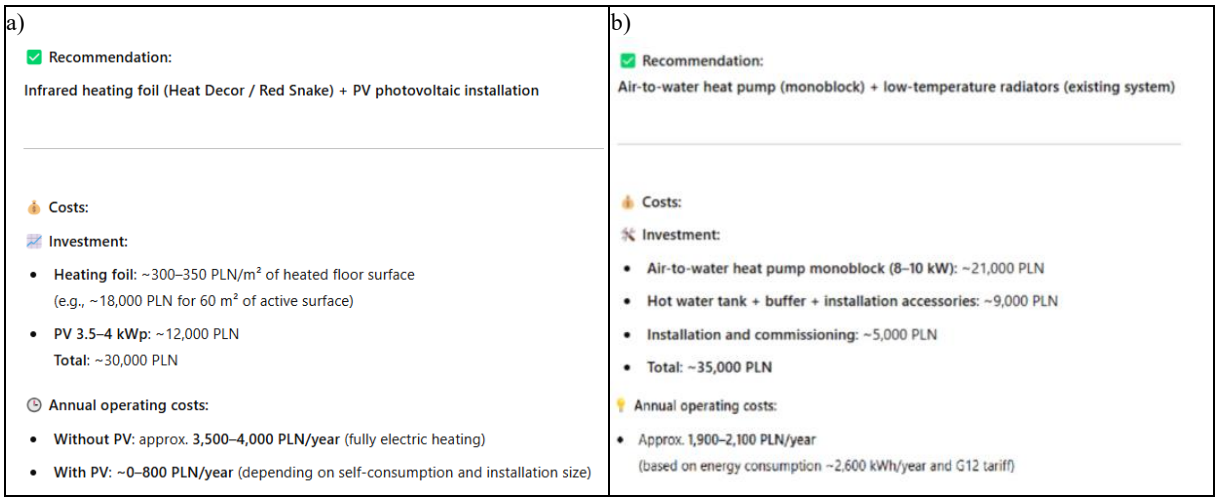


Figure 9. Recommendations of (a) the expert system and (b) the original ChatGPT 4o – case 4
Source: chatgpt.com.

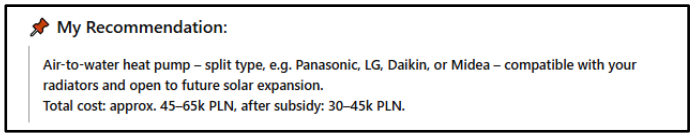


Figure 10. Expert system recommendation for a budget of PLN 60,000 – case 4
Source: chatgpt.com.

Table 1. Comparison of the expert system and ChatGPT recommendations – case 4

	Expert system – heating foils + PV	**ChatGPT 4o – air-to-water heat pump**
Investment cost	PLN 30,000	PLN 35,000
Service	None	None
Annual cost	Without PV: PLN 3,500-4,000 With PV < PLN 800	PLN 1,900-2,100
Disadvantages	No domestic hot water, a boiler needs to be added	Exceeds the budget
Subsidy	Yes	Yes
ETS2 ready	No emissions	Grid emissions (indirect)
Service/maintenance	None	Service every 2-3 years

Source: own elaboration.

4. CONCLUSION

Analysing the research results, it should be noted that in almost all cases both systems correctly recommended heat sources. The expert system, unlike the original ChatGPT, provided more precise calculations and more detailed data. The lack of or partial information provided by the original ChatGPT concerned subsidy programs, ETS2 and expected future costs. The information provided by the user was verified by the expert system in such a way that in the case of incomplete data, the system would ask for details. Thanks to this, the expert system reduced the risk of incorrect recommendations. Additionally, the form of recommendations provided was more user-friendly in the case of the expert system. The research results indicate that modifications of ChatGPT to the role of an expert system are of great importance. Attention should be paid to sociological techniques (approach to user knowledge and information provided by him) and to the creation of knowledge bases dedicated to specific types of recommendation systems. Further research will include the construction of knowledge bases and more advanced GPT-based expert systems related to other complex decision problems.

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THE FUTURE OF AI IN HRM. A CASE STUDY OF THE HR DECISION-MAKING

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ABSTRACT

Purpose: *The purpose of the study was to identify whether companies are actually using artificial intelligence technology in HR departments in relation to the employee life cycle, and to present the possibilities of using artificial intelligence in HRM, in light of the available literature.*

Need for the study: *In the face of dynamic digital transformation and growing challenges in talent management, understanding how AI can transform HRM and HR decisions related to HR functions is becoming crucial for organizations looking to increase efficiency and competitiveness.*

Methodology: *The research methods used in this article include a critical analysis of the source literature, the method of diagnosis of the current state and prospects of the application of artificial intelligence in HRM and the method of synthesis with regard to the construction of conclusions in the theoretical and pragmatic spheres, as well as the analysis of primary data from interviews conducted three Polish companies and presented in the case study.*

Findings: *The analysis and evaluation conducted in the article showed that the implementation of AI in HRM can lead to increased efficiency in HR departments, improved employee and candidate experiences, and more strategic data-driven decision-making. This increases awareness of the potential of technology in improving HR functions and adapting to the challenges of the modern labour market. The future of HR functions using AI will be characterized by greater automation, better data-driven decisions, more personalized employee experiences and a strategic approach to talent management. Nevertheless, potential challenges related to algorithm bias, data privacy and employee acceptance of technology were also identified.*

Practical Implications: *The results obtained can help in planning HR functions and HR decisions, freeing HR professionals from routine tasks, allowing them to focus on more strategic initiatives and contributing to improving overall organizational performance and employee satisfaction. The problems associated with the under-utilization of AI in HRM remain a challenge for the future.*

Keywords: Human Resource Management; Human Resources; Artificial Intelligence; Organizations; Labour Market

Jel codes: J24; O31; O33; M54

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1. INTRODUCTION

With the emergence of AI platforms such as ChatGPT and Google Gemini, the topic of artificial intelligence (AI) has also emerged in organizations. Whether working in a B2B or B2C organization, a start-up, a public institution or a multinational company, executives are thinking about how AI can help the company optimize operations.

Artificial intelligence is a solution that brings more and more benefits and reduces the responsibilities of HR departments. Today, in many companies, AI is responsible for, among other things, the creation of automated candidate databases, detailed analysis of submitted resumes, recording of working hours or posting job offers on multiple portals, and the use of new technologies allows to reduce the costs associated with recruitment and increase the efficiency of HR departments. It should be added that this is because HR departments have developed in a way that is driven by technology and the data that employees constantly provide to enhance their strategic role in the company. One of these technologies is artificial intelligence, treated as a science that aims to replicate aspects of human intelligence, such as learning, reasoning, perception, critical thinking, etc., using logic-driven computer programs (Villani, 2018). Another definition can also be provided, treating AI as the ability of a system to correctly understand input data, learn from it, and apply it to achieve specific goals and tasks through adaptive implementation (Kaplan & Haenlein, 2019). Therefore, human intelligence is enhanced by AI because it frees up workers to perform tasks that can be automated, thus enabling them to develop skills and knowledge in a more productive way (Sanyaolu & Atsaboghena, 2022).

Organizations are undergoing significant digital upheaval, with an apparent shift toward integrating AI into decision-making processes to ensure business success and growth (Varsha, 2023). Companies are being forced to improve their organizational functioning and develop the skills of their human resources to achieve optimal company performance (Wolor et al., 2020). Therefore, companies have begun to recognize the inevitability and importance of AI in human resource management in order to survive in a rapidly changing environment and survive amidst intense competition (Waheed et al., 2019). As AI has permeated almost all fields and gained much attention, researchers are now focusing on constructing strategic human resource management practices supported by AI technology (Wang et al., 2020). Organizations around the world are facing the challenges of cutting costs and saving time, and the combination of Internet-like technologies, machine learning and artificial intelligence in the management process as a strategic element can help solve these challenges (Hemalatha et al., 2021). Undoubtedly, artificial intelligence has a promising future in human resource management. However, it should be noted that integrating artificial intelligence into HR processes comes with challenges such as this, that artificial intelligence can only operate efficiently like a human if it receives high-quality data. There is also a risk that confidential documents and procedures/policies shared by organizations, could be misused.

In the face of dynamic digital transformation and growing challenges in talent management, understanding how AI can transform HRM and HR decisions related to HR functions is becoming crucial for organizations looking to increase efficiency and competitiveness. Therefore, human resource management (HRM) is facing new challenges that need to be solved while ensuring optimal growth and development of the organization. They have begun to wonder in which HR decisions, AI will improve the work of Human Resources (HR) departments. Can artificial intelligence in HRM bring numerous benefits, for example, in improved employee experience, increased productivity, reduced recruiting costs, faster problem solving and decision making, or reduced routine duties? This study identifies the application of technologies and artificial intelligence in HR departments in relation to the employee life cycle: recruitment and selection, induction process, employee retention, compensation management, overall employee management. The purpose of the article is also to present the possibilities of using technology based on artificial intelligence in HRM in light of the available literature. Thus, two research questions are posed: how does AI support HR professionals in practice, and what are the current limitations of this technology and prospects for its development in HRM?

Despite these challenges with artificial intelligence, companies are showing interest and making significant efforts to integrate artificial intelligence into HR functions, as the benefits of using artificial intelligence in HR outweigh its challenges (George & Thomas, 2019). Organizations can enjoy the benefits and potential of artificial intelligence if they are willing to transform their employees to work

efficiently with intelligent machines. This process will undoubtedly take time, but the benefits will be very large (Mathipriya et al., 2019).

2. LITERATURE REVIEW

2.1. Application of Artificial Intelligence in HRM

Digitization, artificial intelligence and automation of business processes arouse much excitement in society. It is also a topic that is being addressed today by a great number of researchers and human resource management specialists. There is much debate over the ethical layer of the solutions used. On the one hand, companies see new technologies as a panacea for the operational problems they face every day. They see them as an opportunity to increase business efficiency, save money, increase the productivity of their employees. With technologies, they want to increase production, reduce prices. New technologies are responding to changes in the work environment and the challenges employers face today (Kohnova et al., 2019). Digitalization is having an impact on both employees and employers in the areas of new professions, competence development or forms of work, among others (Strzelczyk, 2019). On the other hand, others are concerned that the new technology will exclude certain professional groups, especially those in smaller localities with lower levels of education. Many fear that their work will be replaced, automated (Sohani et al., 2025). No doubt this will happen to repetitive, simple administrative jobs. On the other hand, many jobs will be enriched. Increasingly, the acronym AI, instead of artificial intelligence, is translated as augmented intelligence. This approach and concept of AI points to the enrichment, streamlining of human work, in order to better utilize human potential (Singh, 2020).

AI technologies have begun to develop consistently and gain a significant foothold in almost all fields, including medicine, engineering, agriculture, organizational management, tourism, transportation, etc. (Mintz & Brodie, 2019) and have entered both public and business environments (Haenlein & Kaplan, 2019).

Artificial intelligence is among the most influential technologies changing the labor market. Artificial intelligence systems are increasingly being used in the field of human resource management.

To address the topic of AI and its impact on HRM, it was decided to provide a definition of human resource management, which the authors will use throughout this paper. Human resource management is the adoption of specific functions and activities for the efficient and effective use of employees in an organization to achieve its goals, which include maximum satisfaction of key stakeholders and positive contribution to the environment. It includes the formulation, implementation and ongoing maintenance of strategies, policies, procedures, principles, practices and systems for strategic, participatory and sustainable management of employees (Opatha, 2021).

Analyzing the literature on the subject and the studies described therein (Zhai et al., 2024), it can be seen that artificial intelligence has a beneficial impact on the HRM field. This has been noted by, among others: Jia, Guo, Li and Chen (2018), Vivek and Yawalka (2019), George and Thomas (2019), and Garima, Vikram and Vinay (2020), who discussed the advantages of implementing artificial intelligence, throughout the employee lifecycle. Garima, Vikram and Vinay (2020) concluded that artificial intelligence replaces routine tasks in HR with less human intervention. Vivek and Yawalka (2019) noted how AI helps reduce workload and increase efficiency in the workplace.

AI is shaping the future of human resource management in many ways: from streamlining recruitment processes with predictive analytics to personalizing employee development programs with machine learning algorithms (Gigerenzer & Todd, 1999; Jia et al., 2018; Cappelli et al., 2019; Bankins & Formosa, 2020). It should be emphasized that in a process referred to as “algorithmic management” (Bankins et al., 2022), AI systems are used to evaluate candidates in the recruitment and selection process (Marr, 2018), assign jobs (Lee et al., 2015), provide training recommendations (Guenole & Feinzig, 2018) and, for example, terminate employee relationships (Kellogg et al., 2020).

On the positive side, artificial intelligence has the potential to revolutionize HRM by automating routine tasks such as resume screening and data entry (Atsalakis, 2014; Stone et al., 2015; Brynjofsson et al., 2017). What's more, AI-based predictive analytics can facilitate more accurate talent acquisition and workforce planning, ultimately leading to improved recruiting outcomes and reduced turnover rates (Stone et al., 2005; Dineen & Soltis, 2011; Dineen & Allen, 2013). AI can also enhance employee

engagement and development through personalized learning experiences and real-time feedback (Chapman et al., 2003; Orvis et al., 2011; Cleveland et al., 2015; Stone et al., 2015).

Jia, Guo, Li, and Chen (2018) found that most organizations are not fully ready to implement AI in their HR functions, and Vivek and Yawalka (2019) observed that it is difficult to find the right employees to operate AI tools, and artificial intelligence is limiting HR departments in decision-making as technology is apparently taking over this aspect. Nevertheless, it is important to recognize the potential drawbacks of artificial intelligence in HRM. Over-reliance on AI can inadvertently lead to bias in decision-making, as algorithms can perpetuate historical discrimination present in the data they are trained on (Li, 2019; Cheng & Hackett, 2019). In addition, depersonalizing HR processes through AI-based automation can undermine the human element, which is crucial to employee morale and well-being. There are concerns about the lack of privacy and security of sensitive data as HR departments handle confidential employee information (Piccoli et al., 2001; Johnson et al., 2008; Ritzer, 2011; Jeske & Santuzzi, 2015; Duggan et al., 2020; Braganza et al., 2021).

AI works in HRM through two modes of human-machine collaboration: augmentation and automation (Jarrahi, 2018; AlHarthi, 2025). When considering augmentation, it refers to AI's ability to work alongside humans by influencing HRM and is called “computerization of HR tasks”. Automation, on the other hand, is considered as replacing humans with machines and is called “automation of HR tasks” (Raisch & Krakowski, 2021). Rightly, however, Stein and Scholz (2020) proposed that HRM and automated management should be combined into the Human Resources Management and Automation Model (HARM), which can be considered the evolutionary direction of HRM.

The impact of AI on HR is a topic beyond the field of HRM due to its interdisciplinary nature. For example, the development of AI-based HR tools depends on advances in technical fields, while the implementations of such AI tools and the consequences of AI implementations rely on knowledge from the social sciences (Jangbahadur et al., 2025). Scientists from various disciplines have contributed to AI-HRM knowledge. For example, computer scientists have developed AI algorithms to solve HRM problems (e.g., Anandarajan, 2002; Blanchard & Henle, 2008). Economists have discussed the impact of AI on labor markets (Berg et al., 2018). Psychologists have found that the use of AI does not demotivate job candidates during recruitment (Van Esch et al., 2019), but can result in higher employee turnover (Brougham & Haar, 2020).

It is noted that AI can have negative consequences, such as eliminating jobs and increasing social inequality, but it can also provide benefits, such as improving or expanding jobs instead of replacing them (Vashishth et al., 2025). Certainly, AI will have a significant impact on the future of human resource management, and the application of AI to HRM has great potential (Malik, et al., 2020; Malik et al., 2021).

With increasing digitization, artificial intelligence is becoming more prevalent in HR management and HR information systems. AI integration includes tactical procedures such as recruitment, performance and employee satisfaction assessments, compensation and benefits analysis, best practices analysis, discipline management, and employee training and development systems (Votto et al., 2021).

Organizations are undergoing significant digital upheaval, with an apparent shift toward integrating AI into decision-making processes to ensure business success and growth (Varsha, 2023). Companies are forced to improve their organizational functioning and develop the skills of their human resources to achieve optimal company performance (Wolor et al., 2020). Therefore, companies have begun to recognize the inevitability and importance of AI in human resource management in order to survive in a rapidly changing environment and survive amidst intense competition (Waheed et al., 2019). As AI has permeated almost all fields and gained much attention, researchers are now focusing on constructing strategic human resource management practices supported by AI technology (Wang et al., 2020). Organizations around the world are facing the challenges of cutting costs and saving time, and the combination of Internet-like technologies, machine learning and artificial intelligence in the management process as a strategic element can help solve these challenges (Hemalatha et al., 2021). Undoubtedly, artificial intelligence has a promising future in human resource management. However, it should be noted that integrating AI into HR processes comes with challenges, such as the fact that AI can only operate efficiently like a human if it receives high-quality data. There is also the risk that confidential documents and procedures/policies shared by organizations, could be misused.

Despite these challenges with artificial intelligence, companies are showing interest and making significant efforts to integrate artificial intelligence into HR functions (Rabenu & Baruch, 2025), as the

benefits of using artificial intelligence in HR overshadow the observed challenges (George & Thomas, 2019). Organizations can enjoy the full benefits and potential of artificial intelligence if they are willing to transform their employees to work efficiently with intelligent machines. This process will undoubtedly take time, but the benefits will be very large (Mathipriya et al., 2019).

2.2. Artificial intelligence in data analysis for improved decisions in HR business strategy

Data analysis using artificial intelligence opens up new opportunities for companies to optimize their business strategies. Processing huge data sets in real time allows the identification of market trends that may escape traditional analysis methods. As a result, organizations can respond more quickly to changing market conditions, which is key to staying competitive.

Improving data analysis and decision-making in HR departments through AI is predicated on several factors, as shown in Table 1.

Table 1. Determinants of data analysis and decision-making in HR departments through AI

Factors	Characteristics of AI activities
Data availability and quality	AI needs the right quantity and quality of data to effectively analyze and generate valuable insights; HR departments collect a variety of data on employees, candidates, HR processes, etc. (e.g., HR data in applications, results of periodic evaluations, satisfaction surveys, online recruitment data); unifying and storing this data is key; it is also possible to expand databases with data from the external environment
Implement the right AI tools and technologies	The availability and implementation of AI-based HR analytics tools is essential; there are many algorithms and data analysis methods that are particularly useful in HR, such as clustering, classification, time series analysis, pattern detection, causal modeling
Digital and analytical competencies of HR professionals	HR professionals need to be digitally competent and capable of working with AI tools and interpreting analytical results; conferences for HR departments are increasingly focusing on AI, indicating a growing need to develop these competencies
Understanding business needs	HR professionals need to understand the organization's business needs in order to use AI to provide analysis and recommendations that contribute to strategic goals
Compliance with regulations and ethics	The acquisition and handling of employee data through AI must respect legal acts and employee rights, including data protection personal and privacy; ethical and responsible use of automated decision-making systems is important

Source: own elaboration.

To improve data analysis and decision-making by HR departments through AI, there is a need to move from an intuitive and experience-based to a more objective and evidence-based (data-driven) approach. Key aspects of this improvement include automation and efficiency. AI automates the collection, storage and analysis of large amounts of data, which significantly increases the efficiency of HR departments. This reduces administrative burdens and allows HR professionals to focus on more strategic tasks. Insightful analysis and pattern identification are related to the fact that AI excels at finding connections and patterns between any data, which can be difficult to capture with traditional methods. This makes it possible to identify the success factors of top managers, the drivers of errors, fraud and accidents, as well as patterns of employee engagement and exit risk. AI enables predictive analytics and forecasting to use big data to predict staffing needs and optimize hiring strategies. It allows predicting the success of an organization or the performance of employees or teams, as well as forecasting (short- and long-term) and supporting HRM problem-solving activities. Reducing subjectivity and bias, on the other hand, involves reducing subjectivity and using objective data when evaluating employees and candidates through the use of artificial intelligence, subject to appropriate programming and ethical considerations. On the other hand, support in strategic decision-making, through AI's analysis of data, results in the provision of valuable information and conclusions that can be used to improve decisions in HR departments' business strategy.

The implementation of AI in the data analysis process brings a number of benefits, which can be presented as follows:

1. Automation and efficiency: Artificial intelligence can automatically process and analyze data, reducing the need for manual work and minimizing the risk of errors.
2. Personalizing offers: With its ability to analyze customer behavior and preferences, AI enables the creation of more personalized offers, making them more effective. In the HR context, personalization can refer to development programs or career paths.
3. Trend forecasting: Using advanced predictive models, artificial intelligence can forecast future market trends, enabling companies to better plan and strategize. In the HR context, this can include, for example, forecasting employee turnover rates.

The application of artificial intelligence in data analysis not only increases the precision and speed of information processing, but also opens the door to a deeper understanding of the market. As a result, business decisions can be made on the basis of solid data, which significantly affects the efficiency and effectiveness of business strategy. As a result, companies that invest in the development of AI technologies gain a competitive advantage, which in today's fast-changing business world is priceless.

Predictive analytics is becoming a key tool in strategic talent management. AI systems analyze data from a variety of sources, including e-learning platforms, Customer Relationship Management (CRM) systems, project management tools and internal communication systems, to support HR decisions.

HR departments using AI can save a significant amount of budget, allowing reinvestment in employee development and innovation. In addition, AI provides valuable analytics that HR departments can use to appropriately manage human resources, monitor employee satisfaction and engagement, and assess exit risk. AI also makes it possible to continuously monitor competitive offerings in the labor market, allowing companies to respond quickly to changing employee needs.

In conclusion, artificial intelligence is a powerful tool for data analysis in HR departments, enabling more informed and strategic decision-making. Among other things, the use of AI in data analysis contributes to more efficient HR processes, a better understanding of market trends and employee needs, and potentially to cost reductions. It should be emphasized that AI-enabled analytics are playing an increasingly important role in strategic talent management, supporting recruitment, development and retention decisions. Despite the numerous benefits, it is important to keep in mind the ethical aspects of using data and ensuring data security.

2.3. Recruitment and selection

Automating and optimizing recruitment processes and screening candidates are among the key developments in which artificial intelligence is becoming increasingly important. Finding the right candidate for a given vacancy can be difficult, as you need to locate the right candidate from a pool of many talents on the job market and looking for work. Creating a list of candidates and reviewing resumes to find the right job candidate can be a daunting task (Garima et al., 2020). You should reach out to the right candidates while trying to fill positions as quickly as possible, as a vacancy can cost an organization a lot of money due to operational delays. Ensuring that the candidate has good experience and skills is key, as it increases the chances that the candidate will accept the offer.

Artificial intelligence can support recruitment processes in the following ways, through:

- preparation of job offers – AI technology is very quickly able to prepare content templates and concretized job offers,
- analyzing applications – processing huge amounts of information; this advantage can be used to accelerate the analysis of applicants' applications for a given position,
- automation of answers – a properly prepared chatbot sends automatic answers to the most frequently asked questions sent, for example, by job candidates.

By using AI tools, the recruitment process is much faster, while the selection of candidates itself is more efficient and precise. HR departments are using the developing AI to identify the best candidate for a vacancy in the recruitment process.

Many companies that have not yet implemented AI in the recruitment process are planning to do so in the near future, where they will be able to use artificial intelligence in the recruitment process to: create job ads, determine the specifics of the job, post job ads on multiple portals automatically, search for potential candidates on popular portals, e.g. Linkedin, schedule meetings, accurately screen candidates, accurately analyze resumes, upload screening tests, answer repetitive questions, analyze

data. The advantage of using artificial intelligence tools is that it reduces the burden on HR staff over the years and avoids subjective evaluations by recruiters.

Artificial intelligence can thus help speed up the hiring process, even as hiring requirements continue to grow (Skil AI, 2020). It can be involved in automating repetitive tasks by first working on large data sets and analyzing them to obtain employment trends. It can also be used to streamline the hiring process during recruitment. AI technology, such as chatbots, can be added to an organization's sites to engage visitors and increase conversations. This helps save time, as some of the work in recruiting, such as gathering candidate information, prequalifying candidates, scheduling meetings and chat times, and providing the candidate with answers to basic questions, can be done using chatbots (Skil AI, 2020; Aldulaimi et al., 2020). Machine learning techniques can be used to help interpret the large amount of data received and discover patterns not previously identified by the organization. AI technology can help screen resumes and identify suitable candidates for a position.

An organization's experience, skills, education level and many other interests are checked before accepting a candidate for a position using models trained in machine learning. This technology can help narrow down the list of all candidates by sorting those with the most relevant skills. It will only consider candidates based on qualifications and will help eliminate bias if programmed properly (Parveen & Palaniammal, 2019). AI can also perform background checks, such as checking candidates' social media profiles, to ensure that the selected candidate is the most qualified. This will save the recruiter time, ensure a fair hiring process and ensure the best candidate is hired. Most organizations find it difficult to engage and re-engage potential clients because it takes a lot of time. Companies usually do not receive responses from candidates after they have applied for a position or after an interview.

Software that incorporates artificial intelligence, such as Chabot, Applicant Tracking System (ATS) and Customer Relationship Management, helps provide real-time answers to all questions asked by candidates and provides updates on their progress. By implementing artificial intelligence in HRM, subjective criteria such as favoritism and nepotism are less likely to play a role in the recruitment and selection process of potential candidates (Tewari & Pant, 2020). Artificial intelligence can also be used to draft and send personalized correspondence to potential candidates.

In addition, artificial intelligence can analyze conversion rates, that is, measure how many applications lead to interviews, making it possible to identify the most effective strategies for reaching candidates, both during and after the recruitment process. This kind of optimization helps streamline the talent acquisition process and increase efficiency with each new hire.

However, it is also important to note the limitations and need to preserve the human aspect in recruitment. The final hiring decision and the conduct of subsequent recruitment stages still belongs to humans. It is also stressed that AI is meant to support, not replace, human work. In addition, it is important to keep in mind potential AI errors (hallucinations) and the need to verify candidates' knowledge of AI during recruitment interviews.

Artificial intelligence is revolutionizing the way organizations approach human resource management. For example, automating selection processes allows for faster and more efficient screening (selection) of candidates, which is crucial in a dynamically changing business environment. Thanks to advanced algorithms, it is possible to more accurately match the competencies of applicants (applicants), with the requirements of the job, which significantly affects in HRM the quality of the recruitment process.

In summary, AI is transforming recruiting by automating and optimizing processes, streamlining selection, using chatbots, personalizing communications with candidates, and analyzing data to increase efficiency. Despite the many benefits, it is crucial to balance AI's capabilities with the indispensable role of HR professionals and human assessment.

2.4. Onboarding

Once a new employee is hired, the induction process begins. Artificial intelligence in HR can greatly streamline this process by sending employees automatic reminders about missing documents or uncompleted tasks. It can also support employees in completing these tasks correctly, such as filling out forms, to reduce additional questions and correspondence. This makes the implementation process faster, more efficient and less stressful for both employees and HR.

Onboarding is one of the most important stages in an employee's path within an organization, but it traditionally comes with numerous challenges. For many companies, it is a time-consuming process,

and the lack of standardized procedures often leads to mismatched expectations and inefficiencies. As the job market grows and turnover increases, employees expect a better onboarding experience - one that is simpler, more intuitive and tailored to their individual needs. The reality, however, is that many employers are failing to keep up with these changes, which can affect their reputations and cause a decline in new employee engagement. This could represent a breakthrough, reducing implementation time and enabling a more fully personalized experience for new employees.

Various works on AI in HRM refer to onboarding. For example, Prikshat et al. (2021) focus on how to promote employee adoption of AI applications, while Votto et al. (2021) illustrate possible applications of AI applications in onboarding, such as job tracking or training analysis. In related work on using AI to improve the employee experience, most of the focus has been on chatbots. Thus, Meyer von Wolff et al. (2020) suggested using chatbots only to answer newcomers' questions.

Artificial intelligence significantly affects the employee deployment process, streamlining it and making it more efficient (Babic, 2021). In practice, AI supports HR professionals and new employees in a number of ways:

- automation of routine tasks: AI can send automatic reminders to employees about missing documents or unperformed tasks; it helps them perform these tasks correctly, such as by assisting them in filling out forms, which reduces the number of additional questions and correspondence; with AI, information flow and document delivery can be automated,
- streamlining access to resources: AI enables automatic transfer of access to important platforms, training and other specific company resources; new employees can get the necessary tools and information to get started faster,
- information support and problem solving: By automating contact with the HR department and finding answers to frequently asked questions, AI provides new employees with quick support and eliminates the delays associated with waiting for an answer from an HR specialist,
- personalization of the implementation process: AI allows the creation of interactive quizzes, tests, training exercises, scorecards or an automatic reminder system tailored to specific positions and the needs of new employees,
- monitoring progress and identifying needs: the HR department, thanks to AI, has a constant view of data on the deployment process, which allows it to assess the speed of new employees and implement possible assistance when needed; AI can track the cycle of employee development and reduce the need to control the timing of mandatory training,
- reduced deployment time: the use of AI contributes to reducing the deployment time of new employees and ensures that all the steps involved in preparing their workplace will be ready on time; the deployment process becomes faster, more efficient and less stressful for both employees and the HR department.

AI automates many routine and time-consuming onboarding tasks. It streamlines the flow of information and access to resources. AI makes the process more interactive and personalized. HR professionals gain tools to monitor the progress of new employees and respond quickly to their needs. Ultimately, AI contributes to reduced deployment time and increased efficiency.

In the future, AI may further revolutionize the onboarding process, becoming a more intelligent and proactive assistant for both new hires and HR. As such, the trends presented in Table 2 can be expected.

Table 2. The future of using AI in employee adaptation

Trend	Characteristics
Hyper-personalization	AI systems will be able to create highly personalized onboarding paths based on each new employee's role, skills, learning style and preferences; AI can analyze data on existing employees in similar positions to provide the most relatable information and tasks
Virtual assistants and AI mentors	More advanced AI-based chatbots and virtual assistants will be able to answer more complex questions, provide guidance and act as virtual mentors, guiding new employees through their first weeks and months on the job; they can also proactively provide information and reminders about important tasks

Integration with immersive technologies	AI can work with virtual (VR) and augmented (AR) reality to create immersive onboarding experiences, such as virtual office tours, getting to know teams and interactive job training
Sentiment analysis and early detection of problems	AI systems will be able to analyze new employees' communications and interactions (e.g., in internal communication systems) to detect potential problems early on, such as feelings of confusion, lack of integration into the team, or difficulty with tasks, allowing HR to proactively offer support (rapid intervention and provision of support)
Automatic networking	AI can suggest new employees to new contacts in the organization based on roles, projects and interests, making it easier to integrate into the team and build relationships
Continuous evaluation and optimization of onboarding in real time	AI will be able to continuously monitor the progress and engagement of new employees, providing HR with real-time data on the effectiveness of the onboarding process and areas for improvement

Source: own elaboration.

Many studies highlight the growing role of AI in HRM, including onboarding processes. The research indicates that most HR leaders plan to increase their use of AI in at least one area of HR in the coming months, which includes onboarding new employees. The future of onboarding using AI promises to be more personalized, interactive and effective, with AI acting as an intelligent assistant to support new employees at every stage of their adaptation in the organization. Employee onboarding conducted using AI tools thus ensures that the employee is familiar with all the most important information.

2.5. Impact of AI on other personnel functions

In the context of HR, AI refers to the use of artificial intelligence to optimize processes to support an organization. For example, talent management support relies on the fact that AI can support the best employees, can be used to attract the most suitable candidates, and match employees' skills, competencies and personality traits to positions. It can also assist in planning career paths. It is also helpful in detecting informal structures and flows through AI-assisted analysis of HR data, which can identify network nodes, key individuals, user groups and information flows in an organization. In terms of personalizing the employee experience, AI makes it possible to customize development programs and career paths, increasing employee engagement and satisfaction.

As noted above, the implementation of AI solutions in human resource management is not limited to the recruitment process. These systems also support the development of employees by monitoring their progress, including by analyzing training needs and personalizing career paths. As a result, employers can not only retain the best talent in their teams, but also effectively support their professional development. The impact of using AI in HR, is shown in Table 3.

Table 3. The future of using AI in employee adaptation

Functions of HRM	**Using AI in Human Resources**
	The entire personnel cycle
HR in HR decisions using AI and the work of the HR department	• HR processes will begin to work more efficiently, be transparent and effectively attract talent to your organization, • real savings: lower costs associated with HR tasks performed by employees, • efficiency: automation of repetitive HR tasks and less risk of errors, • possible joint integration of HR systems with other tools: possibility to reuse data from all systems, • clear task statuses for different departments/divisions, • automation of data entry into HR and financial systems, • automation of account creation and authorization in IT systems, • supporting managers in managing the team, improving communication with the HR department, • employee self-service, support for employee mobility and remote working.
Employee records	• e-file: automatic collection of documents within an employee's e-file,

	• meeting legal regulations and reducing the cost of storing and handling employee records, • constant and quick access to documents, • security, confidentiality, integrity, availability, accountability.
Register of contracts	• automation of contract preparation based on data, for example, from previous recruitment stages, • generation of a contract document based on the template in force in the company, • integration with systems providing electronic signatures, • monitoring and reporting on terms, types of contracts, terms of employment, • creation of a secure digital archive of contracts, • reduce contract storage costs, • gain better control over contract expiration dates.
Time records	• provide employees with an easy and intuitive platform for time reporting • improve communication with managers and support them in managing their team
Vacations and business trips	• streamlining the process of vacation request notification and approval: the supervisor can verify the date of leave based on the days off of team members, automatic notification of the HR department and setting up a replacement, • accounting for the cost of business trips using a dedicated program/platform..
Managing remote workers	• thanks to applications related to timekeeping, task management or mailroom, you can effectively monitor the tasks that the team is currently performing, • acilitating collaboration outside the office.
Performance management	• create performance management reports based on analysis of a variety of data, • ability to identify areas of inefficiency and help reduce burnout.
Keeping employees engaged	• analyzing data to monitor employee engagement and identify exit risks, • gathering feedback from employees and increasing their engagement through regular surveys and data analysis.
Company culture	• analyze team interactions to identify disruptions in workflow and promote positive interactions,
Planning	• using big data to predict staffing needs and optimize hiring strategies
Recruitment and selection	• automation and optimization of recruitment processesstreamlining the recruitment process, using a dedicated application to help handle and monitor the entire recruitment process, • using a platform that will help process candidate data securely.
Onboarding	• reducing the time to deploy new employees, • all activities related to the preparation of the workplace of new employees prepared on time, • monitoring the employee's progress as part of the onboarding process, • imely completion of onboarding tasks.
Salaries	• payroll processing, allowing employees to manage their financial data themselves, • ensure near 100% accuracy and minimize the risk of payment errors, • managing the employee bonus process with, for example, an app that collects key information in one place and will allow sensitive data to be processed securely.
Evaluation employee	• access to employment history, • effective assessment of employee competence and development, • comprehensive support of the process of periodic evaluation of employees, • tailoring, for example, the application to the individual needs of a given organization, so that the competence assessment is carried out efficiently and effectively.

Employee development and training	• personalizing the employee experience, • customizing career paths and training programs to meet individual employee needs, • tracking the cycle of employee development, reducing the control of the timing of mandatory.
Offboarding of employees	• notifications of ending contracts, • access to the employee's employment history, • automation of locking accounts and revoking privileges when an employee leaves, • monitoring the return of assigned equipment.

Source: own elaboration.

In the future, AI will play an even greater role in HR functions, becoming a more intelligent and proactive tool. Further hyperpersonalization, development of virtual HR assistants, integration with immersive technologies, advanced sentiment analysis and proactive support for employees can be expected. AI will also support continuous evaluation and optimization of all HR processes.

In summary, AI is transforming HR functions, offering tools for efficiency, personalization and data-driven decision-making. The key, however, is to implement these technologies responsibly, taking ethical considerations into account and balancing automation with the irreplaceable human factor.

3. METHODOLOGY

3.1. Scope

At the stage of conceptualization of the study, the research problem and objectives were formulated adequately to the main research subject of interest included in the article. The paper uses the research methodology used in the social sciences, especially the methods, techniques and instruments of qualitative research of a universal nature, including:

- the method of analysis, especially document analysis, i.e., critical analysis of the literature on the subject (compact and periodical), reference materials, industry reports and relevant Internet sources,
- a method for diagnosing the current state and prospects of applying artificial intelligence to human resource management,
- synthesis method with regard to the construction of conclusions in the theoretical and pragmatic spheres.

In the applied research approach, in addition to the determination of the research plan and the selection of appropriate research methods and techniques, the stage of analysis, interpretation and verification of the collected research material was included, as well as implicitly the stage of formulating constructive conclusions and presenting the results of the study. The article also conducts a deductive analysis of the situation in HR departments in Polish companies, based on the research conducted, taking into account the impact of artificial intelligence on HRM-related decisions.

The main objective of this study was to identify:

- whether companies are actually using artificial intelligence technology in HR departments in relation to the employee life cycle: recruitment and selection, induction process, employee retention, compensation management, overall employee management
- to present the possibilities of using artificial intelligence-based technology in HRM, in light of the available literature.

The main objective of this study was to identify whether companies are actually using artificial intelligence technology in HR departments in relation to the employee life cycle: recruitment and selection, induction process, employee retention, compensation management, overall employee management, and to present the possibilities of using artificial intelligence-based technology in HRM, in light of the available literature. To this end, a literature study and inference based on a case study were used. The timeframe of the research questions covers the period from 2020 to 2025.

3.2. Methodology & data description

The research presented in this paper contributes to a better understanding of the gap in the essence and role of artificial intelligence technologies in HR departments in relation to the employee lifecycle, and in particular the use of AI-based technologies in HRM.

This study was based on both secondary and primary data obtained from interviews. The stages of the research process included:

1. To assess the current state of knowledge on the use of AI-based technology in HRM, with a focus on AI and HRM, HR departments' decisions related to the use of AI, Application of Artificial Intelligence in HRM and the employee life cycle (including in HR data analysis, recruitment and selection, employee adaptation and other HR functions). The study focuses on analyzing the literature related to AI, HRM and HR function to answer specific research questions and extract important elements from the literature related to these three areas. To the authors' knowledge, research in this area is still inadequate, as shown by the literature review conducted between January and March 2025. For this purpose, source literature and data were collected from available sources and websites. A review of both Polish and foreign literature was conducted. Completion of this stage made it possible to present the possibilities of using AI in HRM in light of the available literature.

2. Conduct a pilot study, in the form of interviews in 3 medium-sized enterprises in the Kujawsko-Pomorskie Voivodeship in Poland, implemented from February to March 2025. The results of the research are presented in the case study. The implementation of this stage served to prove that companies want to use AI in HRM. It was shown that artificial intelligence supports HR professionals, but to a limited extent. Companies want to use AI more extensively because they see that automation speeds up processes and improves the efficiency of day-to-day work and supports HR decisions, and that all the companies surveyed actually use AI in HRM. The survey also identified the limitations of AI technology in its use in HRM and the prospects for its development in the surveyed organizations, and confirmed that in practice AI supports HR professionals.

3.3. Participants

The pilot study involved interviews with 3 people representing the HR department of the companies surveyed, ranging in age from 35 to 53. Two of the respondents were men, one was a woman. They were experts in their field, holding managerial positions. In the surveyed companies, 2 participants had worked since graduation, for one respondent it was the third job. The participants in the study had a university degree in economics. The sample selection for the interviews was purposive. The number of the sample was 5 interviews, but two respondents did not agree to be interviewed, excusing themselves with too much workload. Two HR Directors and one HR Manager participated in the survey. All respondents agreed to participate in the study. They were informed that the survey would be anonymous.

Each interview was recorded and, after transcription, removed from the recorder. The interviewer asked one question each time, and after obtaining an answer, asked a second question. He did not prompt the respondents or suggest answers. All those who provided answers consented to the recording and use of their answers in the article. Then, the interviews were coded. The case study presents the respondents' answers.

Due to time constraints, the authors did not conduct research in a larger number of companies. They did not use any other European market for research than the market of Polish companies. In the future, the authors intend to deepen and expand the research.

3.4. Procedure

Potential participants were invited to take part in the study, through a telephone interview that took place in the first week of January 2025. Three interviews were conducted with HR managers at three medium-sized companies in the Kuyavian-Pomeranian region. The companies were selected purposively, based on the assumption that these organizations declared on their websites that employees are the most valuable resource for the company. The interviews took place stationary. For security and RODO reasons, it was decided not to present by name the respondents and the names of the companies where the interviews were conducted. Before the interviews began, participants were informed of the anonymity of the study by giving their consent. The companies were named Company X, Company Y and Company Z.

The directors and HR manager were asked to answer the following questions:

Question 1: Has/will your company introduce artificial intelligence technologies in HRM between 2020 and 2025? If it has introduced, which ones and what do they consist of? If not, why and does it want to introduce AI into HR tasks in the future - to what HR functions?

Question 2: Can you identify the limitations of AI technology in use in HRM in your company and the prospects for its development?

The results of these questions are presented later in the article. An HR analysis of three case studies was carried out to identify issues related to the application of AI in HRM. The objective of this study was achieved and the research questions were verified based on the results of the literature analysis and empirical study.

Some sections of the paper are theoretical and review in nature, presenting new approaches to human resource management in the context of modern technology, employment policy, HRM, challenges and HR functions, and presenting concepts and trends in HRM, without describing specific empirical studies.

4. RESULTS

4.1. AI in Human Resources Management – case study 1

The company under study is located in the Kujawsko-Pomorskie Voivodeship in Poland. It is an organization that creates smart homes and uses modern technology, including AI, in human resource management. During an interview with the HR director, the respondent presented specific ways in which technology is integrated into its HR operations.

The first HR function that was discussed was recruitment and selection. Company X conducts its recruitment and selection process remotely, posting job advertisements on specialized online portals. The HR team, working in Germany, had to learn to identify the most suitable sources for sourcing candidates in Poland. The HR director stressed that the company is actively using AI tools for resume analysis and pre-selection. The company is considering other solutions to streamline and speed up the recruitment process and reach the best talent.

1/3 of the surveyed company's employees work online, so consideration was given to managing remote workers. Due to remote work, the company faces challenges in managing the team. The HR team uses modern communication tools to stay in touch and collaborate. The company's software has been improved due to ideas suggested by co-workers, suggesting the use of platforms to collaborate and exchange ideas. In the context of AI, Company X could probably use tools to monitor remote employee engagement and analyze communication patterns to identify potential problems.

When it comes to creating an organizational culture, the HR team plays a key role in creating HR policies to contribute to the development of the company. It works with management to develop leadership and create and develop human resources. In the context of modern technology, Company X uses AI tools to analyze employee feedback and identify areas for improvement in organizational culture.

The process of parting with employees (Exit Interview) is carried out through modern technology. Exit interviews are conducted via video conferencing or online surveys. It is conceivable that analysis of the data from these surveys could be aided by AI to identify reasons for exits and potential areas for improvement in human resource management.

Company X's HR team notes the risks of work-life balance in remote work. The company also offers consultations with an external organizational psychologist who cares about employees' psychological well-being. In the future, Company X would like to use AI tools to monitor burnout rates based on analysis of employee activity patterns (with privacy) and proactively offer support. In conclusion, the surveyed organization cares about work-life balance.

Company X, which creates smart homes, is an example of a company that puts into practice the use of modern technologies, including digitization and online communication tools, in various aspects of human resources management, especially in the context of remote work and recruitment and parting processes. The overall context indicates awareness of the potential of technology in improving HR functions and adapting to the challenges of the modern labor market. Company X focuses on remote

workforce management, the use of technology in recruitment and selection processes (indirectly), and taking care of employee well-being in remote environments.

4.2. AI in Human Resources Management – case study 2

Another company under study was Poland's Company Y, also located in the Kujawsko-Pomorskie region of Poland. It is an organization that creates intelligent homes and uses modern technologies, including AI, in human resource management. During an interview with the HR director, the interviewee presented specific ways in which technology is integrated into its HR operations.

Company Y is using technology in HR to innovatively assess and develop competencies, including through the use of game-based assessment. They use the Digital Fitness Assessment learning application. This shows that Company Y, in practice, has implemented technology-assisted gamification, which can be considered a form of using advanced algorithms and data to assess the competencies of candidates or employees. The HR manager recognized that the organization could make better use of artificial intelligence in the HR process, so he and his team of HR specialists, developed solutions that they intend to present to the company's Board of Directors.

Other AI solutions in HR that the HR Department wants to propose to the Y Company's Board of Directors are:

1. Support in recruitment and selection using AI.
   - resume analysis and candidate preselection: Company Y could use AI to automatically scan and analyze resumes to more quickly select candidates who meet key criteria, saving recruiters time,
   - recruitment chatbots: implementation of AI-based chatbots on the company's website under the 'jobs' tab, which could answer frequently asked questions from candidates, collect preliminary information and engage potential employees,
   - talent search: AI could support recruiters in identifying potential candidates on platforms such as LinkedIn, expanding the talent pool,
   - analyzing recruitment metrics: AI could analyze data from recruitment processes to identify the most effective sources of candidates, as well as optimize recruitment strategies.
2. In the area of development and training.
   - personalized development paths: AI could analyze data on employees' competencies, job performance and career goals to create individual development plans and recommend personalized training,
   - identifying skills gaps: AI could analyze employee skill data against job requirements and organizational goals, identifying areas where additional training is needed,
   - training recommendation systems: AI could recommend courses and training materials to employees based on their role, skills and progress to date.
3. In performance management and engagement.
   - employee opinion analysis: AI could analyze data from employee surveys, comments and other sources of feedback to identify trends, sentiment and areas identified for improvement in the organization,
   - early detection of employee departure risk: AI could analyze employee data (e.g., absenteeism, interactions, performance ratings) to identify signals indicating potential departure risk, enabling HR to take retention actions,
   - performance evaluation support: AI could analyze performance data and provide objective information to support employee evaluation processes, albeit balanced with human judgment.
4. In optimizing HR processes.
   - automation of routine tasks: AI could automate repetitive administrative tasks, such as processing documents, managing employee data, or responding to standard inquiries (e.g., using internal chatbots),
   - onboarding support: AI could automate part of the onboarding process for new employees, providing them with necessary information, reminders and training materials.

The implemented activities in HR using artificial intelligence mentioned by the Company Y respondent have the potential to extend to other HR functions if the company's Board of Directors agrees to use AI in the proposed activities. Implementing these AI solutions could help Company Y further improve the efficiency of the HR department, improve the employee and candidate experience, and

make more strategic data-driven decisions. However, it is important to keep in mind the ethical aspects of using AI, protecting personal data and balancing automation with the human factor.

4.3. AI in Human Resources Management – case study 3

Company Z is a mid-sized technology company operating in a dynamic sector with high competition for talent. The HR director interviewed noted that in the face of increasing challenges in recruitment, retention and the need to continuously improve employees' skills, Company Z's management made a strategic decision to invest significantly in AI-based technologies in the HR department. The goal of this decision was to automate routine tasks, use data analysis to make more strategic decisions, and improve overall HR efficiency. As part of this initiative, a number of AI-based tools were implemented, including intelligent recruiting systems, AI-based performance management platforms, chatbots, and employee sentiment analysis tools and predictive exit risk analysis systems, among others.

A survey participant highlighted that intelligent recruiting systems are associated at Company Z with the use of machine learning algorithms to analyze resumes and conduct initial assessments of candidates and predict their fit with the organizational culture. AI-based performance management platforms have been implemented, offering continuous feedback, tracking employee progress, and identifying areas for development. Also, HR chatbots began to be used, providing employees with instant answers to frequently asked questions about HR policies and benefits and procedures. At Enterprise Y, it decided to introduce employee sentiment analysis tools that use natural language processing (NLP) to analyze feedback from employee surveys and other sources to identify trends and potential engagement issues.

Predictive exit risk analysis systems have also been introduced. These are designed to analyze employee data to identify those with a high probability of quitting and enable proactive retention efforts.

The survey participant stressed that Company Z has no plans to introduce new solutions using AI in HR functions in the near future, unless the development of technology and techniques and the actions of competitors require it.

The HR director of Company Z, listed the results in the area of HR decision-making, thanks to the use of AI. And they are:

- in performance management - AI-based platforms have delivered more of both in recruiting – intelligent recruiting systems have significantly accelerated the candidate selection process, identifying individuals with desired qualifications more quickly and efficiently; predictive analysis of candidate match potential has reduced the number of misguided hires; however, there have also been concerns about potential algorithmic biases and the need to ensure diversity among candidates,
- in terms of performance management – AI-based platforms have provided more objective and continuous assessments of employee performance, based on data and not just on managers' subjective opinions; identification of areas in need of development has become more precise, making it possible to create personalized development paths; nevertheless, employees have expressed some discomfort with continuous monitoring, raising questions about privacy and trust,
- in terms of employee engagement –HR chatbots improved the accessibility of HR information to employees, which contributed to their satisfaction with the service; sentiment analysis tools provided valuable information about potential problems and areas of dissatisfaction, enabling HR to take proactive action; however, the limitations of chatbots in solving complex problems required maintaining a strong role for human HR personnel,
- in terms of employee retention – departure risk prediction systems made it possible to identify employees at risk of resignation, allowing targeted retention measures to be implemented; decisions to offer raises, promotions or additional benefits were more data-driven, making them more effective; however, ethical concerns were raised about the privacy of the data used to predict departure risk.

At the end of the interview, the Respondent summarized the activities being implemented at Enterprise Y. On the one hand, AI offers significant opportunities to increase the efficiency, objectivity and strategic nature of the HR function through automation, data analysis and the provision of predictive insights. Implementing intelligent recruiting systems, AI-based performance management platforms, HR chatbots and sentiment analysis tools can help optimize HR processes, improve employee engagement and make more informed talent decisions. On the other hand, implementing AI in HR also poses significant ethical, technical and organizational challenges. Concerns about algorithm bias, data privacy, excessive employee monitoring and technological limitations must be proactively addressed to

ensure AI is used fairly, ethically and effectively in HR decisions. The concept of the 5P (Philosophy, Policies, Programs, Practices, and Processes) model can provide a useful strategic framework for companies to optimize the use of AI in HRM. Defining an organization's philosophy toward the technology, establishing clear policies for AI integration, implementing appropriate programs and practices, and optimizing processes using AI can ensure that the technology is a strategic asset with HR goals and supporting the success of the organization.

The director added that the future of AI in HR decisions in organizations like Enterprise Y looks promising, but requires careful management. AI has the potential to revolutionize traditional HR practices, making them more effective, data-driven and strategic. Therefore, fully realizing this potential requires a conscious approach to ethical, technical and organizational challenges, as well as continuous monitoring and adaptation of implemented AI solutions. Organizations that can effectively integrate AI with human expertise and strategic thinking in HR will be better prepared to build an engaged, productive and competitive workforce in the digital age.

4.4. Limitations of AI technology in use in HRM and prospects for its development

Artificial intelligence is revolutionizing many fields, and human resource management is no exception. Given the interviews and responses to identifying limitations of the technology, it is important to emphasize that AI technologies offer promising opportunities to automate processes, analyze data and improve the efficiency of HR departments. But the implementation of AI in HRM also comes with a number of significant limitations that must be considered in order to realize the full potential of the technology while minimizing potential negative impacts.

The use of AI in HRM faces various limitations, which can be divided into several key categories. First, related to the lack of understanding of human nuances and emotional intelligence. One of the fundamental limitations of AI is its limited understanding of the complexity of human emotions, intentions and situational context. AI systems operate on data and algorithms, making it difficult for them to interpret subtle non-verbal cues, empathy or intuition-based assessments, which are crucial in many aspects of HRM, such as conflict resolution, assessing a candidate's cultural fit or providing emotional support to employees.

Second, there are risks associated with data and algorithms. The effectiveness of AI largely depends on the quality, objectivity and representativeness of the data on which it is trained. If the data is incomplete, erroneous, biased or inadequately secured, AI systems can generate incorrect conclusions, perpetuate existing biases or violate employee privacy. There is also a risk of misuse of confidential data shared with AI systems. Moreover, AI can sometimes generate completely made-up information (‘hallucinations’) or make mistakes, even in simple calculations.

Ethical and privacy challenges are another category. The use of AI in HRM raises serious ethical and data privacy issues. AI systems collect and analyze vast amounts of data about employees and candidates, including location information or behavioral patterns. It is essential to ensure compliance with data protection regulations (such as RODO), transparency in the use of data, and secure storage and processing.

Another limitation is the need to balance with the human factor. Despite the potential for automation, AI should not completely replace human judgment and interaction in HRM. HR decisions often require consideration of subjective factors, emotional intelligence and experience, which AI does not have. The most effective AI implementations are based on human-technology collaboration, where AI supports HR professionals, not replaces them.

Also, high implementation and maintenance costs and a shortage of specialists limit the use of AI in HRM. The implementation of AI systems in HRM often involves significant investments in new technology and infrastructure, as well as staff training costs. In addition, the labor market may lack qualified specialists capable of effectively implementing and operating AI tools in HR.

The next category of constraints is the risk of limiting HR decision-making. There is concern that over-reliance on AI systems could lead to a reduction in the role and autonomy of HR departments in HR decision-making. It is important that AI be a tool to support, rather than dictate, decisions.

The challenges associated with the rapid development of technology are further constraints. The pace of AI development is very fast, requiring organizations to constantly adapt and update implemented solutions and train employees on new technologies.

To facilitate deliberations on AI in HRM, a SWOT analysis was performed, as shown in Table 4.

Table 4. SWOT analysis of the use of AI in HRM

Strengths	**Weaknesses**
Improved efficiency and productivity	Automation risks
Streamlined processes	Dependence on technology
Data-driven decision making	Bias in algorithms
Cost reduction	Data privacy risks
Opportunities	**Threats**
Diffusion of next-generation innovation processes based on AI	Deepening disparities in the level of socio-economic development – negative socio-cultural transpositions
Possibility of wider implementation of the principles / dissemination of the idea of sustainable socio-economic development	People's resistance to changes related to the implementation of AI in the economy, organizations, enterprises or specific business units
Increased security	Ambiguous liability in the subject and object system when AI-related damages occur
Element of countering disinformation in societies and economies	Dysfunctions in information and communication processes
Component of building a culture of openness, flexible economies, including business entities, modern and dynamic societies	Changes in the labor market - quantitative changes (reduction of jobs), qualitative changes

Source: own elaboration.

Analyzing Table 4, it is important to note that the future of HR functions using artificial intelligence promises a significant transformation in the way human resources are managed. AI will play a key role in every stage of the employee lifecycle, from recruitment to development and engagement. The future of HR functions using AI will be characterized by greater automation, better data-driven decisions, more personalized employee experiences and a strategic approach to talent management. AI will free HR professionals from routine tasks, allowing them to focus on more strategic initiatives and helping to improve overall organizational performance and employee satisfaction. A key element, however, will be responsible and ethical implementation of AI, taking into account the impact of technology on people and organizational culture.

5. DISCUSSION

The application of artificial intelligence in human resource management is comprehensive and includes the automation of such tasks as the deployment of new employees, payroll processing, and benefits management.

AI in HR is a visible trend in the coming time. HR departments are currently undergoing the biggest transformation in history. Artificial intelligence is becoming a key component of modern HR management, changing the way employees are recruited, developed and managed. AI in HR is no longer a distant future, but a reality with tangible benefits. From automating routine tasks to advanced predictive analytics, the technology is revolutionizing traditional HR processes, making them more efficient and accurate.

In an era of digital transformation, HR departments are evolving from the traditional role of employment administrator into a strategic business partner. Artificial intelligence is becoming a catalyst for this change, bringing a new quality to HR management.

Today's HR department is undergoing a fundamental transformation. According to experts, more than half of HR executives are now focused on improving the employee experience and creating a compelling value proposition for employees. This shift in perspective calls for a new approach in which artificial intelligence supports building a more intuitive, as well as human-centered work environment.

HR's digital transformation includes the following key areas:

- digitization of documentation – providing immediate access to documents and enhancing data security,

- process automation – from recruitment to talent management,
- predictive analytics – to support strategic decision-making,
- personalizing the employee experience – tailoring development programs to individual needs.

The benefits of implementing AI in HR include improved efficiency in day-to-day work, automation of routine tasks and speeding up processes, better data analysis to support strategic planning, and a personalized approach to development and training.

It is assumed that about 1/3 of employees positively evaluate the current support of HR departments in increasing their efficiency (Kierzek-Mechlo, 2024). Therefore, the implementation of AI becomes crucial for improving these indicators. AI enables HR departments to focus on strategic aspects of HR management, while routine tasks are automated. The digital transformation of HR is not just a technological change – it is a fundamental shift in the way we think about HR management. It requires a human-centered approach that combines technology with empathy and understanding of human needs (Kierzek-Mechlo, 2024).

The implementation of artificial intelligence (AI) in management processes opens the door to myriad opportunities, while posing a number of challenges for organizations. For example, AI systems can be integrated to forecast market trends, which can significantly improve the ability to respond quickly to changes and optimize sales strategies. It should also be noted that there may be challenges associated with AI implementation, such as the need for significant investment in new technology and staff training so that new systems can be used effectively. The key to success is not only access to advanced technologies, but also the ability of an organization and its employees to adapt to a rapidly changing environment (Naxtech, 2024).

6. CONCLUSION

People's use of technology is an integral part of daily activities in every sphere of society. The large amount of information surrounding each of us requires rapid processing and systematization for high productivity in daily and professional life. The technological orientation of an organization is essential for shaping high economic performance and competitiveness of the organizational system.

Artificial intelligence and cognitive technologies have already entered the lexicon of the world of science, business and technology (Kuzior & Kwilinski, 2022). With artificial intelligence, various capabilities are making it easier for employees to work in many areas of business. A specific task of artificial intelligence is to make specific decisions in managerial activities (Kwilinski & Kuzior, 2020; Kuzior et al., 2019).

The role of AI in HR management continues to grow, changing the way HR processes are executed in almost all key areas of HRM. Due to the significant amount of data related to organizational operations, workforce management, AI is increasingly being integrated into various operational HR procedures. This integration is intended to strengthen a sustainable business framework, as noted by Votto et al. (2021). Implementing AI in HRM makes it easier for organizations to access highly qualified individuals, leading to an efficient recruitment process (Meshram, 2023). Intelligent AI technologies offer a new approach to workforce management, enhancing a company's overall performance and presenting a variety of performance management options (Khaled et al., 2023; Hemalatha et al., 2021). AI-based training enables organizations to evolve into knowledge-based entities capable of meeting personalized training needs and enhancing the quality of learning (Chen, 2022). The increasing adoption of AI in human resource management is due to its ability to generate value for customers, employees and organizations (Chowdhury et al., 2023).

Today's employers are struggling with attracting employees, retaining them and developing them within the organization. Given the fact that the population is aging and there is a growing shortage of workers, also the quality of candidates is a huge challenge for companies (Smolinski & Zakrzewska, 2018).

The overall impact of AI on HRM is related to increased efficiency and productivity: AI automates routine and time-consuming tasks, allowing HR departments to focus on strategic aspects of HR management. Automation speeds up processes and improves the efficiency of daily work.

Modern HR cannot ignore the digital revolution and the spread of artificial intelligence. With the growing use of AI, HR's role as an ethical guardian and advocate of employee interests will increase.

HR professionals will be responsible for ensuring the transparency of AI-based processes, protecting personal data and ensuring that the human aspect is preserved in human resource management.

Artificial intelligence supports HR professionals in many ways, automating routine tasks, providing valuable data for analysis and streamlining key HR processes. AI in practice relieves HR professionals of many time-consuming and routine tasks, allowing them to focus on more strategic aspects of human capital management, building relationships with employees and creating a more effective and engaging work environment.

The future of HR will be based on the concept of 'augmented intelligence', where AI enriches and enhances human work rather than replacing it. A hybrid approach to Augmented Decision-Making (ADM), in which AI supports HR decisions but acts at the behest of humans, will become increasingly common. HR professionals will need to develop new competencies related to the use of AI, such as understanding algorithms, analyzing data, managing AI systems, and being able to collaborate with intelligent technologies. AI training for HR professionals will become essential. There will be personalization on a massive scale. With AI, HR will be able to offer highly personalized employee experiences on a massive scale, from individual development paths to tailored benefit programs. In summary, the future of HR and HR processes will be characterized by close collaboration between HR departments and AI-based systems. AI will take over many routine tasks and provide valuable data for analysis, allowing HR professionals to focus on strategic initiatives and building positive relationships with employees, with an ethical and human approach.

It should be noted that thoughtful application of AI throughout the employee lifecycle can help HR overcome current challenges, and prepare for the risks and uncertainties associated with various types of disasters (e.g., a pandemic) and build a resilient HR function.

The study performed is characterized by certain limitations, such as the geographical scope of research (Polish market) and the time frame (one year) as well as the number (3) of surveyed enterprises. The presented methodology does not exhaust the spectrum of possible research methods. Nevertheless, the authors' aim was primarily to pay attention to presentation of the possibilities of using technology based on artificial intelligence in HRM. Therefore, two research questions were asked: how in practice does AI support human resources specialists and what are the current limitations of this technology and the prospects for its development? This area will be further developed in future in-depth studies. The additional research that the authors plan to conduct will be related, among other things, to deepening the subject with ethical problems of HRM and AI, and conducting interviews in a larger number of HR departments.

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DYNAMIC FILLING OF DATA GAPS IN LARGE AIS DATASETS

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ABSTRACT

Purpose: *This study examines some novel approach for filling missing data in AIS databases. Proposed solution is designed for filling dynamic data in AIS systems.*

Need for the study: *In the era of globalization and intensive international trade, accurate monitoring of vessel and container ship routes is essential for efficient maritime logistics and ensuring the safety and security of maritime traffic. Although widely implemented, the Automatic Identification System (AIS) frequently generates data gaps, particularly in regions with limited signal coverage. These missing entries reduce the reliability of analyses and forecasts, thus undermining operational and strategic decision-making. Such lack of data implies also limits for a modern Artificial Intelligence involvment into the decision-making.*

Methodology: *This paper presents a novel approach to dynamically filling data gaps in large AIS datasets, based on spatio-temporal analysis using weighted averages and data similarity estimation methods. The method was validated on a real-world dataset comprising approximately 32 million records and demonstrated high accuracy and strong potential for practical deployment.*

Findings: *Effectively completing and correcting AIS data not only enhances dataset integrity but also provides a more reliable foundation for decision-making in the maritime sector.*

Practical Implications: *Improved data precision supports the deployment of intelligent management tools for route planning, maritime traffic coordination, port operation optimization, and fleet supervision. In the long term, it also enables the implementation of advanced artificial intelligence (AI)-based systems, paving the way toward predictive and autonomous maritime transport management.*

Keywords: Intelligent management in shipping; Large datasets; AIS data; Missing data prediction; Shipping management; Smart decision-making; Data analysis in intelligent management

Jel codes: C18, C23, C33, C53, C55, C82, O33

1. INTRODUCTION

Data from the AIS (Automatic Identification System) database of maritime vessels plays a key role in monitoring maritime traffic around the world. AIS, which enables the automatic exchange of

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information on the position, course and speed of ships, is an invaluable tool for ensuring safety at sea. It makes it possible not only to prevent collisions and manage traffic in ports, but also to monitor illegal activities such as smuggling and piracy. Data gaps in AIS databases can lead to incomplete analysis, which in turn can affect the safety of navigation and the efficiency of maritime traffic management. Complete AIS data enables accurate tracking of vessel positions, which is essential for preventing collisions, monitoring illegal activities, and responding quickly to environmental accidents. In addition, complete data is invaluable for analyzing traffic patterns, which supports route planning and optimization of port operations. Therefore, filling gaps in the AIS database is not only a technical issue, but also a key element in ensuring safety and efficiency in shipping.

Jeon et al. (2021) proposed a robust data gap analysis method using meta-learning models to detect and remove abnormal data from real-time ship and maritime data, which can improve the accuracy and robustness of ship performance monitoring. In their work they proposed the data gap analysis framework, which includes the meta-learning model, used to monitor the condition of ships and accurately identify normal and abnormal data. The paper of Yan et al. (2016) proposes an unsupervised data mining method using a density-based strategy to analyze vessel trajectories and extract traffic patterns from historical AIS data.

Wijaya and Nakamura (2013) used Apache HBase, a distributed big data storage and processing system, to store and analyze a large amount of AIS (Automatic Identification System) data generated by ships to predict the behavior of ships navigating through heavily trafficked fairways around busy harbors. Aiello et al. (2020) discuss the gap between current and future digitized shipping industry models, focusing on the use of big data to increase efficiency, sustainability and safety, and taking into consideration the maturity level and technological barriers.

A novel vessel trajectory and navigating state prediction methodology was developed by Xiao et al. (2020). Authors combine adaptive learning, motion modeling, and particle filtering techniques using AIS data. The study addressed key challenges in vessel trajectory prediction, including determining the optimal training window for the learning process and improving the efficiency of waterway pattern retrieval.

DAISTIN is a novel data-driven method to interpolate vessel trajectories and address signal gaps in Automatic Identification System (AIS) data proposed by Magnussen et al. (2023). Described method uses a graph-based approach to interpolate missing AIS data points by finding the shortest path between known locations. Authors also used a geometric sampling method to handle the large volume of AIS data when constructing the graph. Zhang et al. (2023) proposed TLGAN model which exhibits superior performance in repairing AIS data compared to different baseline models. The Savitzky-Golay filtering and cubic exponential smoothing techniques to further improve the quality of the repaired ship trajectory data were employed to that task.

A logistic regression (LR) model was developed by Mayers et al. (2022) to predict vessel class based on length, beam, and draft. Model was tested using Automatic Identification System (AIS) data, demonstrating skill in verifying AIS-transmitted classification and detecting incorrectly classified vessels. The study outlines possible levels of quality analysis and control (QA/QC) for AIS data, including raw data, identification of vessels using reported MMSI and IMO number, and the use of interpolative schemes and AI/ML methods to fill missing static values and detect errors.

Djenouri et al. (2023) proposed framework, DCNN-TFO, is a deep learning-based approach for anomaly detection in maritime data, which combines decomposition, clustering, and fusion techniques to improve detection accuracy and efficiency. Authors show also potential of the framework application for missing data filling.

The authors Yuan et al. (2020) proposed a multi-task analysis and modelling framework using Long Short-Term Memory (LSTM) for multi-source monitoring data of inland vessels, tackling three important tasks: vessel trajectory repair, engine speed modelling, and fuel consumption prediction. The paper results show that LSTM network outperformed other modeling methods in vessel trajectory repair, engine speed modeling, and fuel consumption prediction, with at least 17% and 44% improvement in accuracy, respectively.

The study of He et al. (2021) proposed a novel repair model for abnormal AIS data in inland river environments, using a combination of cubic spline interpolation and Least Squares Support Vector Machine (LSSVM) methods to improve the completeness of AIS data for intelligent shipping. The repair accuracy of AIS error data using cubic spline interpolation is more than 93%. The repair accuracy of

AIS short-time lost data using cubic spline interpolation is above 90%. The repair accuracy of AIS long-lost data using LSSVM regression fitting is not specified. Liang et al. (2019) proposed method consists of two steps: using Random Forest to automatically identify missing position records within vessel trajectories and using LSTM-based supervised learning to reconstruct the vessel trajectories with missing AIS data.

This study examines some novel approach for filling missing data in AIS databases. Proposed solution is designed for filling dynamic data in AIS systems. The article is organized as follows: section 2 describes the importance of AIS data consistency, the methods of filling of dynamic data are described in section 3, section 4 presents the results of simulations. The discussion is carried out in section 5 and conclusions are placed in section 6.

2. LITERATURE REVIEW

Automatic Identification System has revolutionized maritime domain awareness, enabling real-time tracking of vessels globally (Šakan et al., 2018). This system, mandated for larger vessels by the International Maritime Organization (IMO, 2014), transmits data such as vessel identity (name, IMO number, MMSI number), position, course, speed, port of departure and arrival, contributing significantly to safety, security, and efficiency in the maritime domain in a regulated way (IMO, 2015). However, the effectiveness of AIS relies heavily on the consistency and completeness of the transmitted data.

Although currently we can evaluate AIS as mature tool (Lee et al., 2019), several gaps and threats, following Eriksen et al. can be still observed (Lee et al., 2019; Eriksen et al., 2018), which negatively impact of data inconsistencies, further on emphasizing the need for robust data quality management, challenging AIS development in near future (Fournier et al., 2016). It is also crucial for all ship owners in real-time monitoring and supervision of owned fleet, allowing constant and quick reactions towards optimizing vessels' voyage (Di Ciaccio et al., 2019). Consistent and reliable AIS data is paramount for a multitude of maritime applications:

- collision Avoidance,
- search and Rescue,
- maritime Security,
- environmental Protection,
- traffic Management and Efficiency,
- maritime spatial planning,
- monitoring of vessels' traffic.

Accurate and timely AIS data is crucial for collision avoidance systems, allowing vessels to identify and maneuver in relation to other ships in their vicinity. Data gaps or inaccuracies can lead to misjudgments and increase the risk of collisions (IMO, 2015; Goudossis & Katsikas, 2019). In SAR (Search and Rescue) operations, real-time vessel tracking through AIS is vital for locating and assisting vessels in distress. Incomplete or inaccurate data can hinder rescue efforts and lead to delays in providing assistance (IMO, 2015).

AIS also plays a crucial role in maritime security by enabling the detection of suspicious activities, such as piracy, smuggling, illegal fishing, as well as following and investigating ship owners hiding the real origin or ownership or other data they would like to hide (against different bans or sanctions). Data inconsistencies can create loopholes for illicit activities to go undetected (Aziz et al., 2020; Sciancalepore et al., 2021; DNV-GL, 2016; Balduzzi et al., 2014). In case of environmental protection AIS data is used to monitor vessel movements in sensitive marine environments, ensuring compliance with environmental regulations and supporting efforts to protect marine ecosystems. Data gaps can hinder the effectiveness of such monitoring efforts (IMO, 2014).

Port authorities and Vessel Traffic Services rely on AIS data for efficient traffic management, optimizing vessel routing, and minimizing congestion. Inconsistent data can lead to inefficiencies and delays in port operations (DNV-GL, 2016). Maritime spatial planning is used by maritime authorities, regional and national governments. The authorities are using the data for different stakeholders (Fiorini et al., 2016) and therefore can predict real need for it in the future and to divide ares by types of use in case of such excluding each other. With AIS authorities can monitor vessel traffic, allowing for better management of traffic in ports and sea lanes, as well as optimization of shipping routes (Fu et al., 2020).

Despite its importance, AIS data consistency faces several challenges:

- technical Limitations,
- data Manipulation,
- human Error,
- data lack and inaccuracy,
- data Overload and Management.

In case of technical limitations AIS transmission range is limited by factors such as weather conditions, signal interference, and geographical obstructions. This can result in data gaps, particularly in remote areas with limited AIS receiver coverage (Fournier et al., 2018; Sciancalepore et al., 2021). Intentional manipulation of AIS data, known as 'AIS spoofing', poses a significant threat to data integrity. Malicious actors can transmit false information, creating ghost ships or disguising a vessel's true identity and activities (Aziz et al., 2020; DNV-GL, 2016; Androjna et al., 2021).

Human errors in AIS configuration, data entry, or system operation can lead to inaccuracies and inconsistencies in transmitted data, where intelligent management systems could be applied (John, 2014). Data lack and inaccuracy can cause gaps in data continuation provided by each vessel, as well as data apparently out of the reality (i.e. speed of 100 kn at sea), which degenerated the outcomes of any analysis made based on the data by looking for trends, exemptions, dominants and other factors being of stakeholders' interest. This has also negative impact on the research performed with the use of AIS data. The vast volume of AIS data generated globally presents challenges for data storage, processing, and analysis (data overload and management). Effective data management strategies are crucial for ensuring data quality and consistency (John, 2014).

To mitigate the challenges to AIS data consistency, a multi-faceted approach is required:

- Technological Advancements: Continuous improvements in AIS technology, such as increased transmission power, enhanced receiver networks, and satellite-based AIS, can enhance data coverage and reduce data gaps (John, 2014; Chen, 2014).
- Data Validation and Verification: Implementing robust data validation techniques, including cross-checking AIS data with other sources and using algorithms to detect anomalies, can help identify and flag inconsistencies (Šakan et al., 2018; Di Ciaccio et al., 2019; Lee et al., 2019; He et al., 2021).
- International Cooperation and Regulation: Strengthening international cooperation and regulations related to AIS data quality, including mandatory data reporting standards and penalties for data manipulation, is crucial (IMO, 2020).
- Data Sharing and Collaboration: Promoting data sharing and collaboration among maritime stakeholders, including governments, industry, and research institutions, can facilitate the development of comprehensive solutions for data quality management (IMO, 2020).

Addressing the challenges to data quality requires a collaborative effort involving technological advancements, robust data management practices, and strengthened international cooperation.

3. METHODOLOGY

3.1. Methods

By prioritizing AIS data consistency, we can unlock the full potential of this vital system for a safer, more secure, and more efficient maritime domain. In this meaning, the data provided by AIS should undergo permanent improvement. One of the possible pathways is presented by this paper attempting addressing the data validation and verification for further elaboration using method proposed below.

The modelling and calculations included in this study were rehearsed on a commercially purchased database covering ship traffic in the North Sea and Baltic Sea for the period 2011 – 2022 reported to the AIS. The size of the datasets exceeds 32 millions of records.

3.2. Methods of filling in missing telemetry data

In the case of telemetry data included in the AIS database, we are dealing with a very specific time series. It is a kind of convolution of two real time series and each of them can be analyzed separately or both at the same time. The methods in both cases are similar. Let us denote by

$$\big(X(t), Y(t)\big)$$

the values of geographic coordinates at subsequent moments of time.

The most intuitive way of filling in missing data is to use a simple arithmetic mean of two adjacent (available) positions, i.e.

$$\big(X(t), Y(t)\big) = \left(\frac{X(t-1)+X(t+1)}{2}, \frac{Y(t-1)+Y(t+1)}{2}\right) \tag{1}$$

A generalization of this approach is to use the average of the adjacent 2k moments of time. In this case, the formula used is

$$\big(X(t), Y(t)\big) = \left(\frac{\sum_{i=1}^{k} X(t-i)+\sum_{i=1}^{k} X(t+i)}{2k}, \frac{\sum_{i=1}^{k} Y(t-i)+\sum_{i=1}^{k} Y(t+i)}{2k}\right) \tag{2}$$

In both above cases, a specific amplification can be applied, consisting in the use of weighted averages. It is proposed to use average speeds at subsequent moments of time as weights.

Another proposed method of filling in the gaps in telemetry data is to use available historical data. As estimators of the missing position $\big(X(t), Y(t)\big)$, it is proposed to use the value $\big(X(t-24), Y(t-24)\big)$. That is, the position from the previous day. This approximation is justified only in the case of passenger ships moving cyclically on set courses. In the case of other types of ships, such an estimator is not justified. A generalization of this approach is to use the average from several previous days.

3.3. Methods of filling in missing data in the average speed

Similarly to telemetry data, it is proposed to use the averages from neighboring moments of time to fill in missing data for the 'average speed' variable. In other words,

$$\tilde{V}(t) = \frac{V(t-1)+V(t+1)}{2} \tag{3}$$

or more generally:

$$\tilde{V}(t) = \frac{\sum_{i=1}^{k} V(t-i)+\sum_{i=1}^{k} V(t+i)}{2k} \tag{4}$$

A less trivial way of filling in missing information on the ship's speed is to use its position from neighboring moments of time. It should be mentioned here that the assumption is used that the ship is moving in a straight line. Alternatively, it is possible to use information on designated shipping channels.

The second approach is justified for passenger ships, while the first is for ships travelling long distances. In such a case, it is possible to consider the average speed based on historical data for:

- Average speed in each ship operating mode
- Average speed for a given hour
- Average speed for a given day of the week
- Average speed for a given time of day
- Combinations of the above cases.

4. RESULTS

The effectiveness of the proposed methods for filling gaps in missing data was verified on a selected passenger ship. Out of 640 passenger ships, the unit with the most available records was chosen. This unit has the following designations: LRIMOShipNo = '9375654'; MMSI = '265611110'; ShipName = 'VIKING XPRS'; CallSign = 'SBXN'. This ship is presented in the figure 1.



Figure 1. A picture of the analyzed ship
Source: https://www.vesselfinder.com/.

The positions of the chosen ship at successive moments in time, based on the records in database, are shown in the figure 2.

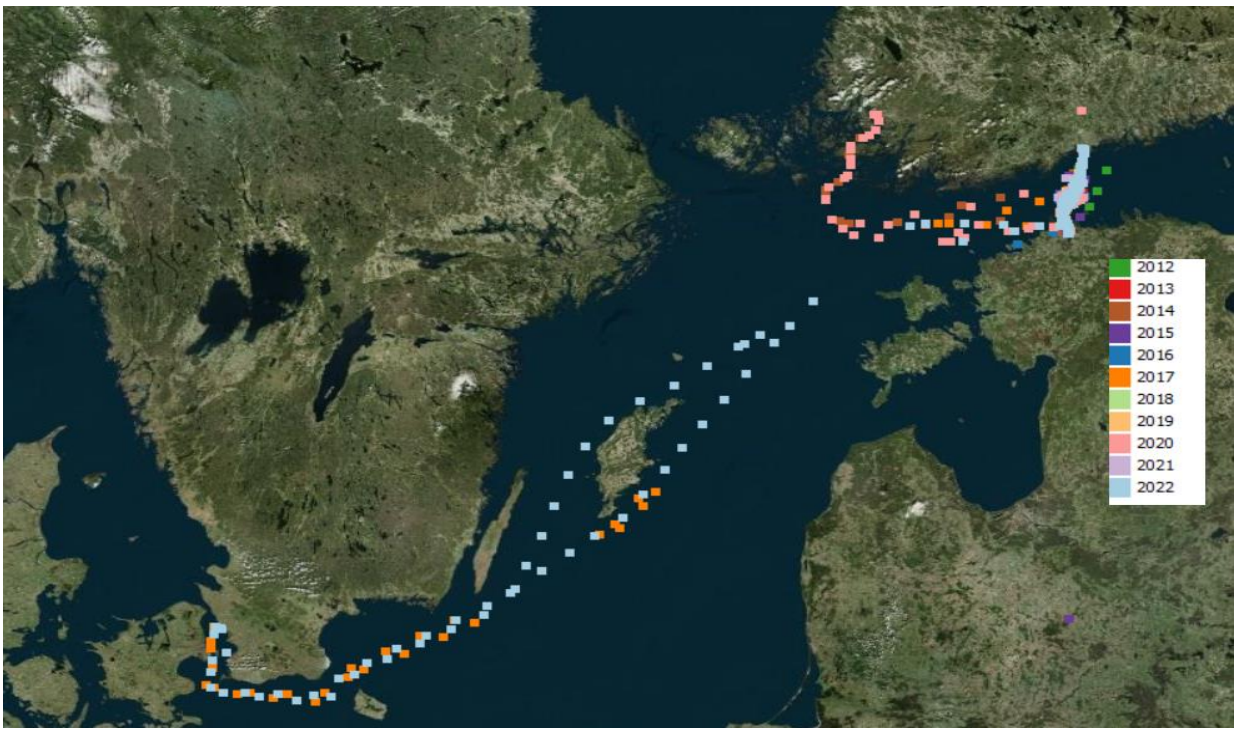


Figure 2. Positions of the ship in the following moments of time
Source: own elaboration.

Recently, the movement of this ship has been limited to the Helsinki-Tallinn route. After limiting the consideration to a typical route, the ship does not always move on the same track. In addition, the ship's speed is not constant. The level of recorded speed is marked in Figure 3.

In the numerical experiments, each position of the ship was modeled using various techniques proposed in the theoretical part, and the obtained result was compared with the actual value. For the completion of telemetry data, two measures were considered to evaluate the effectiveness of the data imputation models. The first was the sum of the absolute differences of both geographical coordinates, referred to as the measurement error. The second was the straight-line distance between the actual position of the ship and its estimated position.

The first measure is typical for numerical considerations, while the second has more practical significance. Using the distance expressed in kilometers allows for an easier assessment of the effectiveness of the individual data imputation techniques.

The first technique for imputing telemetry data was the use of a simple average of two adjacent time points described by formula 1. A comprehensive error analysis for the analyzed ship over a period of nearly 11 years is characterized by the statistics presented in Table 1.

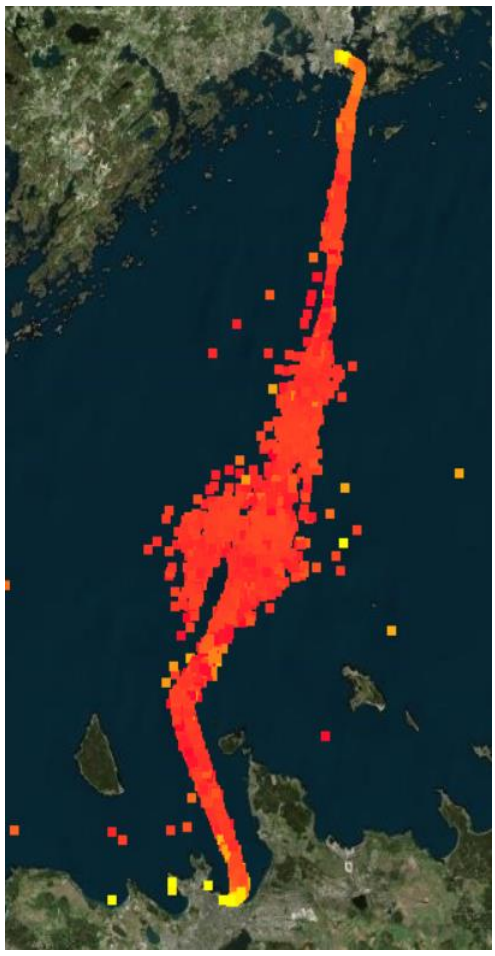


Figure 3. Helsinki - Tallinn route including speed (red - high speed, yellow - low speed)
Source: own elaboration

Table 1. Error statistics for filling in missing ship positions using position averaging from adjacent moments in time

Measure	Absolute error Longitute (deg)	Absolute error Latitude (deg)	Error Longitute (deg)	Sum of absolute errors (deg)	Longitude relative error	Latitutde relative error	Distance (km)
Avarage	0.056704	0.032773	0.089477	0.000949	0.001333	0.002282	7.428436
Median	0.026178	0.007229	0.090113	0.000438	0.000292	0.002170	6.739207
Deviation	0.070922	0.088020	0.136626	0.001193	0.004498	0.005144	10.263246
Q1	0.000013	0.000016	0.000024	0.0000002	0.0000006	0.0000007	0.001855
Q3	0.115698	0.072156	0.153601	0.001926	0.002902	0.003776	14.205352
max	4.218922	12.14175	16.36067	0.070223	0.486247	0.556469	1116.18496
min	0	0	0	0	0	0	0

Source: own elaboration.

The relative error statistics for individual geographical coordinates and their sum suggest that the proposed solution, despite its simplicity, is very effective. This is also clearly confirmed by the relative error statistics. However, the most illustrative way to assess the quality of the model seems to be the use of the distance between the actual and predicted position of the ship. In this case, the average value is 7.428 kilometers. This value seems relatively large; however, it should be remembered that the values are analyzed over a large sea area. It is worth noting that the first quartile value is only 0.001 km. This means that for at least one in four cases, the model error does not exceed one meter. In other words, in nearly 23,000 cases, the actual and predicted positions coincide. An interesting point here is the maximum value of over 1000 km. This value is closely related to the occurrence of outliers (see Fig. 4).

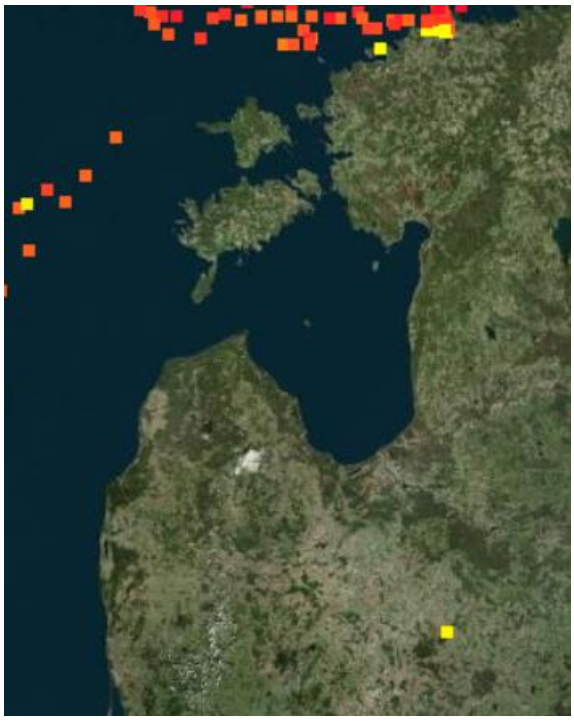


Figure 4. Visualisation of outliers
Source: own elaboration

The statistics of the distance between the actual position of the ship and the predicted position based on other data completion methods are shown in Table 2 (distances expressed in km).

Analyzing the results presented in Table 2, it should be noted that in all cases, the first quartile does not exceed 600 meters. This undoubtedly confirms the high effectiveness of the proposed methods for gap filling in telemetry data. It is also worth noting that when using the position from the previous day at the same time, the median value is only 65 meters. This means that in half of the cases, we observe perfect modeling of the ship's position. This observation was the starting point for the construction of methods for missing 'Speed' values. This variable stores values expressed in nautical knots.

The first model for predicting the ship's speed assumes that the ship moves at a constant speed at a given hour on subsequent days. This assumption is justified for passenger ships that move cyclically on predetermined routes. For each hour of the day, the average and median were determined based on all available data. The obtained results are presented in Table 3.

Analyzing the results presented in Table 3, it is easy to notice that the ship makes two trips on the Helsinki – Tallinn route during the day. It operates daily in both directions at fixed times. The journey starts before 5 AM, and the return trip begins after 2 PM. Using the average or median of the remaining values at a given hour as an estimator of the unknown speed provides a very good estimate. The basic error statistics for the two discussed methods are presented in Table 4.

Table 2. Statistics for the various methods of completing telemetry data

Measure	Generalized average distance formula (2) for k=2 (km)	Speed-weighted average of adjacent moments (km)	Speed-weighted average for k=2 (km)	Previous day's position (km)	Averaged position from the previous day and the next day at this time (km)
Avarage	13.73711	6.49993	12.90427	9.40811	12.94912
Median	9.36427	5.43529	8.18494	0.06578	5.21499
Deviation	14.60376	9.71237	14.88333	36.61767	43.46451
Q1	0.59455	0.00189	0.51573	0.00087	0.00161
Q3	24.91113	12.27018	22.69571	2.26544	17.88727
max	1728.644	1116.184	2133.902	1167.321	3589.591

Source: own elaboration.

Table 3. Values of basic statistics for speed by hour

Hour	Average speed (kt)	Median speed (kt)
0	0.40856	0.0
1	0.41139	0.0
2	0.62580	0.0
3	2.45694	0.0
4	9.67433	10.0
5	16.36187	19.1
6	13.86156	18.5
7	9.25168	0.1
8	13.79253	19.9
9	14.99404	20.5
10	7.25779	0.7
11	2.42390	0.0
12	1.46483	0.0
13	3.99423	0.0
14	9.74442	8.8
15	15.29010	19.6
16	13.60361	18.8
17	9.71031	4.8
18	14.92565	20.0
19	15.49434	20.4
20	6.16320	0.5
21	1.20377	0.0
22	0.76298	0.0
23	0.95679	0.0

Source: own elaboration.

Table 4. Effectiveness of models based on mean and median speed at a given hour

Measure	Average based model	Median based model
Average	5.676828	4.589149
Median	4.838435	0.500000
Min	0.003613	0.000000
Q1	1.203769	0.000000
Q3	9.251676	6.100000

Measure	Average based model	Median based model
Max	25.237020	26.700000
STD	4.829380	7.177070

Source: own elaboration.

The analysis of the obtained results confirms the high effectiveness of the proposed solution. In particular, the quartile values confirm the high efficiency of the compared methods. Using the median provides better estimates. This is undoubtedly due to the high sensitivity of the mean to outliers. Aggregating individual hours into times of day yields slightly different results. Using the mean and median for times of day allows for the construction of models, the error statistics of which are presented in Table 5.

Table 5. Effectiveness of models based on mean and median speed at a given time of day

Measure	Average based model	Median based model
Average	6.924781	5.258425
Median	5.767203	0.500000
Min	0.013306	0.000000
Q1	3.475168	0.100000
Q3	8.624831	8.400000
Max	22.886694	26.600000
STD	4.492704	7.986359

Source: own elaboration.

Data aggregation worsens the model. Only the maximum error values are smaller. The reasons for this should be sought in the proper selection of the ranges for different times of day. In the analyzed case, the times of day unfortunately do not coincide with the ship's sailing cycle. A similar approach is to use the average and median speed for a given day of the week. In this case, the error statistics are presented in Table 6.

Table 6. Effectiveness of models based on mean and median speed for a given day of the week

Measure	Average based model	Median based model
Average	9.013844	7.652475
Median	7.495598	0.300000
Min	0.000428	0.000000
Q1	7.395598	0.100000
Q3	11.707902	19.300000
Max	19.299571	26.600000
STD	2.923241	9.382153

Source: own elaboration.

Using such a high level of granularity significantly reduces the effectiveness of the forecasts. The differences between individual days are small, and daily fluctuations are smoothed out. Nevertheless, using this approach can be the starting point for more precise analyses, namely, it is advisable to determine the average and median speed at a given hour for each day of the week.

When considering a combination of several cases, such as the time of day or hour for a specific day of the week, the effectiveness of the models increases significantly, as can be seen by analyzing the results presented in Table 7.

Additionally, models based on the average and median for the status of the ship, as well as models based on the average and median for a given month of the year, were analyzed. The obtained results are like those described above. The effectiveness of the individual models is relatively good; however, it is still possible to improve it. It turns out that the use of appropriate aggregation methods significantly enhances effectiveness. The results of the aggregation of individual models are presented in Table 8.

Table 7. Effectiveness of time-of-day and hour-based models for a given day of the week

Measure	Average for hour	Median for hour	Average for time of day	Average for median
Average	5.488025	4.459019	6.884876	5.256195
Median	4.640402	0.500000	5.624272	0.500000
Min	0.000369	0.000000	0.001802	0.000000
Q1	0.876950	0.000000	3.262312	0.100000
Q3	8.789424	5.550000	8.716275	8.400000
Max	25.927338	26.700000	23.104480	26.600000
STD	4.824862	7.252486	4.500655	7.955922

Source: own elaboration.

Table 8. Performance measures of aggregate research results

Measure	Aggregation
Average	0.154496
Median	0.032250
Min	0.000000
Q1	0.010625
Q3	0.191109
Max	7.171023
STD	0.283505

Source: own elaboration.

5. DISCUSSION

The numerical experiments conducted as part of the analysis of the effectiveness of various methods for imputing missing telemetry data for the passenger ship VIKING XPRS provide interesting and valuable results. It has been shown that a simple method of averaging telemetry data from adjacent time points allows for results with surprisingly low error. The analysis of the distance errors between the actual and predicted positions indicated that in nearly 25% of cases, the error did not exceed 1 meter, which is an impressive result for telemetry data over a large sea area.

Methods based on speed-weighted averages and averages from previous days, especially for determining speed, also proved effective, though varied depending on the model used. For example, using the position from the previous day at the same time resulted in a median error of about 65 meters, indicating the models' good ability to predict the ship's position on repetitive routes.

In the context of speed prediction, the analysis highlights the significance of the daily cycle. The ship regularly operates on the Helsinki-Tallinn route, which facilitates speed modeling based on data from previous days. Models based on the average and median for specific hours proved effective, and using the median to eliminate the impact of outliers yielded better results than models based on averages.

However, data aggregation presented challenges. Models based on data from entire days of the week or larger time intervals lost accuracy, which can be attributed to differences in speed distribution depending on the time of day. Therefore, precise models require more detailed data segmentation, such as dividing days into hours and daily segments. This was confirmed in Table 7, where models considering the combination of time of day and hour for a specific day of the week showed the highest effectiveness.

An extended focus on effective data dissemination highlights its crucial role in enhancing maritime situational awareness and reducing collision risks. Timely and accurate sharing of AIS data across stakeholders – such as vessel operators, port authorities, and maritime traffic controllers – ensures a common operational picture, which is vital for avoiding navigational conflicts, especially in congested sea lanes. When data imputation techniques are employed to recover missing telemetry, the quality of shared data improves, leading to better-informed decisions and enhanced responsiveness in dynamic conditions. This data continuity enables the integration of real-time analytics and predictive models, laying the foundation for intelligent management systems. As a result, improved data dissemination directly supports the implementation of AI-driven collision avoidance tools and automated traffic coordination platforms. Ultimately, the ability to fill data gaps not only strengthens individual vessel safety but also fosters a safer, smarter, and more resilient maritime ecosystem.

6. CONCLUSION

Proposed method demonstrated that simple averaging of telemetry data from adjacent time points can achieve low errors in most cases less than 1 meter. Speed-weighted averages and averages from previous days also proved effective, particularly for speed prediction, with a median error of about 65 meters for repetitive routes. The daily cycle's significance in speed prediction was highlighted, with models using historical data for specific hours showing effectiveness. However, data aggregation posed challenges, as models based on entire days or larger intervals lost accuracy due to variations in speed distribution. Detailed data segmentation, such as dividing days into hours and daily segments, improved model accuracy. These findings emphasize the potential for refining telemetry data imputation methods and the importance of detailed data segmentation for accurate predictions. Future research should focus on further improving these models.

Focusing only on the primary application of AIS relating to navigational safety and improving data availability (Yang et al., 2019), the article authors' findings are highly relevant given the changes that are taking place in the global shipping fleet (increase in tonnage) and in maritime safety more generally. In addition to the traditional factor related to ship collisions and accidents and their consequences (e.g. oil spills), other aspects of maritime safety are clearly increasing in importance. These include threats to shipping from factors such as maritime piracy or political instability and armed conflicts in the vicinity of important shipping routes (example of Yemeni rebel activities). Threats from ships due to concealment of true nationality (the so-called 'shadow fleet') or damage to energy infrastructure located on the seabed (example of incidents in the Baltic Sea) are also an important issue.

The proposed gap-filling methodology lays a foundational framework upon which advanced artificial intelligence techniques can be effectively built. By restoring the completeness and consistency of AIS datasets, the model creates reliable input for AI-driven analytics, such as deep learning models, real-time route optimization algorithms, and predictive movement simulations. Incorporating machine learning into the post-processing stage could enable adaptive error detection and dynamic correction strategies, further improving data quality over time. Additionally, AI-based models trained on repaired data can forecast vessel trajectories with greater precision, enabling more efficient voyage planning and enhanced collision avoidance. The integration of these intelligent systems with robust data preprocessing workflows, such as the one presented in this paper, offers a promising direction for smart maritime traffic management. Future work may focus on hybrid frameworks that combine data imputation with AI optimization to support autonomous shipping operations and next-generation maritime logistics.

Future research should explore how the proposed data gap-filling techniques can be extended to support AI-driven solutions within maritime supply chain management. Accurate and complete AIS data is a prerequisite for implementing dynamic vessel routing systems, which adjust to changing port conditions, weather, and traffic in real time. Integrating predictive analytics with enriched AIS datasets can also enhance cargo flow forecasting, inventory coordination, and just-in-time delivery models. Moreover, the combination of machine learning and historical shipping patterns may support early detection of supply chain disruptions and optimize resource allocation across logistics networks. These AI-enabled applications extend the relevance of the proposed methodology beyond navigation and safety, positioning it as a strategic enabler of intelligent and resilient maritime logistics. Future work could investigate hybrid platforms where data quality enhancement, decision-making algorithms, and real-time system feedback operate within a unified digital infrastructure for supply chain management.

The findings not only support improved vessel positioning and movement prediction but also create a solid foundation for the deployment of intelligent management systems in maritime operations. By enabling more accurate, data-driven decisions, the proposed approach contributes to the broader vision of smart and adaptive shipping infrastructure.

Funding: The analyzed database was purchased on a commercial basis from the company S&P Global data provider. The database consists of more than 225 indicators describing a ship, where data is sourced from the vessels registration authority. The database purchased for the study was selected by the region of ships' appearance with the limitation to the Baltic Sea and the North Sea in the time frame of 2011 – 2022, where each unique record related to the unique (in time at least) ship's position. This research was

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AN INNOVATIVE APPROACH TO INTELLIGENT MANAGEMENT OF RETINAL PATHOLOGY RECOGNITION BASED ON DEEP LEARNING AND INTUITIONISTIC FUZZY SETS

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ABSTRACT

Purpose: *This study aims to improve the diagnostic effectiveness of rare retinal diseases by introducing a novel classification approach that not only enhances accuracy but also supports the intelligent management of the diagnostic process through AI-based decision systems.*

Feed for the study: *Retinitis pigmentosa (RP), cone-rod dystrophy (CORD), and Usher syndrome are inherited retinal disorders with low prevalence but significant clinical impact. Their early symptoms are subtle and often missed, posing serious challenges for timely diagnosis. The shortage of trained specialists and limited availability of medical imaging data further complicate diagnostic workflows and uncertainty management in clinical settings.*

Methodology: *The proposed method combines the outputs of several deep learning models—EfficientNet, InceptionV3, and Residual Attention Vision Transformers (RS-A-ViT)—and applies intuitionistic fuzzy sets to model uncertainty and refine classification results. This fusion-based approach enables better handling of ambiguous or borderline cases and improves classification robustness despite limited datasets, which is critical for effective diagnostic workflow management.*

Findings: *The results demonstrate a notable improvement in diagnostic performance, with classification accuracy increasing by up to 5.9 percentage points for the RS-A-ViT model. The approach proved especially beneficial in cases with overlapping visual features, effectively reducing uncertainty and increasing reliability in multi-class classification of RP, CORD, Usher syndrome, and normal cases—thus supporting more controlled and informed diagnostic decision-making.*

Practical implications: *Beyond increasing diagnostic accuracy, the proposed method facilitates intelligent management of diagnostic workflows in ophthalmology. By providing automated triage, real-time decision support, and interpretability based on uncertainty modeling, it can alleviate the workload on specialists and enable earlier and more reliable detection of rare retinal diseases, even in resource-limited clinical environments.*

Keywords: Retinitis Pigmentosa (RP), Classification, Deep Learning, Intuitionistic Fuzzy Sets, Multi-class Classification, Cone-Rod Dystrophy (CORD), Intelligent Management

Jel codes: I10, C45, C52, C63

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1. INTRODUCTION

Retinitis Pigmentosa (RP) is one of the inherited retinal dystrophies, affecting 1 in 4,000 individual (Liang et al., 2023). It is characterized as the gradually degeneration of rod and later on cone photoreceptors (Song et al., 2024). Its first stage is night blindness, caused by rod photoreceptors degeneration, and its consequence may be loss of the peripheral field of vision, induced by decline of rod photoreceptors (Cross et al., 2022). Thus, rod-dominant (classical RP) and cone-dominant – cone-rod dystrophy (CORD) may be distinguished. Moreover, USHER syndrome is characterized with blue fundus pigmentation typical for RP accompanied by sensorineural hearing loss (Bauwens et al., 2024). Rare retinal diseases demand not only accurate identification but also efficient management of the diagnostic workflow, as their initial manifestations are often subtle and prone to being missed during standard screening procedures.

Machine learning is widely used in the diagnosis of medical diseases (Sun et al., 2023; Bhambra et al., 2020; Nowomiejska et al., 2024). The dynamic development of Artificial Intelligence (AI) has resulted in development of new neural models that allow for the diagnosis of diseases, as well as the distinction of healthy images from those containing various distortions with increasing accuracy and precision. These automatic tools have become a significant element supporting modern health care. Medical imaging data analysis has also found great application in diagnosing eye diseases. These up-to-date methods allow one to recognize and locate characteristic patterns for a given disease, even in images in which different distortions occur (Jain et al., 2018). Moreover, these automatic methods can be utilized to diagnose rare retinal eye diseases as a way of supporting the work of specialists. It should be emphasized that there is only a limited number of ophthalmologists specializing in this type of diseases and training new experts is highly ime-consuming. Thus, recognition rare eye diseases is still a challenging task which will have a huge impact on the development of medicine, as well as early detection of diseases. In this context, AI-based methods are becoming increasingly important not only as diagnostic tools, but also as intelligent systems that support the management of diagnostic workflows – particularly by prioritizing uncertain cases, assisting clinical decision-making, and alleviating the workload of specialists.

The integration of AI into ophthalmologic diagnostics thus represents a shift towards intelligent diagnostic management, where machine learning models form part of a broader system that coordinates tasks, manages diagnostic uncertainty, and facilitates effective triage—especially in the case of rare retinal diseases.

By automating complex tasks such as disease recognition and classification, AI systems help streamline diagnostic processes, enabling healthcare professionals to focus on more critical aspects of patient care. In doing so, they also provide scalable solutions for managing the growing volume of medical data, offering real-time analysis and supporting timely interventions—even in contexts with limited specialist availability.

Various Convolutional Neural Network (CNN) architectures have found particular application in recognizing eye diseases based on diagnostic imaging (Sun et al., 2023; Chen et al., 2021). They involve convolutional operations utilizing filters applied on images and thus extracting features that are further used for recognition particular patterns. For medical purposes both binary and multi-classification are often applied. In the case of rare eye diseases, where a small data set is a major limitation, pre-trained CNN architectures are widely utilized. Networks trained on a large data set, such as ImageNet, are finetuned on appropriate datasets representing the analyzed distortions. Transfer learning allows to obtain satisfactory results. An example of binary classification, distinguishing RP from healthy cases, was performed using deep learning models like InceptionV3, Resnet V2, and Xception, achieving up to 91% accuracy (Chen et al., 2021). VGG-19 was also proposed for recognition of RP and normal cases (Masumoto et al., 2019). The results are very satisfactory, with a mean area under the curve of 0.998 achieved on ultrawide-field pseudocolor images.

Multi-classification methods of various retinal distortions have also gained great interest, recently. The models such as EfficientNet-B7, DenseNet, and ResNet-101 were applied with high success for eight retinal diseases classification, including RP obtaining accuracy, equal to 93% (Sun et al., 2023). Four retinal diseases, Glaucoma, Maculopathy, Pathological Myopia, and RP, were detected utilizing MobileNetV2 model with high accuracy, up to 96.2% (Guo et al., 2021). Three retinal distortions, involving RP, were recognized to a high degree utilizing ResNet, obtaining 94% accuracy (Miere et al.,

2022). Retinal diseases (RP and diabetic retinopathy) and healthy cases based on fundus images were classified with great achievement, exceeding 86% accuracy (Jain et al., 2018).

Recognition of RP, cone-rod dystrophy (CORD) and normal cases with Convolutional Gaited Recurrent Units U-Net was proposed in (Skublewska -Paszkowska et al., 2024). Applying augmentation methods and bidirectional convolutional GRU allowed one to gain 94.05% accuracy for this model. Nowadays various modern architectures are applied in the studies and compared with CNN approaches. Among five deep learning models, such as ResNet152, Vision Transformer (ViT), Inception, ResNetV2, RegNet, ConVNext for RP detection. The first one was stated to achieve the highest testing area under the curve score, equal to 96.47% (Nguyen et al., 2024). It should be emphasized that all the architectures obtained this score exceeding 94%.

To increase classification effectiveness, intuitionistic fuzzy sets are increasingly being used, as they allow for better modeling of uncertainty in the results. These techniques enable the consideration of both membership and non-membership to a given class, leading to more precise and reliable outcomes. In the context of retinal pathology detection, the application of intuitionistic fuzzy sets can contribute to improved diagnostic indicators, especially in cases that are difficult to classify. Additionally, they support more informed uncertainty management within diagnostic decision systems, further enhancing the robustness of clinical support tools.

The main motivation of this study is as follows:

1. Evaluate the ability of various deep learning models to recognize rare eye diseases such as RP, CORD, USHER and healthy cases. Additionally, two groups of pigmentary changes in fundus photo of RP were distinguished: those that arose as a result of the existence of genotypes (RPG) and those where genotype has not been confirmed (RPNG).
2. Improving the detection performance of RPG, RPNG, CORD, USHER and normal cases using a new classification method based on the method introduced in (Żmudzińska et al., submitted).
3. Demonstrating how deep learning-based classification combined with fuzzy logic can support the intelligent management of diagnostic workflows, including prioritization, triage, and uncertainty handling in rare retinal disease detection.

We address the problem of improving the effectiveness of multi-class classification of rare eye diseases by utilizing a new approach using the idea of intuitionistic fuzzy sets (Atanassov, 1989). The aim of this method is to achieve more accurate and reliable predictions in the context of detecting retinal pathologies, including rare diseases such as RP and CORD. This technique can provide significant improvement in classification results, especially in cases that are difficult to classify.

The major contributions and findings of our study are as follows:

1. We implement deep learning architectures for detection of various pigment changes in fundoscopy in retinitis pigmentosa and normal cases such as: EfficientNet, InceptionV3, ResNet50, VGG16, ViT and Residual Attention Vision Transformers (RS-A-ViT). The following rare eye deformations were selected: RPG, RPNG, CORD and USHER. The Efficient model was stated to be the most effective tool for this type of retinal disease classification.
2. Building on the technique (Żmudzińska et al., submitted), we propose a novel method that employs intuitionistic fuzzy sets. This technique enables better modeling of uncertainty and the structure of output data generated by the classifier, significantly increasing the precision of evaluation in borderline cases. The method is based on analyzing the two highest probabilities generated by the classification model and intelligently modifying the True Positive (TP) measure. Typically, classification relies on selecting the class with the highest probability. However, in this approach, the second-highest probability is also considered. The key assumption is that if the difference between the first and second probability is smaller than the difference between the second and third, it indicates that the model is uncertain between the top two classes. In such cases, the algorithm accounts for this uncertainty and may increase the TP measure if the actual class corresponds to the second-highest probability. As a result, this method allows for better utilization of the model's knowledge, improving overall classification effectiveness, especially in situations where class differences are subtle. The application of intuitionistic fuzzy sets enhances the modeling of cases where the classifier struggles to assign an object to a single class.

3. We show that our method not only improves diagnostic accuracy but also strengthens the management of rare disease diagnostics by integrating uncertainty information into triage logic, providing a valuable support layer for ophthalmology decision-making systems.

The approach enhanced the accuracy of the classification of rare eye diseases by up to 5.9% for the RS-A ViT. The achieved results confirm that the innovative method based on intuitionistic fuzzy sets is a perfect tool for improving multi-classification of blueRPG, RPNG, CORD, USHER syndrome and normal cases.

The rest of the paper is as follows. Dataset and methods of classification are described in Section II. In Section III detailed are the results of numerical experiments. Finally, Section IV is devoted to conclusions and future work directions.

2. MATERIAL AND METHODS

2.1. Datasets

The dataset containing fundus images obtained from patients with retinitis pigmentosa (RP), cone-rod dystrophy (CORD), and USHER syndrome was collected at the Chair and Department of General and Pediatric Ophthalmology of the Medical University of Lublin from 186 patients who provided informed consent prior to data collection. The study was conducted in accordance with ethical standards using the Optos 200TX (Optos PLC) device. Ultra-wide-angle pseudo-color (UWPC) and ultra-wide-angle FAF (UWFAF) images were obtained. Each examination was performed after dilating the pupils with topical 0.5% tropicamide. All patients underwent visual acuity testing, slit-lamp biomicroscopy, and dilated fundus examination. All gathered images were assessed by two independent experts. Totally, 692 image data were qualified for the study: 419 for RP with the occurrence of genotype (RPG), 145 for RP with the negative occurrence of genotype (RPNG), 49 with CORD and 79 with USHER distortions.

In order to compare the gathered dataset with healthy cases, the images from Masumoto RP data normal optos were added (Kameoka, 2018). The subset of normal images consisted of 223 cases. The whole dataset prepared for this study is depicted in the Figure 1.

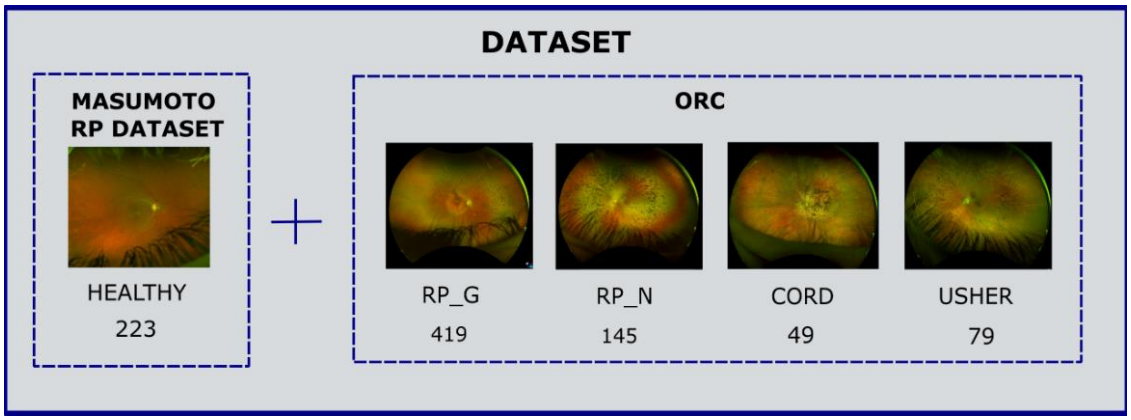


Figure 1. Dataset structure. The data consisting of Retinitis pigmentosa, CORD and USHER were collected at the ORC. The control group was gathered from (Kameoka, 2018). ORC stands for Chair and Department of General and Pediatric Ophthalmology of the Medical University of Lublin in Poland.
Source: own elaboration.

The obtained dataset was enlarged utilizing standard augmentation methods. The following image transformations were applied: Scaling, color jittering, rotating, cropping and resizing, adding small amount of Gaussian noise, elastic deformation, randomly area erasing, masking, vertical, and horizontal flipping. All the described modifications were involved in the training of the successive models applied in this study.

2.2. VGG-19

The VGG19 network is a variation of the deep CNN architecture introduced by (Simonyan & Zisserman, 2015). It is a member of the VGG family of models, noted for its depth and uniform use of small convolutional filters. Specifically, VGG19 comprises 19 layers with learnable parameters: 16 convolutional layers organized in five blocks, followed by three fully connected layers dedicated to classification. The VGG19 model utilizes multiple stacked convolutional layers, each employing 3×3 filters with a stride and zero-padding of 1. These small kernel sizes effectively increase the network's representational capacity without introducing a prohibitive number of parameters. Every convolutional block is followed by a 2×2 max-pooling layer with stride 2, reducing the spatial resolution of feature maps while increasing the depth of feature representations. The network thereby progresses through an increasing number of channels (from 64 filters in the initial layers to as many as 512 in the deepest layers) while continuously halving the spatial dimensions. This approach facilitates the extraction of increasingly abstract and high-level features from the input image. The overall configuration, applied to an input image of size 224×224×3. Upon input, the image is first preprocessed, typically mean subtracted, and then fed into the first convolutional layers. At these early stages, the network extracts low-level features such as edges and simple textures. As the feature maps propagate through subsequent blocks, the network aggregates intermediate-level representations capturing more complex patterns, textures, and object parts. Max-pooling after each block not only reduces the spatial dimensions but also enhances translation invariance and focuses the network's attention on increasingly abstract constructs. By the deepest layers, VGG19 is able to learn sophisticated, high-level features corresponding to the semantic components of the objects present in the image. Finally, the fully connected layers integrate all the extracted features, synthesizing them into class-level predictions. Here, the network effectively maps from a rich and compressed feature representation to a set of class probabilities, culminating in a final decision regarding the object categories present in the input image. This model was chosen because classical approaches based on maximum likelihood do not account for the level of uncertainty in predictions, which can lead to errors when dealing with similar classes. Intuitionistic fuzzy sets enable the implementation of a mechanism that distinguishes between high- and low-confidence cases, thereby increasing the reliability of classification outcomes in medical tasks.

2.3. EfficientNet

EfficientNet is a family of CNNs introduced in (Tan & Le, 2019) that systematically and efficiently scale the dimensions of depth, width, and resolution to achieve state-of-the-art accuracy on image classification tasks while maintaining computational efficiency. Unlike earlier approaches that scale these dimensions in an ad-hoc manner, EfficientNet employs a compound scaling approach to simultaneously balance network width (number of channels), depth (number of layers), and input resolution according to a predefined set of scaling coefficients.

The architecture typically starts with a simple stem convolutional layer, followed by a sequence of mobile inverted bottleneck convolution-based blocks, each with its own expansion ratio, kernel size, and number of output channels. Throughout the network, squeeze-and-excitation (SE) blocks (Hu et al., 2018) are often incorporated to recalibrate channel-wise feature responses, further enhancing performance. Finally, the network includes a classification head consisting of a global average pooling layer, a dropout layer, and a fully connected layer to produce class probabilities.

Similar to other CNNs, input images are often resized to the model's designated resolution (in out case: 224×224) and normalized. The preprocessed image first passes through a stem convolution, which begins extracting low-level features such as edges and simple textures. As the image progresses through subsequent mobile inverted bottleneck convolution blocks (MBConv), the network expands channels to learn richer, more abstract representations, then applies depthwise convolutions to further refine feature channels without excessive computational cost. Each set of MBConv blocks reduces the spatial dimensions (via stride-2 convolutions) while increasing or maintaining the complexity of the representations. Mid-level layers capture increasingly abstract patterns, textures, and semantic parts of objects. The SE modules selectively weight informative channels, improving the network's discriminative capabilities.

In the final stages, the spatial dimensions are collapsed through global average pooling, dealing the information from feature maps into a single vector. A fully connected layer then transforms this feature vector into class logits. Finally, a Softmax activation function produces a probability distribution over the target classes, enabling the network to output a class prediction for the given input.

The choice of EfficientNet for this study was based on its ability to achieve optimal performance with fewer parameters, which is particularly beneficial when working with limited datasets. The model's compound scaling approach allows for balancing the complexity of the model with the available computational resources. This makes it ideal for our study, where computational efficiency and high accuracy are crucial.

2.4. ResNet-50

ResNet-50 is a deep convolutional neural network introduced in (HE et al., 2016). Its main innovation is the use of residual connections to overcome the vanishing gradient problem, enabling the training of very deep architectures. Unlike conventional stacks of convolutional layers, ResNet-50 employs 'bottleneck' blocks, each consisting of three layers: a 1×1 convolution for reducing dimensions, a 3×3 convolution for spatial feature extraction, and another 1×1 convolution for restoring dimensions. A shortcut connection bypasses these layers, adding the input to the output before activation. This residual link preserves information and stabilizes gradients, facilitating the optimization of a 50-layer network.

The network begins with a 7×7 convolution and a max-pooling layer to downsample the input image, typically resized and mean-subtracted to 224×224 pixels. It then proceeds through four stages of bottleneck blocks, each stage reducing spatial dimensions while increasing representational depth. Early layers capture low-level features (edges, textures), intermediate layers detect more complex structures, and deep layers encode high-level semantic concepts (object parts and whole objects).

A global average pooling layer condenses the final feature maps into a single vector, passed to a fully connected layer and a Softmax output for classification.

The use of residual connections ensures that information is not lost as it passes through the layers, maintaining stability during training and allowing the model to learn more complex patterns in retinal images.

2.5. InceptionV3

InceptionV3 is a convolutional neural network that refines the Inception architecture originally proposed in (Szegedy et al., 2015). It employs carefully factorized convolutions, dimension reductions, and architectural tweaks to improve efficiency and accuracy. Instead of using a single large convolutional filter, InceptionV3 factorizes larger kernels into multiple smaller ones (e.g., a 5×5 convolution into two consecutive 3×3 convolutions). This reduces computational cost and increases representational power. It also incorporates asymmetric convolutions (e.g., 3×1 followed by 1×3) to further reduce parameters while preserving feature extraction quality.

The network typically accepts 299×299 RGB images, which are preprocessed (e.g., mean subtraction and scaling). Initial layers use stride-2 convolutions and max-pooling operations to reduce spatial dimensions. Subsequent "Inception modules" combine multiple filter sizes, capturing a range of feature scales in parallel. Between these modules, pooling layers maintain manageable feature map sizes. As the image flows deeper into the network, the extracted features grow increasingly abstract, shifting from low-level edges and textures to intricate, high-level object parts.

After passing through multiple Inception modules, a global average pooling layer aggregates spatial information into a compact descriptor. Finally, a fully connected layer and Softmax activation produce class probabilities. InceptionV3 achieves high performance on classification tasks (Szegedy 2016), offering an effective balance between accuracy and computational complexity.

This model was selected for its balance between computational efficiency and performance. It is particularly effective in medical imaging tasks where complex patterns must be extracted from images

with varying structures. By capturing features at multiple scales, InceptionV3 can provide more accurate and robust predictions, which is critical when differentiating between similar retinal conditions.

2.6. ViT

The Vision Transformer (ViT) applies the Transformer architecture (Vaswani et al., 2017), originally designed for sequence processing in natural language tasks, to image recognition (Dosovitskiy et al., 2021). Instead of using convolutions, ViT treats an image as a sequence of flattened patches, allowing self-attention mechanisms to capture long-range dependencies and global context without explicit spatial priors.

A ViT model typically begins by splitting an input image (e.g., 224×224 pixels) into fixed-size patches (e.g., 16×16), flattening and linearly projecting each patch into a latent embedding. Positional embeddings are added to preserve spatial order. These patch embeddings form a sequence that is fed into multiple layers of standard Transformer blocks, each containing a multi-head self-attention module and a feedforward network. Layer normalization and residual connections help stabilize training.

Through self-attention, the network identifies relevant patterns and relationships across all patches, not limited to local neighborhoods. As the sequence progresses through the Transformer layers, representations evolve from low-level features, suchas: edges or textures, to increasingly abstract concepts like: parts, objects, etc.

A classification token, added to the patch embeddings, aggregates the learned information. After passing through the Transformer layers, this token is used as the final image representation. A simple fully connected layer maps it and a Softmax yields class probabilities.

ViT transforms images into a sequence of patches, allowing it to model interactions between distant regions of the image more effectively than traditional convolutional networks. This approach is particularly useful in medical image analysis, where global context (such as the relationship between different regions of the retina) can be crucial for accurate diagnosis.

2.7. Residual Attention ViT

Residual Attention Vision Transformers (RS-A-ViT) build upon the standard ViT paradigm (Dosovitskiy et al., 2021) by enhancing feature extraction capabilities through residual connections that refine the attention mechanism (Diko et al., 2024). In this approach, images are first divided into uniform patches and projected into latent embeddings. These embeddings, augmented with positional encodings, form a token sequence processed by Transformer blocks.

Unlike original ViTs, Residual Attention ViTs introduce skip connections that bypass parts of the attention layers. This ensures that crucial information does not degrade as it moves through the deep network, thereby improving the stability and effectiveness of training. The multi-head self-attention layers themselves learn global relationships between patches, capturing both low-level patterns and high-level structures as they progress through the network's depth. Residual paths retain essential features from earlier representations, counteracting any potential loss of spatial or semantic cues.

As the processing advances, the network's representations evolve from edge-like features to more complex concepts. Each Transformer block, composed of attention and feed-forward sub-layers with residual shortcuts, refines these representations. Finally, a global pooling operation aggregates the learned features, and a classification head translates the resulting rich representation into class predictions.

The structure of the paper is as follows. Section II discusses in detail the data and methods used in the study. Section III presents the results of the conducted experiments. Finally, Section IV discusses the conclusions and directions for future research.

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3. EXERIMENTS AND RESULTS

The experiment involved a comparison of two methods of classifying retinal diseases. One of the methods employed a new technique that utilizes intuitionistic fuzzy sets. This method enabled better modeling of uncertainty and the structure of output data generated by the classifier, significantly improving the precision of evaluation in borderline cases. The detection of RP_G, RP_N, CORD, USHER syndromes and healthy cases were utilized. For the purpose of this study six deep learning models were applied: VGG-19, EfficientNet, ResNet50, InceptionV3, ViT and RS-A ViT.

As part of the conducted experiments, two classification methods were compared: the standard maximum likelihood method and a new method based on intuitionistic fuzzy sets, which, unlike the classical method, examines the two highest probabilities. If the second probability is closer to the highest one than to the third in order, the True Positive measure is increased. The results obtained for both approaches are presented in the figure 2.

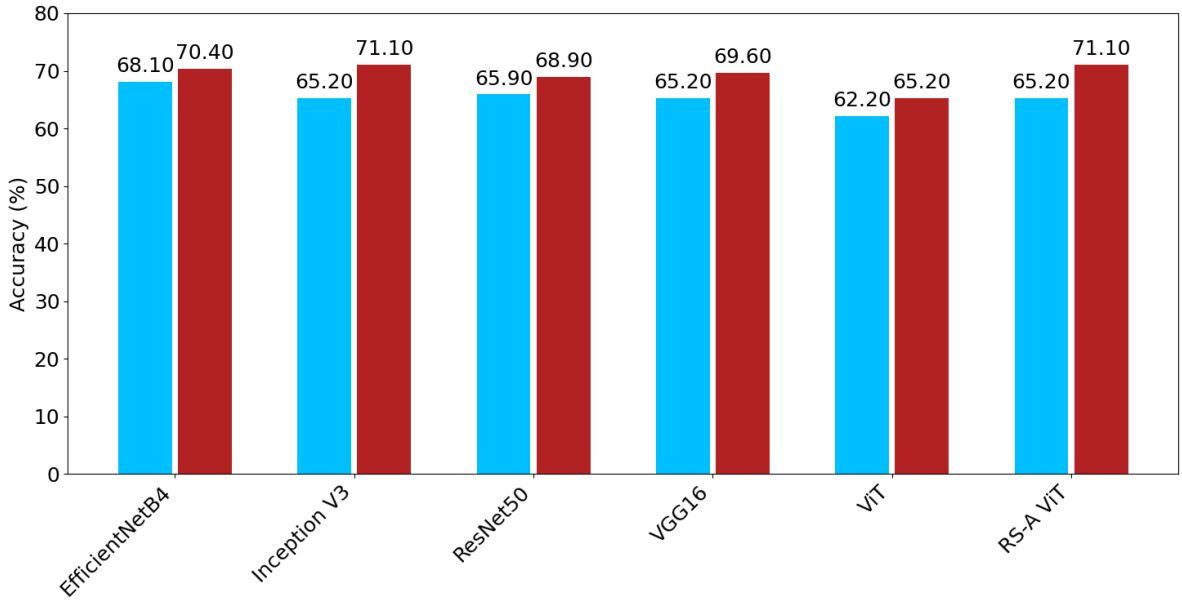


Figure 2. Obtained classification results using normal (max probability) approach (blue) and own method (red)
Source: own elaboration.

The classification results obtained using the traditional maximum likelihood method, shown in the first chart in in the figure 2, indicate that the accuracy of the models ranged from 62.2% to 68.%. The highest result was achieved by the EfficientNet model (68.1%), while the lowest accuracy was obtained for the ViT model (62.2%). These results suggest that the classical approach performs moderately well in the analyzed classification task; however, none of the applied models achieved an accuracy above 70%.

The application of the new method, utilizing intuitionistic fuzzy sets, as well as the two highest probabilities and increasing the True Positive measure when the second probability is closer to the highest than to the third, led to a significant improvement in classification accuracy for all models, as shown in the second chart in the figure 2. The classification results in this case ranged from 65.2% to 71.1%. The best results were achieved by the RS-A-ViT and Inception models (71.1%), while the lowest accuracy was obtained for the ViT model (65.2%). It is worth noting that the models that previously achieved the highest results also achieved higher accuracy with the new method, emphasizing their potential in classification tasks.

The new classification method, based on intuitionistic fuzzy sets with consideration of the two highest probabilities, clearly surpasses the standard maximum likelihood approach. The improvement in accuracy is evident across all models, with particularly large differences observed for the RS-A-ViT model (an improvement of 5.9 percentage points) and the Inception model (an improvement of 5.9 percentage points). The smallest differences were observed for the EfficientNet model, which may indicate a limited potential of this model in more advanced data processing methods.

The obtained results unequivocally demonstrate the effectiveness of using intuitionistic fuzzy sets with a mechanism that considers the two highest probabilities. This method allows for better handling of uncertainty and ambiguity in data, resulting in a significant increase in classification accuracy compared to the traditional approach. The proposed solution can be successfully applied to other classification tasks requiring high precision.

To evaluate the performance of the analyzed deep learning models, a detailed analysis was conducted in addition to basic classification accuracy. This analysis included four key metrics: precision, recall, F1-score, and specificity, as well as confusion matrices. The introduction of an additional method—such as data balancing techniques, advanced augmentation, or preprocessing—had a significant impact on the models' performance.

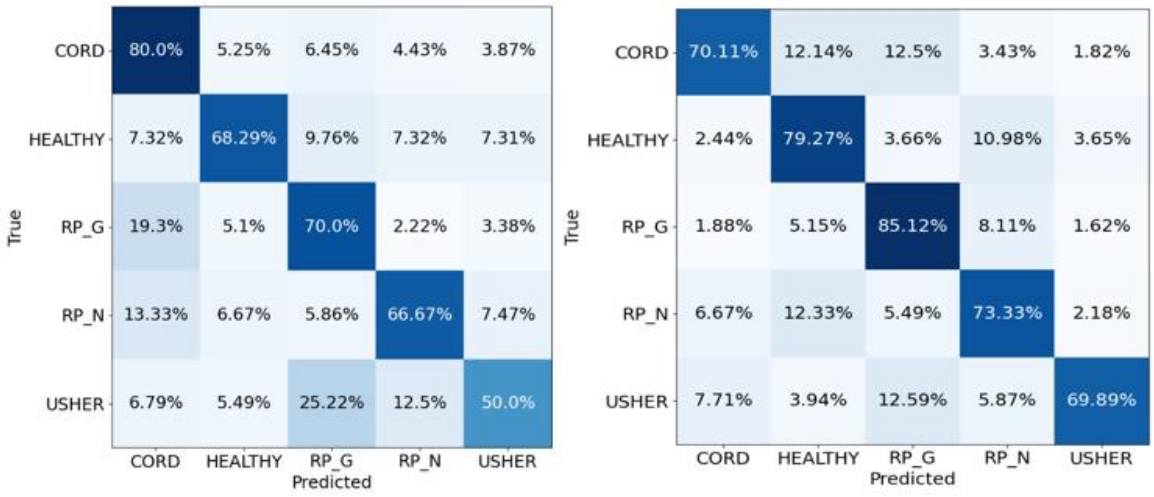


Figure 3. Confusion matrix for the EfficientNetB4 model before (left) and after (right) applying the method

Source: own elaboration.

The EfficientNetB4 model, after applying the proposed method (Figure 3), demonstrated a significant improvement in classification performance compared to the baseline version (also Figure 3). The accuracy for the RP_G class increased from 70.0% to 85.12%, while for the USHER class it rose from 50.0% to 69.89%. Misclassifications among degenerative disease classes (e.g., RP_G, RP_N, USHER) were notably reduced. The model also achieved a better overall balance between recall and specificity, which is particularly important in the context of medical diagnostics.

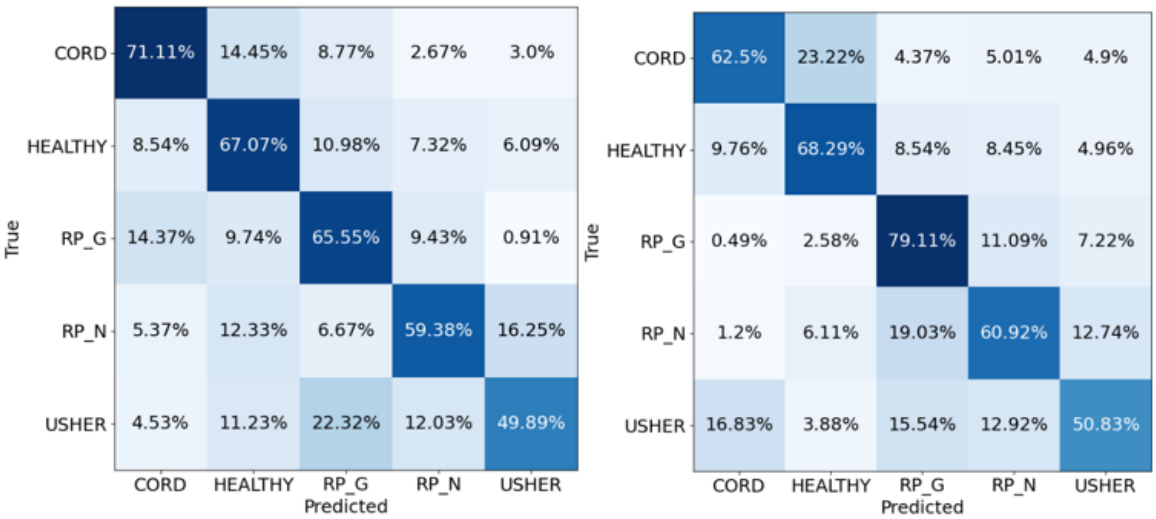


Figure 4. Confusion matrix for the Inception V3 model before (left) and after (right) applying the method

Source: own elaboration.

In the case of the Inception V3 model (Figure 4), the application of the method led to a significant improvement in the classification accuracy for the CORD class – from 75.0% to 87.65% – as well as

for the HEALTHY class, which improved from 69.51% to 81.71%. The number of misclassifications between the RP_G, RP_N, and USHER classes was reduced, resulting in more precise identification of disease cases. After the modification, the model also demonstrated noticeably greater stability.

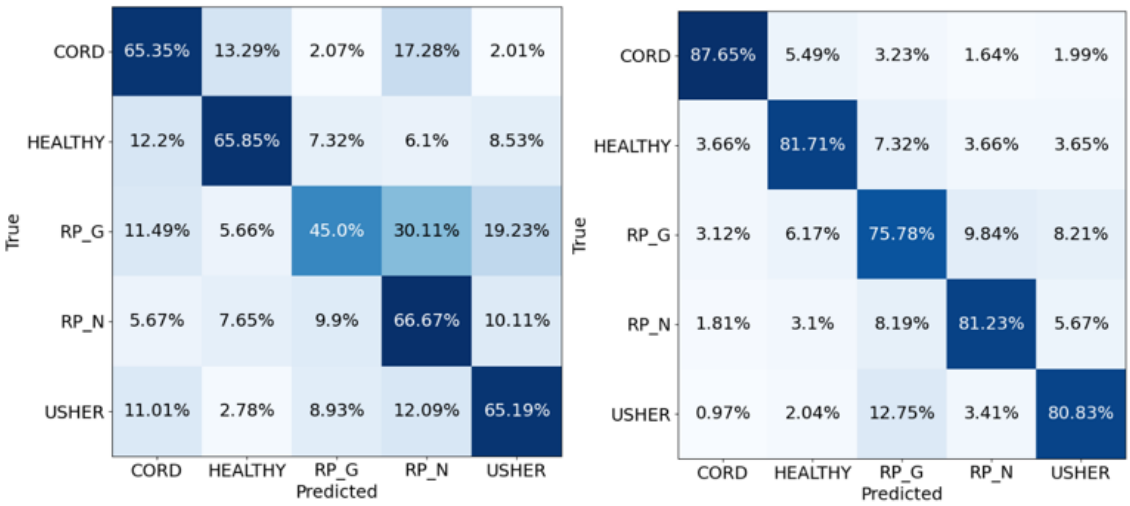


Figure 5. Confusion matrix for the RSA-ViT model before (left) and after (right) applying the method
Source: own elaboration.

The RSA-ViT model showed the most substantial improvement for the RP_G class, with accuracy increasing from 51.1% to 85.12% after applying the method (Figure 5). Prior to the modification, the model struggled to differentiate between degenerative disease classes, resulting in numerous misclassifications—for instance, assigning RP_G to CORD in 19.3% of cases. Following the implementation of the method, the model achieved some of the best results across the entire set, particularly in terms of the F1-score.

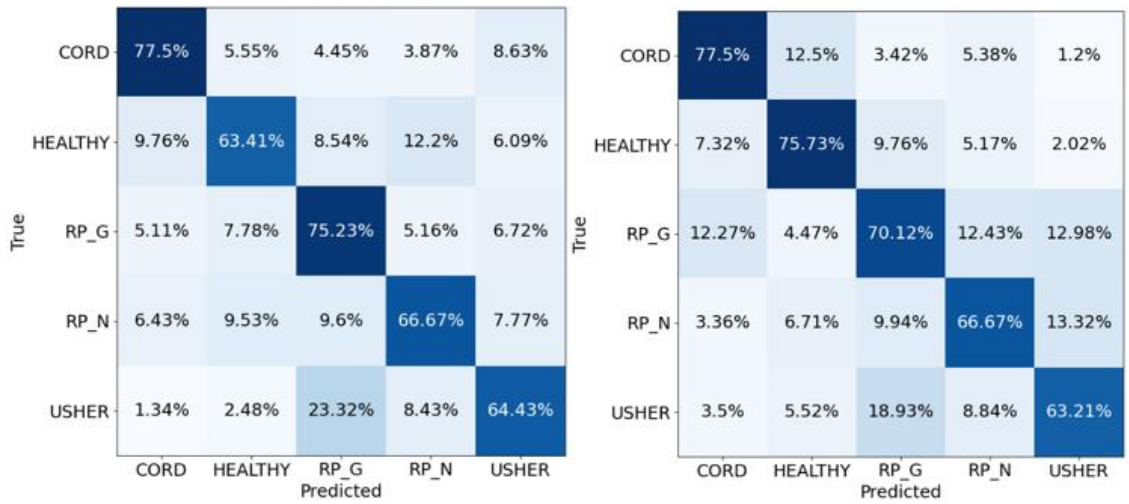


Figure 6. Confusion matrix for the ResNet50 model before (left) and after (right) applying the method
Source: own elaboration.

The ResNet50 model also responded positively to the application of the proposed method (Figure 6). The classification accuracy for the RP_N class increased from 66.67% to 81.23%, and for the CORD class from 77.5% to 87.65%. At the same time, misclassifications involving RP_G and USHER were reduced, contributing to an overall improvement in accuracy. The model was previously characterized by relatively good specificity, which was successfully maintained while also improving recall.

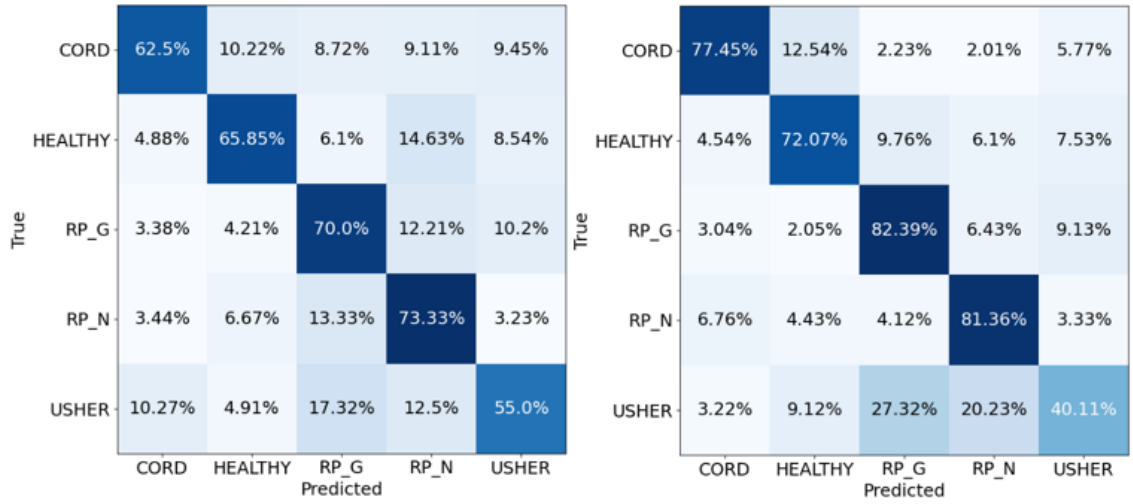


Figure 7. Confusion matrix for the VGG16 model before (left) and after (right) applying the method
Source: own elaboration.

Before applying the method, the VGG16 model (Figure 7) exhibited the greatest difficulty in correctly classifying the RP_G class, achieving an accuracy of only 45%. After the modification, the accuracy rose to an impressive 82.39%, indicating that the previously observed limitations were effectively overcome. Misclassifications involving the USHER class were also significantly reduced, and the overall balance across evaluation metrics improved substantially.

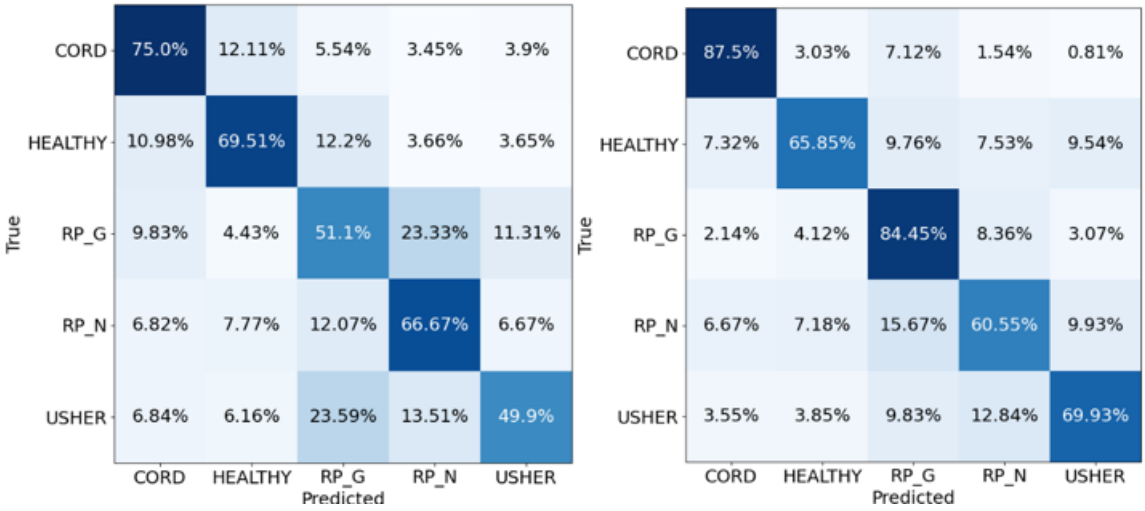


Figure 8. Confusion matrix for the ViT model before (left) and after (right) applying the method
Source: own elaboration.

In the case of the ViT model (Figure 8), the applied method contributed to a significant improvement in classification performance for the RP_G class – from 65.55% to 84.45% – and for the CORD class – from 71.11% to 87.5%. Despite some ongoing challenges in classifying RP_N, the overall F1-score and recall values increased notably. The model became more effective at distinguishing between similar classes while maintaining high specificity.

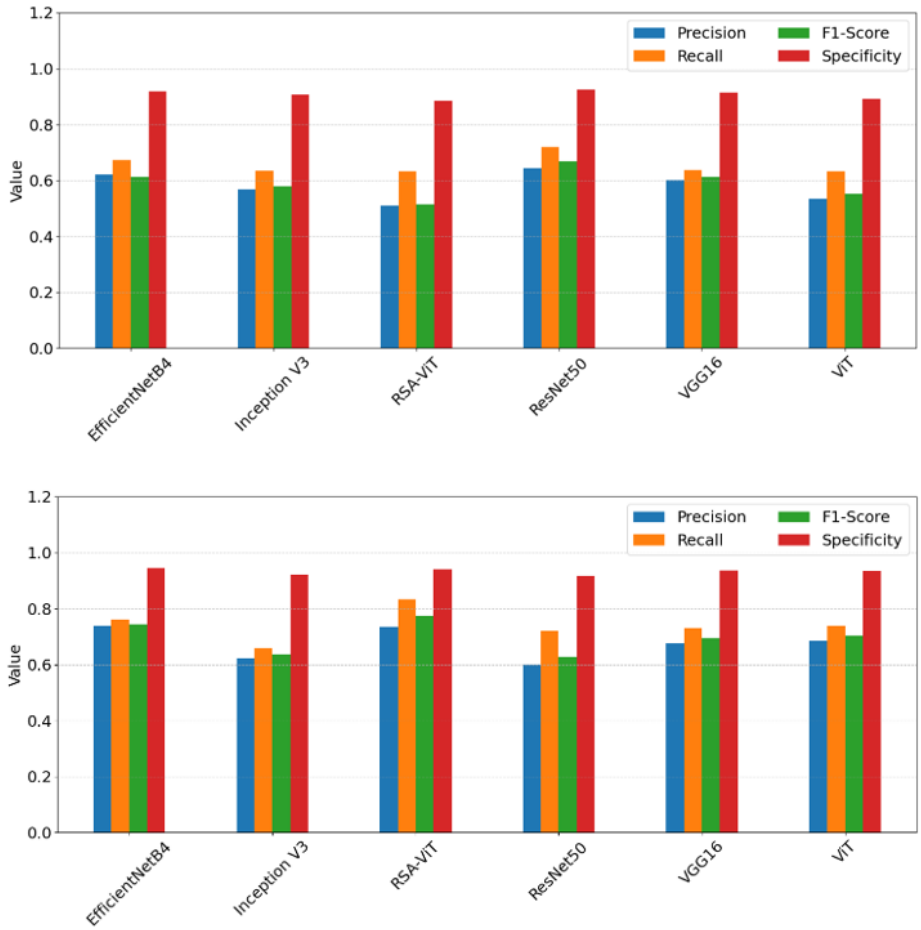


Figure 9. Comparison of the average values of precision, recall, F1-score, and specificity for all models before (top) and after applying the method (bottom)
Source: own elaboration.

A comparison of the precision, recall, F1-score, and specificity metrics for each model before and after applying the method is presented in Figure 9. The chart clearly shows that all analyzed models exhibited an improvement in at least two of the four key metrics. The most notable performance was achieved by the RSA-ViT model, which demonstrated the highest increase in both F1-score and recall following the modification. The ViT model also stood out, achieving the highest value of Specificity.

In summary, the use of intuitionistic fuzzy sets led to improvements across all metrics and models, particularly for classes that were previously prone to misclassification. This reinforces the value of probabilistic interpretation and uncertainty-aware modeling in sensitive classification tasks such as medical image analysis.

However, it is important to acknowledge certain limitations of the presented analysis. First, the dataset used in this study, while augmented, remains relatively small and imbalanced across classes, which may affect the generalizability of the results. Second, the evaluation was conducted using data collected from a single medical center, which could introduce bias related to the imaging protocol or patient population. Additionally, the performance of the models may vary when applied to data from different devices or under real-world clinical conditions, which were not tested in this study. Finally, the interpretation of the intuitionistic fuzzy logic output still requires expert knowledge and could be challenging to integrate into routine clinical workflows without further development of explainable interfaces.

4. CONCLUSION AND FUTURE WORKS

This study employed an innovative method based on the modification of the True Positive measure using intuitionistic fuzzy sets to improve the accuracy of classifying rare eye diseases, such as Retinitis

Pigmentosa (RP), Cone-Rod Dystrophy (CORD), and Usher syndrome. This method utilizes uncertainty to enhance the classification process by considering the two highest class probabilities rather than only the most probable one. The proposed technique demonstrated a significant improvement, achieving up to a 5.9% increase in classification accuracy for complex cases using the RS-A Vision Transformer (ViT) model. This method not only improves classification accuracy but also supports intelligent management of diagnostic processes by enabling more reliable decision-making based on the nuanced handling of uncertainty.

Future research directions include extending this method to broader classification tasks, exploring additional statistical measures (e.g., quartiles and distributions), and investigating its practical applications in intelligent healthcare management to further enhance clinical decision-making processes.

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28th European Conference on Artificial Intelligence (ECAI 2025)

AI-POWERED KNOWLEDGE MANAGEMENT AND DECISION SUPPORT FOR IVF WITH PGT: LITERATURE REVIEW AND MODEL PROPOSAL

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ABSTRACT

Purpose: *This study aims to apply machine learning as an AI-based tool for comprehensive literature review and to propose an Integrated Clinical Management Model (ICMM) that leverages AI-driven decision support, data integration, and change management to optimize decision-making in reproductive medicine. The medical context is exemplified by Preimplantation Genetic Testing-In Vitro Fertilization (PGT-IVF) for rare monogenic diseases, focusing on improving clinical outcomes and patient-centered care through personalized and transparent support systems.*

Need for the study: *As PGT-IVF procedures become more common in reproductive medicine, there is a need to better assess their effectiveness in monogenic diseases. Machine learning can enhance literature analysis and support decision-making, leading to more informed choices for both doctors and patients.*

Methodology: *Literature review based on the Machine Learning Perspective.*

Findings: *Machine learning has enabled an in-depth analysis of available knowledge and the identification of research gaps in the context of implementing new AI-driven solutions in reproductive medicine using PGT-IVF: The scientific evidence is based mainly on case studies with a lack of comprehensive population-level data (1); PGT-IVF in couples at risk of genetic disease is justified, but the procedure does not guarantee a healthy birth (2); Effectiveness analysis boils down to demonstrating a birth to a healthy child (3); The possibilities of implementing the solution differ between countries, Poland is an example (4).*

Practical Implications: *The effective implementation of the proposed AI-powered ICMM requires comprehensive access to clinical, genetic, financial, and psychosocial data across all stages of the PGT-IVF process. This integrated approach supports complex, multi-dimensional decision-making, enabling personalized treatment pathways that balance medical effectiveness, cost-efficiency, and emotional well-being for couples undergoing treatment.*

Keywords: machine learning, decision support system, predictive analytics, preimplantation genetic testing (PGT), in vitro fertilization (IVF), knowledge management, personalized medicine

Jel codes: I10, I18, C63, C80, D81, D83

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1. INTRODUCTION

The use of AI-based methods enhances the understanding of the dynamics of scientific discourse across many fields – here, focusing on rare diseases – by revealing patterns of knowledge and the evolution of terminology. Integrating these advanced computational techniques in research underscores the crucial role of machine learning in knowledge discovery. This study contributes to the broader discussion on artificial intelligence applications in text mining, reflecting on how computational models can optimize literature synthesis and research assessment in highly specialized and rapidly evolving domains. These methods enable identification of key research areas and conceptual frameworks. Additionally, hierarchical clustering (using Manhattan and Ward metrics) and word enrichment analysis facilitate classification of thematic clusters and detection of semantic relationships between concepts.

Our literature review highlights opportunities to apply AI tools for predictive analytics and decision support in reproductive medicine, particularly regarding in vitro fertilization combined with preimplantation genetic testing (PGT) for couples at risk of transmitting rare monogenic diseases.

Rare diseases, often chronic and genetically determined, affect approximately 6–8% of the global population – around 400 million people worldwide, including 27–36 million in the European Union (Nguengang Wakap et al., 2020; Pieklak et al., 2023). According to Orphanet, nearly 72% of these conditions have a genetic origin (Orphanet, 2024). In reproductive medicine, 2–4% of couples are at risk of passing autosomal recessive or X-linked genetic disorders to their offspring (Capalbo et al., 2021).

Modern reproductive medicine offers two main diagnostic strategies for such couples: prenatal diagnosis (PND) and preimplantation genetic testing (PGT). While PND is performed during pregnancy, PGT allows early selection of unaffected embryos prior to implantation, reducing emotional and legal complexities related to pregnancy termination (De Wert et al., 2014; Klein & Mahoney, 2007).

The aims of this study are:

- To apply machine learning in literature review and identify potential research gaps in the field of reproductive medicine, with a focus on Preimplantation Genetic Testing-In Vitro Fertilization (PGT-IVF) in the context of rare monogenic diseases.
- To apply machine learning for literature review and identify research gaps in reproductive medicine, focusing on PGT-IVF in the context of rare monogenic diseases.
- To evaluate the legitimacy and effectiveness of PGT-IVF for couples at risk of transmitting rare monogenic diseases, defining effectiveness as the ratio of benefits to all associated financial, non-financial, and psychological costs related to choosing this strategy to have a healthy child, thereby supporting informed decision-making.
- To explore the potential of intelligent knowledge management and artificial intelligence in supporting decision-making processes in PGT-IVF from both medical and patient perspectives.
- To present Poland as a case study illustrating challenges related to the implementation of PGT-IVF under specific legal conditions that vary internationally.

The literature review highlights a clear need for decision support systems integrating medical, genetic, economic, and psychosocial data to enable patients and clinicians to make informed, personalized, and ethical therapeutic decisions (Khalfallah et al., 2023; Haude et al., 2017).

2. LITERATURE REVIEW

Intelligent management in healthcare involves the deployment of artificial intelligence (AI) systems designed to assist clinicians in their decision-making processes. These systems are responsible for aggregating, storing, organizing, retrieving, and analyzing medical data to support informed clinical judgments. By streamlining data workflows, intelligent management enhances the efficiency of healthcare delivery for both practitioners (doctors) and service providers (Kuo, 2023, p. 3).

Central to intelligent management is the application of machine learning, which is becoming increasingly embedded in clinical environments. This integration bridges preclinical data analysis with real-time bedside diagnostics, enables patient stratification (e.g., clustering based on clinical profiles), and supports decisions related to treatment planning or early intervention. These capabilities are essential for both primary and secondary prevention and contribute to improved decision accuracy and treatment effectiveness (Belciug & Gorunescu, 2020, pp. 642, 659).

Such management systems often rely on intelligent decision support systems (i-DSS), a category of AI-driven tools that facilitate both administrative and clinical processes. In clinical contexts, these are referred to as Clinical Decision Support Systems (CDSS) – platforms that provide tailored recommendations and predictive insights based on individual patient data. These tools assist clinicians in diagnosing conditions, selecting interventions, and reducing the likelihood of errors. By leveraging extensive clinical and biological datasets, CDSS apply algorithmic models to correlate patient data with phenotypic patterns, ultimately enabling more precise and personalized care (Khalfallah et al., 2023, p. 28).

The broader notion of digital health management encompasses the integration of digital technologies – including mobile health apps, health information systems, the Internet of Things (IoT), and AI – into the organization and delivery of care. This approach seeks to enhance decision-making, foster patient and caregiver engagement, and improve overall health outcomes (Pyper, McKeown, Hartmann-Boyce, & Powell, 2023; Zhou et al., 2024; Zajac, Braun, Klein, & Kolbe, 2024; Oshni Alvandi & and Bain, 2023).

Knowledge-based management, by contrast, is an approach grounded in the systematic use of existing knowledge to guide decision-making, particularly in complex or uncertain clinical scenarios such as rare diseases. This method depends on solid infrastructural and technological foundations and should be a core element of digital health strategies, especially those aimed at supporting vulnerable populations (Montani & Bellazzi, 2002; Qiu, Gorantla, Rajan, & Tan, 2021; Oshni Alvandi et al., 2023; Zajac et al., 2024; Zhou et al., 2024).

Preimplantation genetic testing (PGT) is a multi-step, highly specialized procedure that enables the identification of genetic disorders in embryos before implantation. This paper focuses on PGT-M, which targets monogenic conditions (De Rycke & Berckmoes, 2020). The process is medically and emotionally demanding for patients, involving strict clinical protocols, significant financial costs, and complex decision-making. The emotional burden associated with repeated procedures and uncertain outcomes further highlights the need for decision-support tools and personalized guidance (Harper et al., 2012; Takeuchi, 2021; Haude et al., 2017).

3. METHODOLOGY

Initially, 275 publications on PGT and rare diseases were searched in the most popular databases: 174 items in Scopus, 26 items in Web of Sciences, 28 items in PubMed, and 47 items in EBSCO. A query string such as '(ALL (rare AND disease*) AND ALL (PGT))' was used (in different databases, the query syntax could have slightly different field tags, but the syntax expressed the same query). 46 duplicates were then eliminated after being assessed for topical relevance. Many important papers in other languages, those indexed in other databases, or those that weren't indexed were not included in the analysis. It was required to embrace these limitations to tokenize and alter the text, including lemmatization. Finally, 229 publications [Appendix A1] in English and German were selected for the analysis of text mining and machine learning.

The analysis used such techniques in the field of text mining and machine learning, i.e. word cloud (Gárate-Escamilla et al., 2022; Qu et al., 2022; Sun & Zhao, 2023), a bag of words (with L1) (Bagherzadeh et al., 2021; Castro et al., 2022), topic modeling by Latent Semantic Index (LSI) (Lossio-Ventura et al., 2021; Venugopal et al., 2023) and keyword extraction by TF-IDF scoring (Veisi et al., 2019; Yahya Saeed et al., 2021), hierarchical clustering (with Manhattan Metric and Ward Metrics) (Amine et al., 2010), word enrichment (Kuhr et al., 2020; Ning et al., 2018) and sentimental analysis (with SentiArt method) (Jacobs, 2019, 2022; Jacobs & Kinder, 2022).

The research process was divided into eight steps (Figure 1). The approach is multi-dimensional. The pre-processing of the text took place in the first stage. This stage included transformation (lowercase, remove URLs), tokenization (regexp) and normalization (LemmagenLematizer), and filtering (stopwords, lexicon, regexp). The second stage involved generating the word cloud. The corpus included: 1388 tokens and 20 types. Parallel to the second stage was the third stage. The third stage used the Bag of Words (term frequency - count, regularization – L1 (sum of elements)).

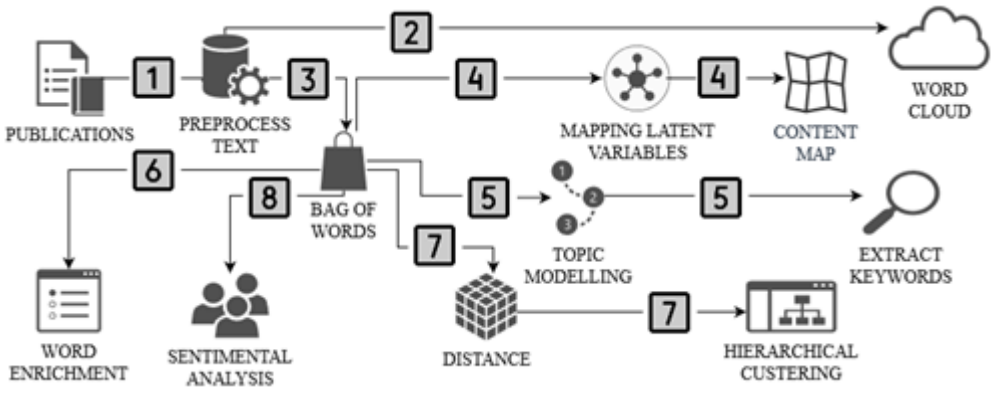


Figure 1. The framework of the authors' research procedure (methodology)
Source: own elaboration.

Stages 4 –8 continued the third stage and were interconnected. In step 4, mapping latent variables was conducted with the presentation of the publications' content map. Stage 5 involved topic modeling (Latent Dirichlet Allocation) and the extraction of 10 keywords.

In step 6, word enrichment analysis was employed to evaluate significance in the corpus's studied subset (i.e. it is not a random word, but a word closely related to the examined term). Later, hierarchical clustering was performed (using Ward linkages). Stage 7 uses the SentiArt method for sentimental analysis to recognize moods: happiness, surprise, disgust, anger, fear, and sadness.

Using the aforementioned methods, we can evaluate how the automated process aids in choosing the right publications for an extensive literature review. It also provides a suggestion as to which topics are worthwhile researching and which publications are more similar in terms of their themes. The approach is multi-dimensional. The results are shown in the next section.

The literature analysis revealed significant gaps in the systematic evaluation of effectiveness and comprehensive decision support in IVF with PGT procedures. In response to these challenges, we propose developing an AI-based decision support model that combines clinical information, treatment success predictions, financial aspects, and emotional and psychosocial factors that are integral to patient experience (Takeuchi, 2021; Capalbo et al., 2021).

4. RESULTS

Figure 2 shows word clouds based on the examined corpus, which included the title and keywords. It illustrates the most common terms around the studied issue. In the initial examination, it could be noticed that the most important words were: genetic (weight 541), PGT (weight 305), testing (weight 301), preimplantation (weight 217), disease (weight 183), gene (weight 181), clinical (weight 180), sequencing (weight 170), diagnosis (weight 164), patients (weight 164).

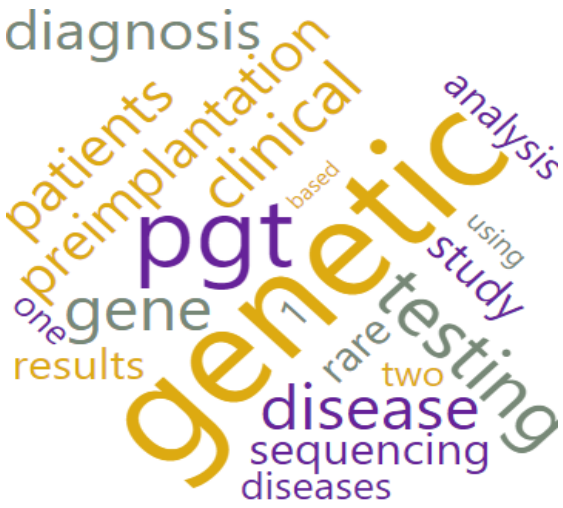


Figure 2. Word clouds of terms. Limitations: The authors did not take into account many valuable publications in the study, instead taking into account the need to narrow the thematic scope of the described issues

Source: own elaboration based on 229 references [A1].

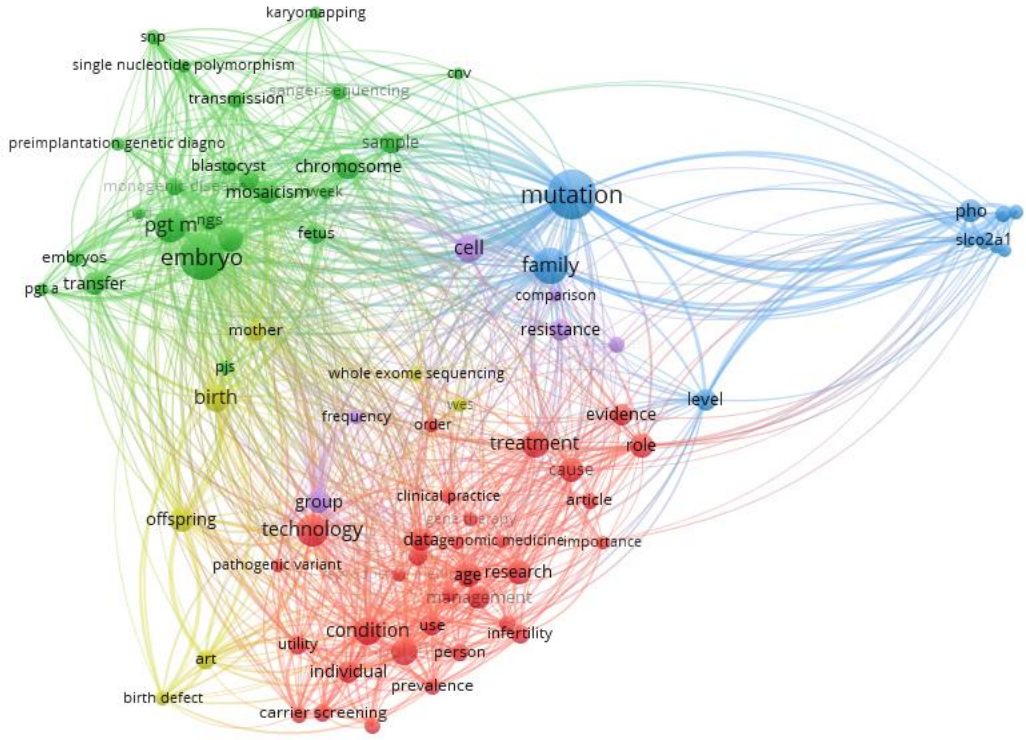


Figure 3. Mapping latent variables from titles and abstracts of the publications on issues connected with rare diseases and PGT. Note: Technical publication on mapping and clustering using VOSviewer (Ding & van Eck, 2014; Szaruga & Załoga, 2022). Limitations: The authors did not take into account many valuable publications in the study, instead taking into account the need to narrow the thematic scope of the described issues

Source: own elaboration based on 229 references [A1].

While exploring the studied publications in-depth, particular attention was paid to mapping latent variables in the network connections map (Figure 3 and Figure 4). The larger the ball, the more often the latent variable in the analyzed texts appeared. The shorter the bond line, the stronger the bond, and the longer, the weaker the interdependence of the latent variables.

Based on the titles and abstracts of the analyzed publications, 5,991 terms (latent variables) were found, 131 of which appeared 10 times in the text. On their basis, using the "association length" method, 5 clusters were found in the connection network, with a total number of 1657 links (Figure 3):

- cluster 1 - red (32 items),
- cluster 2 - green (24 items),
- cluster 3 - blue (10 items),
- cluster 4 - yellow (7 items),
- cluster 5 - purple (6 items).

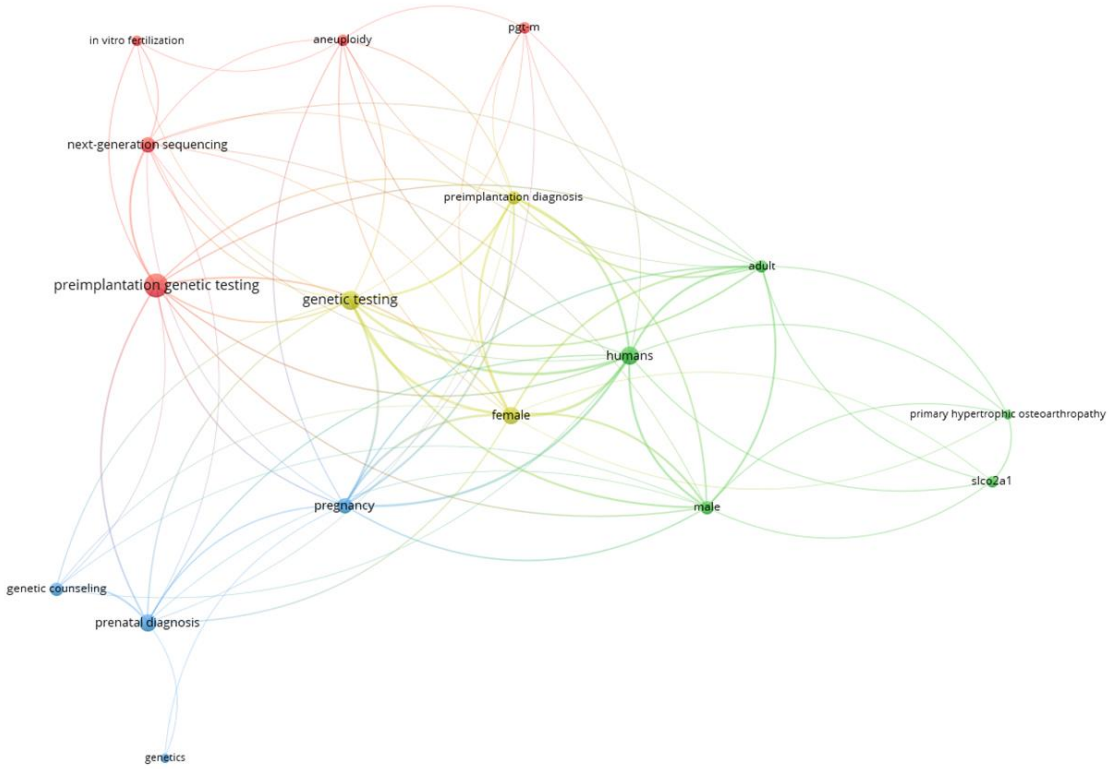


Figure 4. Mapping latent variables from keywords of the publications on issues connected with rare diseases and PGT. Note: Technical publication on mapping and clustering using VOSviewer (Ding & van Eck, 2014; Szaruga & Załoga, 2022). Limitations: The authors did not take into account many valuable publications in the study, instead taking into account the need to narrow the thematic scope of the described issues

Source: own elaboration based on 229 references [A1].

Using bibliographic data and analyzing only 'keywords', 17 keywords were selected (out of 776) that appeared at least 5 times in the text (full counting). 4 clusters with 174 connections were obtained (Figure 4):

- Cluster 1 (red) includes 5 latent variables: aneuploidy, in vitro fertilization, next-generation sequencing, PGT-M, and preimplantation genetic testing.
- Cluster 2 (green) includes 5 latent variables: adult, humans, male, and primary hypertrophic osteoarthropathy.

- Cluster 3 (blue) includes 4 latent variables: genetic counseling, genetics, pregnancy, and prenatal diagnosis.
- Cluster 4 (yellow) includes 3 latent variables: female, genetic testing, and preimplantation diagnosis.

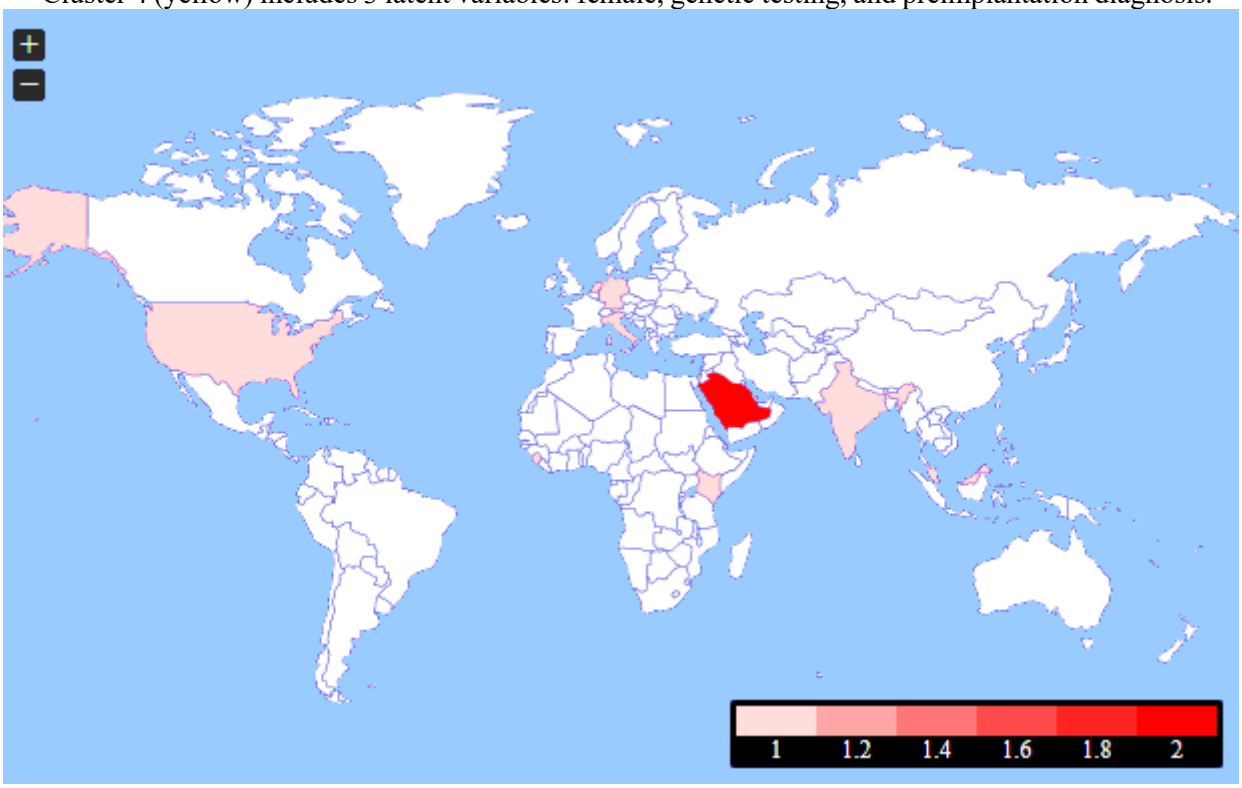


Figure 5. Publications' Content Maps from titles, abstracts, and keywords. Note: The more intense the color in the legend, the more often the geographic location is mentioned
Source: own elaboration based on 229 references [A1].

Figure 5. shows which locations were most often referred to by the authors in the context of rare diseases and PGT: United States, Netherlands, Germany, Italy, Cyprus, Israel, Saudi Arabia, Kenya, Sierra Leone, India, and Malaysia.

Words closely related to the term PGT are presented in Table 2.

From the results of thematic modeling (Latent Semantic Indexing; log perplexity = 8.0531; topic coherence = 0.8935) keywords were extracted using aggregation by average and the TF-IDF scoring method (Table 1).

Table 1. Extract keywords by TF-IDF scoring

Word	TF-IDF scoring	Word	TF-IDF scoring
genetic	0.247	preimplantation	0.122
PGT	0.147	disease	0.121
testing	0.146	patients	0.118
clinical	0.133	diagnosis	0.109
gene	0.125	sequencing	0.107

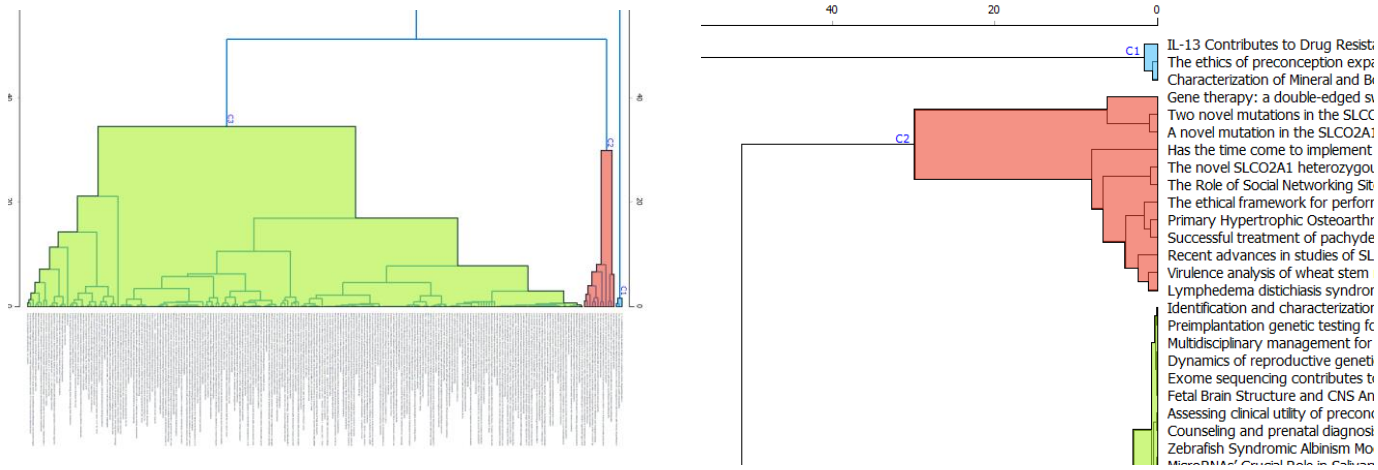
Source: own elaboration based on 229 references [A1].

Table 2. Word enrichment

Related word with PGT	p-value	FDR	Related word with PGT	p-value	FDR
preimplantation	1.8×10^{-22}	1.8×10^{-21}	results	1.2×10^{-4}	2.9×10^{-4}
testing	2.2×10^{-17}	1.5×10^{-16}	gene	5.1×10^{-3}	7.8×10^{-3}
genetic	1.7×10^{-9}	8.3×10^{-9}	diagnosis	7.4×10^{-3}	0.0106
analysis	6×10^{-6}	2×10^{-5}	rare	8.4×10^{-3}	0.0112
sequencing	1.6×10^{-6}	2.7×10^{-5}	diseases	9×10^{-3}	0.0113

Source: own elaboration based on 229 references [A1].

Table 2 presents statistically significant relationships (p-value < 0.05, FDR < 0.2). If publications are concerned with PGT, important in this context are preimplantation, rare diseases, gene diagnosis or genetic testing/analysis, sequencing, and results. Figure 6 shows the classification of publications into three thematic clusters. We can distinguish one cluster containing 3 publications (blue cluster), the second - containing 12 publications (red cluster), and the most numerous (green) - containing 214 publications.



(a) (b)

Figure 6. Hierarchical clustering. Note: (a) all publications, (b) zoom of clusters
Source: own elaboration based on 229 references [A1].

The presented method of clustering (grouping), called taxonometrics or hierarchical classification, suggests that green thematic clusters should be analyzed further, while blue and red clusters should be rejected.

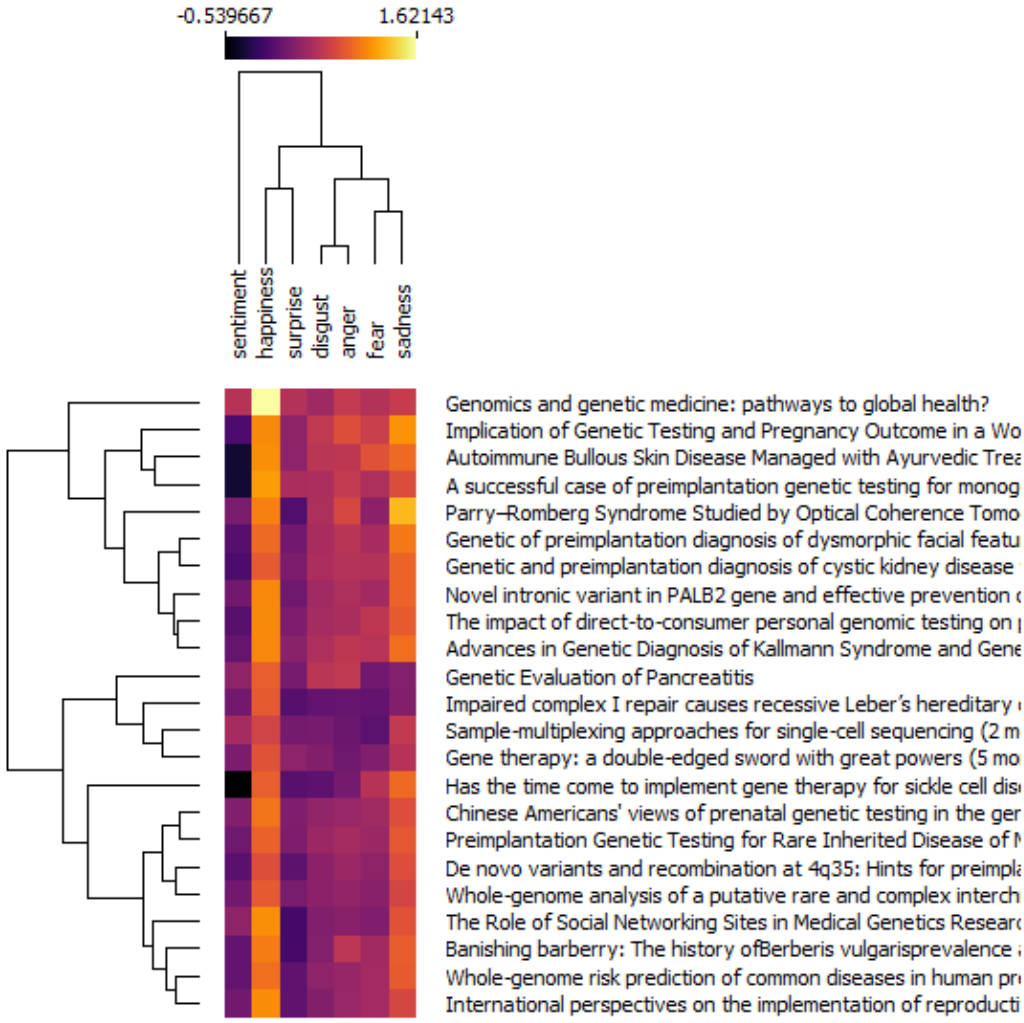


Figure 7. Sentiment analysis
Source: own elaboration based on 229 references [A1].

The last step was to conduct a sentimental analysis (Figure 7). Sentiment map using the method (SentiArt), sample type: bootstrap. Figure 7 presents 23 publications (representing 10% of all; merge by k-means). Black color represents negative values and light yellow - positive values. The presented heat map visualizes the sentiment in a collection of publications, which calculates sentiment scores for each of them. The analysis results include 7 columns. The first column 'sentiment' aggregates the remaining types of sentiment and is the resultant of all sentiments in the publication. Column 2 shows happiness, third - surprise, fourth - disgust, fifth - anger, sixth - fear, and seventh - sadness. Clustering was used to group moods. Fear and sadness formed one group of moods, anger and disgust another. The first and second groups of moods formed the third group of moods: sadness, fear, anger, and disgust together. The fourth group of moods consisted of happiness and surprise. It contrasted with the third group of moods. Generally, it can be noticed that the publications had a negative expression of moods (dark colors), although it is also possible to identify those in which negative and positive moods were balanced (sustained). In general, happiness was associated through the prism of a positive mood, surprise, disgust, and fear mainly as negative strong moods, and sadness dichotomously positive and negative (although theoretically, it could be a negative mood, in combination with hope or other moods - it could take the form of a positive attitude).

The frequency of terms related to the effectiveness of IVF with PGT in the analyzed publications was low, and these terms were excluded from the clustering analysis (Table 3). Among the identified records, some studies were directly relevant to the aim of this research. The results suggest that

preimplantation genetic testing (PGT) may be an effective tool to help couples with hereditary disorders achieve healthy offspring. However, available data often focus on successful cases, and the overall effectiveness of IVF with PGT varies widely. Couples should understand that the number of eggs retrieved, embryos obtained, and unaffected embryos selected after PGT can vary greatly, and the procedure is not always successful.

Effectiveness rates reported in the literature depend on the condition and patient population, with live birth rates ranging broadly from approximately 10% to 80%. Additionally, economic evaluations indicate that IVF with PGT may be more cost-effective than natural conception with prenatal diagnosis for certain genetic diseases.

These findings highlight the complexity of treatment outcomes and emphasize the importance of individualized counseling and decision support for couples considering IVF with PGT.

Table 3. Terms related to the effectiveness of the IVF+PGT procedure are mentioned in the analyzed publications

Term	Number of articles	Relevant to our study	Case study	Other than case study
efficiency/effectiveness/effective/efficient	53	9	2	7
success/successfully	40	12	7	5
goal/aim/objective achievement	0	0	0	0
total	93	21	9	12

Source: own elaboration based on 229 references [A1].

Our review revealed a research gap in the assessment of the effectiveness of IVF with PGT, which has serious implications for making an informed decision by couples at risk of developing a rare monogenic disease in their offspring. Considering the seven defined research gaps presented by Miles (Miles, 2017), we suggest possibilities to develop a research agenda in the following areas:

- Knowledge gap – available reports focus on the reliability and effectiveness of IVF with PGT measured by the successful detection of selected disorders in embryos, the birth of healthy babies, and optimized time and financial cost of testing procedures. However, for many couples, it would also be important to answer other questions regarding the survival of embryos obtained through IVF, the number of stimulation cycles necessary to achieve the goal, and financial and non-financial costs, including side effects. This knowledge is important for couples who request IVF not because of fertility problems but because the procedure offers a chance to stop the occurrence of the disease in their family. To achieve their goal, they need a larger number of embryos than in the standard IVF without PGT. It should be noted, however, that in autosomal recessive disorders, embryos with a carrier status can be transferred because they are usually phenotypically normal.
- Methodological and theoretical gap – currently, the effectiveness of the presented solutions is measured with a successful live birth of a healthy baby and there is no analytical model that would estimate the relation between all benefits and all costs (financial and non-financial). The complexity and multi-stage character of the PGT-IVF procedure, particularly the uncontrollable randomness involved in the combination of parental alleles, contributes to considerable psychological burden experienced by patients. Couples appear to downplay this factor at the outset of their journey with the procedure, being highly focused on achieving success. As a result, any failures become especially psychologically distressing. The results of the sentiment analysis appear to confirm this.
- Population gap – available publications concern case studies describing single couples or cohorts of couples affected by a specific genetic disease. The results of such a scale only indicate the potential for success of the PGT-IVF procedure. They do not provide insight into the overall effectiveness of the procedure or the effectiveness at its individual stages – hormonal stimulation, embryo testing, embryo transfer, pregnancy, and birth. The absence of statistically reliable, population-level data

presents a significant challenge to the effective application of artificial intelligence–based management tools, such as: integrated clinical and genetic data management across all stages of the procedure; the use of AI and machine learning for outcome prediction; decision support systems for both physicians and patients; standardization and knowledge sharing; data security, privacy, and ethical compliance; and the automation of laboratory processes and procedural workflows.

Detailed problems associated with the definition of effectiveness in the context specific to IVF with PGT and components considered in the assessment of this procedure are presented in the Discussion.

5. DISCUSSION

5.1. The Future of PGT-IVF in the Context of Intelligent Management

Intelligent management in reproductive medicine is grounded in key theories such as the Knowledge-Based View (Grant, 1996; Nonaka & Takeuchi, 1995), Clinical Decision Support Systems (Belciug & Gorunescu, 2020; Khalfallah et al., 2023), Decision Theory under Uncertainty and Multi-Criteria Decision Analysis (Keeney & Raiffa, 1993; Dyer & Forman, 1992), and Systems Thinking (Ackoff, 1999; Senge, 1990). These frameworks support the use of AI tools tailored to patient contexts and ethical considerations.

Families with a child affected by genetic disease face complex decisions, including relationship strain and family planning choices. IVF with preimplantation genetic testing for monogenic disorders (PGT-M) offers a potential solution, though it raises ethical and systemic challenges (Kruse et al., 2022). Genetic counseling and education remain critical to address fears and improve awareness.

Integrating databases and intelligent management tools can reveal patterns to improve success rates, reduce failures, and lower financial and psychological burdens. Proposed directions include machine learning to predict IVF success based on clinical data, AI-powered decision support for clinicians and patients, automation in laboratory processes, and psychological well-being assessment throughout IVF cycles.

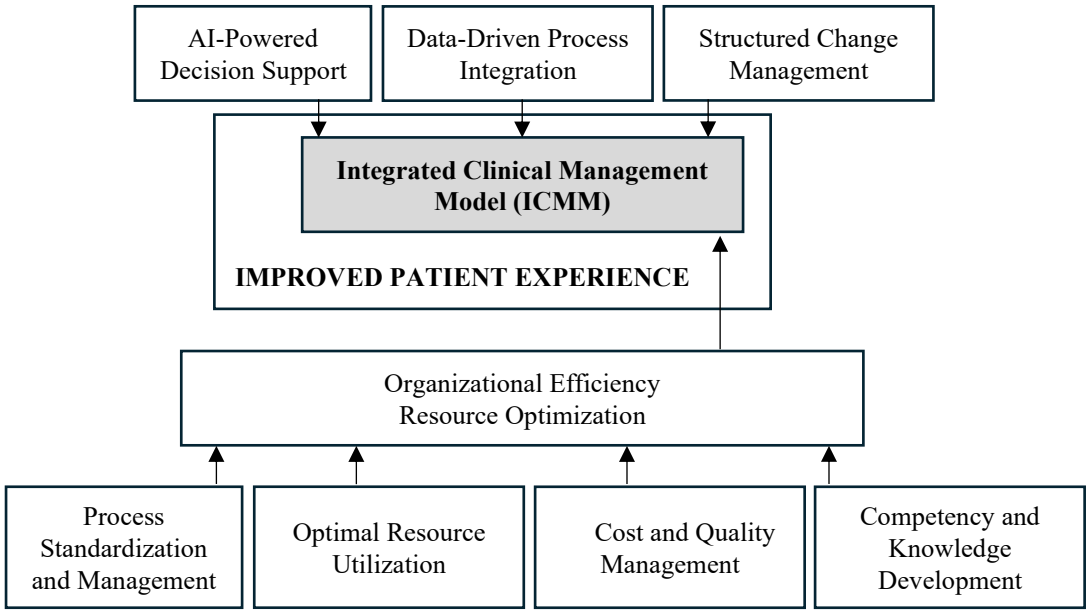


Figure 8. Integrated Clinical Management Model (ICMM) for IVF with PGT
Source: own elaboration based on Khalfallah et al. (2023), Belciug & Gorunescu (2020), and Greenhalgh et al. (2017).

We propose the ICMM, combining AI-powered decision support, data-driven integration, and structured change management (Figure 8). The model improves clinical precision and patient experience by enabling transparent, personalized pathways and fostering trust and emotional resilience. This

improved patient experience is a core outcome of integrating AI-powered decision support, data-driven processes, and organizational efficiency, ensuring patients feel more supported and engaged throughout their reproductive journey.

ICMM integrates clinical, genetic, economic, and emotional data to simulate treatment scenarios, supporting informed decisions (Belciug & Gorunescu, 2020; Khalfallah et al., 2023). It is flexible, scalable, integrates with EHR and LIS, and continuously learns from data, improving decision efficiency, reducing unnecessary interventions, and optimizing resources.

Beyond patient support, the ICMM enhances organizational efficiency by automating decision processes, standardizing care pathways, reducing clinical workload, and improving resource planning. By optimizing resource allocation and standardizing care, ICMM not only enhances organizational performance but also contributes to a more positive and supportive patient journey. Predictive components within the system support staffing allocation and laboratory scheduling, which is crucial for the time- and resource-sensitive IVF clinics (Topol, 2019; Davenport & Kalakota, 2019; Jiang et al., 2017). This dual focus on individual patient care and organizational effectiveness makes the model well-suited for reproductive healthcare settings where precision and efficient resource management are critical.

5.2 Efficacy and Efficiency in IVF with PGT

Effectiveness in IVF with PGT refers to achieving the birth of a healthy child, while efficiency concerns optimizing resources such as hormonal stimulations and embryos used to maximize success (Drucker, 2024; Gasparski, 2022; Nowosielski, 2008; Polski Komitet Normalizacyjny, 2001). These concepts overlap but differ: effectiveness means ‘doing the right things’, whereas efficiency means ‘doing things right’ (Drucker, 2024).

Depending on patient goals – avoiding genetic defects or successfully having a healthy child – success criteria vary. AI-powered decision-support tools help clinicians and patients set realistic, personalized goals by integrating medical, genetic, emotional, and financial data, thereby improving transparency and informed decision-making (Khalfallah et al., 2023).

For example, AI platforms like AIVF’s EMA analyze embryo viability and genetics in real time to guide embryo selection, illustrating AI’s potential to enhance IVF success rates (Chavez-Badiola et al., 2019; AIVF, 2024).

5.3. Financial and Emotional Costs of IVF with PGT

IVF with PGT is often chosen not due to infertility but to ensure the birth of a genetically healthy child. This procedure entails significant financial burdens, especially where public funding is limited by age or other criteria (BGH, 2019). Emotional costs are also substantial, as failed stimulation cycles, embryo loss, or embryo freezing for donation cause considerable stress. Despite these challenges, couples persist in pursuing IVF with PGT to maximize their chances of a healthy child.

Support systems for couples vary across countries, influencing the financial and emotional experience during treatment. AI-driven digital health tools like the iYoni mobile application offer valuable support in early reproductive planning. Although iYoni is not directly integrated with PGT procedures, it provides functionalities such as menstrual cycle tracking, infertility treatment assistance, and reproductive health education (iYoni, 2024). By delivering personalized insights based on user data, the app empowers users to better understand their reproductive health, anticipate fertility windows, and make informed decisions. This helps reduce emotional uncertainty and stress throughout the complex reproductive journey, especially for couples at genetic risk who face heightened psychological challenges. iYoni exemplifies how AI-based digital solutions can extend support beyond clinical settings, promoting well-being throughout the continuum of reproductive care.

5.4. Dynamic Efficiency and Ethical Considerations

Effectiveness and efficiency in IVF with PGT must be considered alongside ethical and social dimensions. The ‘3Es’ model – effectiveness, efficiency, and ethics – provides a comprehensive framework for evaluating clinical performance (Dietl & Gasparski, 2000). Static efficiency involves minimizing waste and optimizing processes, while dynamic efficiency focuses on long-term benefits such as family well-being and risk reduction (Górecka et al., 2021; Kotarbiński & Kleszcz, 2019; McGrath, 1970).

This approach recognizes couples as clients within a reproductive medicine business model, emphasizing a holistic perspective that balances immediate clinical outcomes with psychological and social impacts. IVF with PGT strives to achieve both a healthy live birth and the efficient use of resources, considering emotional and ethical implications for families facing genetic risks (Gasparski, 2022; Nowosielski, 2008).

6. CONCLUSION

A key feature of the proposed Integrated Clinical Management Model (ICMM) is its capacity for continuous learning from clinical data and patient feedback. This enables increasingly personalized recommendations, fostering more effective and empathetic decision support for couples undergoing IVF with PGT. The next steps involve pilot collaborations with clinics and further research to validate the model in clinical practice (Greenhalgh et al., 2017; Hughes et al., 2021).

This study employed a range of AI-based techniques, including word cloud visualization, bag of words with L1 regularization, Latent Semantic Indexing (LSI), and keyword extraction using TF-IDF scoring. Sentiment analysis via the SentiArt method added contextual interpretation of the emotional dimensions associated with different research areas.

In the context of PGT for rare diseases, text mining and machine learning provide a systematic means of extracting, structuring, and interpreting large volumes of unstructured data. IVF with PGT offers at-risk couples an alternative to prenatal testing and potential pregnancy termination, supporting the goal of having a healthy child while minimizing physical, emotional, and financial burdens.

Our interdisciplinary literature review revealed thematic clusters related to IVF with PGT and highlighted a major gap: the lack of large-scale, population-level studies capturing both successes and failures. These limits understanding of real-world effectiveness and obscures the full scope of emotional and financial burdens carried by patients. Defining standardized success criteria remains a challenge, particularly given that couples at risk of rare diseases differ significantly from traditional infertility patients.

The sentiment analysis confirmed the high emotional toll experienced by these couples. For many, success is defined strictly as the birth of a healthy, unaffected child, often requiring more embryos and higher emotional and financial investments. Current systems of support are not well-equipped to address these unique needs, and cost-effectiveness models tailored to this population are largely absent.

Several limitations affect this study. The available evidence is based mainly on case reports and small-sample research. Publication bias and limited jurisdictional context (focused on Poland) further constrain generalizability. Machine learning was used solely for literature analysis, not clinical prediction. Real-time, patient-level clinical data were unavailable due to access restrictions. The literature review covered four databases, and keyword selection—though expert-informed—may have overlooked relevant studies. The focus on monogenic disorders points to the need for future research into polygenic and multifactorial conditions.

Future work should expand the assessment model to include economic and psychological variables, moving toward a multi-criteria framework. This expanded framework is embodied in the Integrated Clinical Management Model (ICMM), which integrates clinical, genetic, economic, and psychosocial data to provide comprehensive, personalized, and ethically sound decision support. The model's flexibility and scalability allow adaptation across different healthcare settings, supporting both patient-centered care and organizational efficiency. Broader collaborations with clinics and patient advocacy organizations are planned to gather more representative data across various populations. These efforts will support the use of AI not only for knowledge management but also for the development of predictive tools to enhance PGT-IVF effectiveness.

In addition to personalized decision support, the ICMM contributes to organizational performance. The expanded ICMM integrates multiple data dimensions and emphasizes continuous learning and adaptation, positioning it as an innovative solution for the complex needs of IVF with PGT. By streamlining workflows, supporting resource allocation, and enhancing scalability through digital infrastructure, it promotes both clinical precision and operational efficiency (Kellermann & Jones, 2013). As AI becomes more integrated into healthcare systems, its dual role in improving patient care

and organizational function becomes increasingly important (Topol, 2019; Davenport & Kalakota, 2019; Jiang et al., 2017).

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ARTIFICIAL INTELLIGENCE FOR PERSONALIZED RANKINGS OF ARTICLES – NOVEL EMBEDDING METHOD SUPPORTING DECISION-MAKING IN SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Purpose: *This work presents a new Artificial Intelligence (AI) method to support decision-making in selecting optimal articles from the user's perspective. The technique leads to selecting high-quality works that fit the researcher's needs by enabling hierarchizing scientific publications based on their similarity to a predefined researcher problem. This article is the first in a planned series on AI-powered systematic literature reviews.*

Need for the Study: *The rapid development of AI over the last few years has caused the number of publications to grow rapidly and their quality to decrease. Developing a filtering method to select adequate papers is imperative in an AI-dominated environment where classic methods are no longer effective.*

Methodology: *The embedding model transforms research queries and publication metadata into numerical vector representations. The cosine similarity metric ranks publications based on their semantic closeness to the research query. Next, bibliometric analyses validate the effectiveness of the selection process.*

Findings: *The proposed AI-powered selection method significantly improves the thematic consistency of selected publications compared to entire datasets downloaded from the Scopus database. Selected articles exhibit higher bibliometric similarity in shared references, keywords, and co-citations. The approach efficiently filters large datasets while maintaining relevance, providing researchers with a refined subset of highly pertinent publications.*

Practical Implications: *The proposed method can improve systematic literature reviews by automating the selection of relevant publications, reducing manual workload, and ensuring thematic accuracy. The findings suggest that AI-driven text embedding techniques can enhance the efficiency and reliability of literature filtering, benefiting researchers across various disciplines.*

Keywords: Systematic Literature Review, Text Embeddings, Decision Making, AI-Driven Publication Selection, Bibliometric Analysis, Cosine Similarity, Transformer-Based Models

Jel codes: M15; D70; M10

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1. INTRODUCTION

1.1. Novelty of the Proposed Embedding Method Compared to Other AI Techniques

The embedding models are essential artificial intelligence (AI) tools in natural language processing (NLP). These tools are based on artificial neural networks (ANN) designed to detect similarities between textual data. The technology of word embedding models (WEMs) is also used in popular generative chats like ChatGPT, DeepSeek, or perplexity. The most significant advantage of the proposed method over other AI techniques used in systematic literature reviews (SLR) is its orientation to the user's needs. The proposed method allows users to describe their research problems in natural language freely. Next, the WEM finds publications that best match this description. In contrast, other AI methods use a machine learning approach that allows only to classify publications into strict categories defined in the learning process (van Dijk, Brusse-Keizer, Bucsán, 2013; Ferreira, Quiles, Nazaré, Rezende, Demarzo 2021; Feng, Liang, Zhang, Chen, Wang, Huang, Sun, Liu, Zhu, Pan, 2022). Unfortunately, a machine-learning approach usually cannot meet the user's needs. This makes the embedding method much more flexible and valuable than adversaries, not only to scientists conducting literature research before scientific investigations but to anyone who needs a reliable answer based on scientific knowledge. This AI method can be especially relevant for managers and entrepreneurs who are not experts in AI and database searching but need reliable information, e.g., to obtain a market advantage.

Most SLR automation is currently applied using statistical methods such as Naive Bayes Classifier (van Dijk et al., 2013), neural networks (Ferreira et al., 2021), or other machine learning methods (Feng et al., 2022). These active solutions require class labeling (training set) and human action in the learning/validation. The proposed method allows the elimination of the human factor completely, replacing arbitrary judgment with objective semantic similarities and bibliometric indicators, leading to a more complete and less biased AI-powered SLR.

The most widely used method for acquiring knowledge is currently generative artificial intelligence. Models of this type, similar to the proposed method, are based on embedding models. However, unlike our technique, generative AI often provides a false bibliography, and its sources are sometimes unreliable. Methods of this type are devoid of scientific rigor, and specific bibliometric indicators are not used in the selection. Even though generative models are more universal and convenient, their credibility is much lower than that of a specialized SLR method based on similar techniques (Gwon, Kim, Chung, Jung, Chun, Lee, Shim, 2024; Kacena, Plotkin, Fehrenbacher, 2024). Therefore, due to its specialization, the presented method can also be considered a further evolution of AI in NLP.

1.2. Importance of literature reviews in research

A systematic literature review (SLR) is usually crucial in the early stages of research projects. The methodology provides an objective, replicable, and transparent process for aggregating and synthesizing available knowledge (Hiebl, 2021). In contrast to narrative reviews, SLR can minimize bias in study selection and offer evidence-based decision-making and clear procedures (Clark, Clark, Raffo, Williams, 2021). The methodology can also identify research gaps and be used to form a research agenda (Webster & Watson, 2002). The clear search strategies and inclusion/exclusion criteria enhance transparency and allow other researchers to repeat the process and the results (Hiebl, 2021). SLR makes it easier for researchers to prepare high-impact research (Durach, Kembro, Wieland, 2017). All these factors show how important it is to improve SLR procedures and develop more effective tools to use in the process.

Systematic literature reviews establish the current state of knowledge, which is crucial considering the growing number and diverse quality of existing studies. The method enables researchers to map the existing knowledge, identify knowledge gaps, and outline future directions for development, thus providing an indispensable foundation for further empirical investigations (Amjad, Kordel, Fernandes, 2023; Clark et al., 2021; Durach et al., 2017; Linnenluecke, Marrone, Singh, 2020).

The SLR approach consists of several steps. Firstly, clear research questions and search strategies (inclusion/exclusion criteria, data extraction, and synthesis methods) are defined (Lenart-Gansiniec, 2022). Next, a huge preliminary sample of studies is collected. Usually, multiple search iterations are required to account for varying definitions and terminologies. Researchers systematically apply inclusion and exclusion criteria to identify the most relevant. Then, significant information is gathered based on the selected articles (Tranfield, Denyer, Smart 2003), and collected knowledge is used to

update the theoretical framework (Durach et al., 2017). In the next step, to answer research questions, findings are integrated, and finally, the review is reported. Created reports should be structured and transparent, including methodology, findings, limitations, and conclusions (Clark et al., 2021). The report can also include a visualization of the importance of publications. The visualization is usually demonstrated as maps presenting intersections between field papers. The importance of the specific paper may also be presented in numerical form using bibliometric analysis (Linnenluecke et al., 2020).

The bibliometric analysis (BA) is an important tool that complements SLR with quantitative analysis. BA usually operates in data such as author affiliations, publication sources, keywords, references, and citations. This kind of analysis allows for uncovering patterns, trends, and key research clusters in a field (Linnenluecke et al., 2020). Standard citation (co-citations) and network analysis reveal how authors, theories, and subfields are connected. On the other hand, citation context analysis shows how core ideas evolve throughout the literature (Simsek, Fox, Heavey 2015). The BA is especially beneficial in fields like management sciences, where diverse interdisciplinary links can be observed (Amjad et al., 2023; Zupic, Čater, 2015).

1.3. Selection of the research topic

The principles of the operation and results obtained with the proposed method are presented in the examples related to management. Management is the primary field in which systematic literature reviews (SLRs) are conducted, and it is one where the developed technology may be most needed due to the demand for current and accurate scientific knowledge. Moreover, a significant rise in publications connected with SLR in management has been observed in the last few years. According to Scopus, the number of publications that addressed the words “management” AND “systematic literature review” in titles, abstracts, or keywords increased from 697 in 2018 to 3,010 in 2024 (Fig. 1a). Researchers are also interested in the subject of management. The number of publications with a “management” word in titles, abstracts, or keywords increased from 893,893 in 2018 to 1,564,492 in 2024 (Fig. 1b).

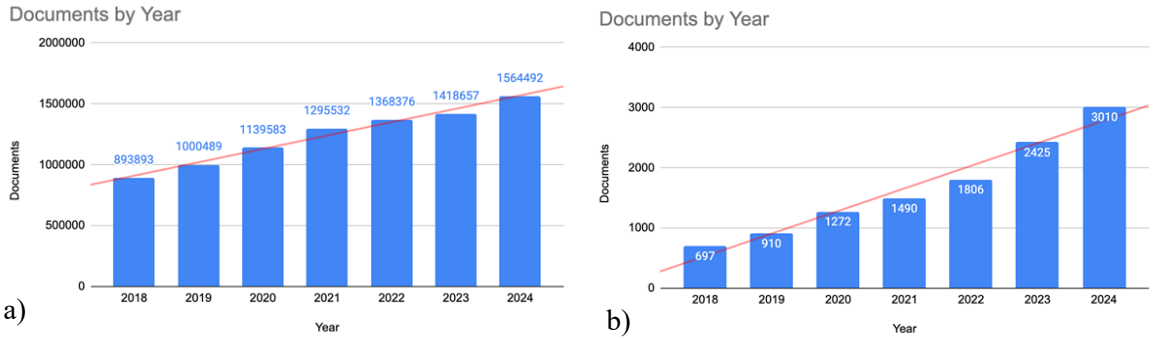


Figure 1. Growth of publications in years 2018 - 2024: a) publications related to management; b) publications related to management AND systematic literature review
Source: own elaboration based on data from the Scopus database.

The trends presented in Fig. 1 show that interest in SLR subjects is growing faster than in management (175% and 432% in the past six years, respectively). Table 1 and Table 2 compare the dynamic growth of these two disciplines.

Table 1. Comparison of the number of publications on management published between 2018 and 2024, included in the Scopus database

	2019/2018	**2020/2019**	**2021/2020**	**2022/2021**	**2023/2022**	**2024/2023**	**2024/2018**
Dynamics	112%	114%	114%	106%	104%	110%	175%

Source: own elaboration based on data from the Scopus database.

Table 2. A comparison of the number of publications on systematic literature reviews in management published between 2018 and 2024, included in the Scopus database

	2019/2018	2020/2019	2021/2020	2022/2021	2023/2022	2024/2023	2024/2018
Dynamics	131%	140%	117%	121%	134%	124%	432%

Source: own elaboration based on data from the Scopus database.

1.4. Embedding AI models in content analysis and hierarchization

Word embedding models (WEMs) convert textual data to numerical, multidimensional vectors that are easy to process (Egger, 2022). Such representation enables the capture of underlying meanings (Moreo, Esuli, Sebastiani, 2021). Words with similar meanings are placed closer to each other in the space, which allows the identification of semantic relationships even if different terminology is used (Asudani, Nagwani, and Singh 2023).

The first WEMs were based on histogram features (Pittaras, Giannakopoulos, Papadakis, Karkaletsis 2020). Later, shallow textual representation was replaced with deep learning (Mikolov, Chen, Corrado, Dean, 2013). First, neural networks WEMs modeled word co-occurrence via Continuous Bag-Of-Words (CBOW) or skip-gram (Pittaras et al., 2020). Current WEMs encode both semantics and syntactic information (Gao et al., 2019). They can also capture lexical regularities typical for specific languages (Moreo et al., 2021). These AI models can serve for text classification, sentiment analysis, topic modeling, text naming, and searching for important documents from large collections of documents. Some models can also incorporate external knowledge or solve the problem of sparsity in short texts. The problem is solved, e.g., by merging semantically similar short texts into pseudo-documents (Asudani et al., 2023; Wang et al., 2024; Egger, 2022; Moreo et al., 2021; Gao et al., 2019).

As shown in Fig. 2, WEMs' great versatility and usability made them increasingly popular over time. Scientific interest in text embedding has grown significantly in recent years (Fig. 2), which is related to the fast development of generative intelligence. According to Scopus, the number of papers, including the phrase 'text embeddings' in titles, abstracts, and keywords, increased from 30 in 2018 to 430 in 2024.

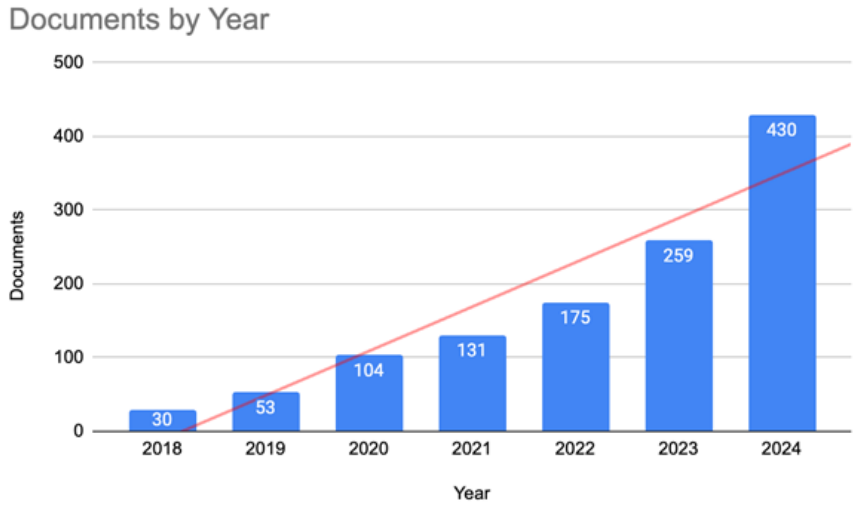


Figure 2. Publications on text embeddings published between 2018 and 2024
Source: own elaboration based on data from the Scopus database.

The trends presented in Fig. 2 show that scientific interest in topics related to text embedding grows quickly and monotonously but not systematically. From 2018 to 2024, scientific interest in this field increased by 1443%; more detailed data are presented in Table 3.

Table 3. Comparison of the number of publications on text embeddings published between 2018 and 2024, included in the Scopus database

	2019/2018	2020/2019	2021/2020	2022/2021	2023/2022	2024/2023	2024/2018
Dynamics	177%	196%	126%	134%	148%	166%	1 433%

Source: own elaboration based on data from the Scopus database.

The increasing interest in text embedding is not only due to its high usefulness in language processing text data. Open-source tools and libraries have made implementing word embedding models (WEMs) straightforward and very accessible. Therefore, WEMs are becoming fundamental to text document analysis. Consequently, the authors believe that the models can be utilized to automate the article selection process effectively. WEMs can be used not only to support readers' decision-making but also to revolutionize systematic literature reviews.

1.5. Classic methods of selecting publications

The correct method of paper selection is crucial for the reliability of systematic literature reviews (Hiebl, 2023; Harari, Parola, Hartwell, Riegelman, 2020; Li, Wang, 2019; Snyder, 2019; Meade, Richardson, 1997; Chigbu, Atiku, Plessis, 2023). In order to reduce errors, usually, at least two independent reviewers evaluate the title, abstract, or even full text (Meade, Richardson, 1997; Robson, Maden, Misso, Tugwell, Tricco, 2019). Excluded publications are often reported at each stage (Santos, Coelho, Marques, 2024). The remaining publications can be categorized as highly relevant, potentially relevant, or minimally relevant (Hiebl, 2023). Full-text reviews are conducted only on relevant articles, ensuring thorough assessment (Meade, Richardson, 1997; Snyder, 2019). The list of essential techniques for selecting scientific publications in a systematic literature review process is presented in Table 4.

Table 4. Overview of the many essential, classic techniques dedicated to selecting scientific publications in a systematic literature review process

Selection Method	Description	Source
Keyword search in databases	Keywords related to the research question are used to find potentially relevant publications in electronic databases.	(Hiebl, 2023; Harari et al., 2020; Li, Wang, 2019; Snyder, 2019)
Title screening	The first selection stage involves assessing the titles of identified publications for their potential relevance to the research question.	(Hiebl, 2023; Meade & Richardson, 1997; Chigbu et al., 2023)
Abstract screening	The second selection stage involves analyzing the abstracts of publications more precisely than in the previous step to assess their relevance and alignment with the inclusion criteria.	(Hiebl, 2023; Meade & Richardson, 1997; Chigbu et al., 2023)
Consideration of keywords	Analyzing the keywords provided by the authors of publications during the title and abstract screening stages to determine their alignment with the scope of the review.	(Hiebl, 2023)
Reading full texts	In the final selection stage, the full texts of publications that passed the previous stages are thoroughly analyzed to ensure they meet all established inclusion criteria.	(Hiebl, 2023; Meade & Richardson, 1997; Snyder, 2019)
Applying inclusion and exclusion	Systematically applying predefined inclusion and exclusion criteria at each selection stage ensures that only the most relevant publications addressing the research question are included in the review.	(Hiebl, 2023; Meade & Richardson, 1997; Snyder, 2019)

criteria		
Classification system	A categorization system for relevance is used to prioritize and narrow the number of publications during the title and abstract screening stage.	(Hiebl, 2023)
Considering the type of study	Selecting publications based on their research methodology, prioritizing study types that best address the research question.	(Meade & Richardson, 1997)
Considering the type and format of the publication	Making inclusion or exclusion decisions regarding different publication formats, such as abstracts, non-peer-reviewed publications, and unpublished studies (grey literature), to minimize the risk of publication bias.	(Meade & Richardson, 1997; Harari et al., 2020; Chigbu et al., 2023)
Searching for duplicates	Identifying and excluding duplicate publications to avoid overestimating the impact of individual studies.	(Mead & Richardson, 1997)
Considering the language	Making decisions about including publications in different languages (with possible translation) to avoid language bias. However, time and resource constraints may affect this decision.	(Meade & Richardson, 1997)
Selection based on citation count	Using citation counts as an inclusion or exclusion criterion to focus on the most influential studies in a given field or to narrow down the number of publications when dealing with a large volume of literature.	(Hiebl, 2023)

Source: own elaboration based on (Meade, Richardson, 1997; Harari et al., 2020; Chigbu et al., 2023; Hiebl, 2023; Snyder, 2019; Li, Wang, 2019).

The methods presented in Table 4 aim to provide a clear, reproducible pathway from the initial search to the final selection. This process enables the minimization of bias and the synthesis of existing evidence. However, the discussed methods also have limitations. Table 5 presents examples of the limitations.

Table 5. Elemental limitation of selection methods

Selection Method	Limitation
Keyword search in databases	Risk of miss studies that use alternative terminology; balancing sensitivity; ensuring comprehensive coverage without retrieving excessive irrelevant results.
Title screening	Risk of missing relevant studies; low precision; potential for bias. Screening based on titles causes the risk of excluding significant studies whose importance is only apparent after an abstract or full-text review.
Abstract screening	A method similar to title screening causes the risk of excluding significant studies whose importance is only apparent after a full-text review.
Consideration of keywords	Similar to title and abstract screening. An author who highlights issues other than those searched in the title and abstract will probably also highlight them in the keywords.
Reading full texts	Potential for bias; very time and resource-consuming.
Applying inclusion and exclusion criteria	Risk of bias; time-intensive process; ambiguity in criteria; potential for missing relevant studies. Strict inclusion/exclusion criteria can overly narrow the scope of the review, potentially missing broader trends or alternative perspectives.

Classification system	Risk of bias, challenges with evolving topics, risk of missing relevant studies, complexity of implementation. Classification systems often struggle to generalize across different contexts or disciplines.
Considering the type of study	Bias in study selection; limited scope; challenges with mixed-methods research; difficulty in defining criteria; risk of excluding relevant studies. Focusing on study type may ignore contextual factors critical for interpreting findings in specific disciplines.
Considering the type and format of the publication	risk of exclusion bias, limited scope, overemphasis on established formats, and often challenges with accessibility (e.g., if the format is an industrial report). Screening and evaluating diverse formats often require additional time and expertise to account for structure, terminology, and quality differences.
Searching for duplicates	Technical methods are mainly used to keep the process smooth and easy to handle.
Considering the language	Including works in other languages can lower clarity, make the process much longer (preparing solid translations), and introduce mistakes.
Selection based on citation count	Methods such as selecting by citation count can favor older or more mainstream studies, potentially overlooking emerging or niche findings.

Source: own elaboration.

Besides the limitations presented in Table 5, the methods presented are time-consuming and require much human work and attention. According to the authors, the process can be successfully automated, making SLR significantly faster, less biased, and more accurate.

1.6. A short review of fundamental bibliometric indicators

Several bibliometric methods can be used to measure the similarities between publications. These techniques can be divided into four groups: bibliographic coupling, common keywords, common references, and co-cited references. Table 6 describes the fundamental bibliometric methods. Some of them are used in this paper to validate results.

Table 6. Fundamental bibliometric methods for testing publication similarities

Verification of Filtering	Bibliometric Measure	Analysis
Do the publications cite the same articles?	Bibliographic Coupling	Analysis of relationships between analyzed publications based on shared references.
Do the publications have overlapping keywords?	Common Keywords	Analysis of keyword co-occurrence and relationships between them.
Do the publications cite each other?	Common References	Analysis of relationships based on mutual citations.
Are there connections between references?	Co-cited References	Analysis of relationships between commonly cited references.

Source: own elaboration based on Donthu, Kumar, Mukherjee, Pandey, and Lim (2021).

Different approaches focus on the co-occurrence of words within titles and abstracts (Table 7). These methods highlight the common terminology and shared themes among the analyzed publications. Examining these word patterns provides insights into the conceptual similarities across the entire dataset. The research uses a group of fundamental bibliometric methods to automate publication filtering.

Table 7. Methods based on co-occurring words in titles and abstracts for testing publication's similarities

Verification of Filtering	Analysis
Do the publications have common words in their titles?	Analysis of co-occurring words in publication titles and their relationships.
Do the publications have common words in their abstracts?	Analysis of co-occurring words in abstracts and their relationships.

Source: own elaboration.

Bibliometric analyses are often complemented visually using tools such as VOSviewer. These two methodologies can be integrated to verify the coherence and thematic connections within a selected set of scientific works (Fellnhofer, 2018). When bibliometry can present similarities between whole works, tools like VOSviewer enable the visualization of details of these relationships, facilitating the interpretation of numerical analysis results (Van Eck, Waltman, 2009).

The bibliographic coupling indicator enables the assessment of connections between publications based on shared references (Kleminski, Jankowski, Knapik, Szufa, 2022). This method is beneficial for identifying current research trends. Particularly in emerging scientific fields, it minimizes the lag characteristic of direct citation analysis (Kleminski et al., 2022).

The common keywords indicator is more valuable in analyzing relationships between keywords assigned to publications (Chen, Xiao,2016). This approach is based on the assumption that frequently co-occurring terms indicate related research concepts (Chen, Xiao, 2016).

Analyzing mutual citations between publications provides direct evidence of an active scientific dialogue. These connections between authors and their works within a given set can be informative. A high number of mutual citations suggests a very closely related group of publications.

The common references index reveals relationships between the most frequently cited works within the analyzed publications. This index identifies key intellectual foundations and influential works that shape a given field. Based on this parameter, it is also possible to detect thematic groups (Small, 1973).

Each of the bibliometric indicators has advantages, disadvantages, and limitations. The combined application verifies relationships and thematic coherence within a selected publication set (Zupic, Čater, 2015).

1.7. Motivation

The daily amount of information uploaded to the internet has already reached 400 million terabytes. The annual growth of new data is predicted to increase from about 147 zettabytes (10^{21}B) in 2024 to 181 zettabytes in 2025. Moreover, it is believed that 90% of the world's data has been generated in the last two years (Duarte, 2025). A massive part of this information is generated by artificial intelligence (AI). Market analyses indicate that the AI-powered website builder sector was valued at $3.17 billion in 2023. However, according to business reports, the market could reach $31.5 billion by 2033. That means an annual growth rate of 25.8% (AI-Powered Website Builder Market Size, 2024). AI-powered website builders cannot only create a website but also fill it with automatic content. Moreover, AI generators dedicated to generating scientific content are becoming increasingly popular. AI has already revolutionized the process of preparing scientific work. Currently, tools of this kind are used at every step of preparing a manuscript, making it faster and easier (Májovský, Boháč, Uhrinčať, Kurča 2023). Software like Perplexity or SciSpace can help find literature. Notebooklm can find interesting, needed information in the papers. Grammarly, ChatGPT, DeepSeek, and Paperpal can help as writing quality checkers. Other tools serve as plagiarism detection platforms (Turnitin, Copyscape). Tableau is a data analysis solution. All of these tools are just the tip of the iceberg. However, recent research shows that AI is not ready to prepare a paper alone. The main problems are a massive amount of incorrect information, fake references, and, in general, shallow content. However, authors in the same work confirm that AI, under strict control and fact-checking, can significantly speed up the process of preparing valuable papers (Kacena, Plotkin, Fehrenbacher, 2024). Alongside useful tools, commercial solutions that promise to do all the scientific work instead of the researcher are also developing. It should be noted that these solutions cannot provide either the required reliability or depth. Researchers must be aware of not only current potential and limitations but also ethical challenges in using AI-powered tools.

Artificial intelligence enhances rather than undermines scientific rigor (Khlaif, Farid, Alkaissi, Farouk, 2023)

Nina Schick (an AI thought leader) predicted that up to 90% of online content could be AI-generated by 2025 (Garfinkle, 2024). Even if her estimations were overcalculated. The trend is clear. The percentage of AI-generated content on the internet will grow systematically in the following years. This tendency can have unexpected and dangerous consequences. The AI usually averages results. Increasing the amount of AI-generated content will deepen the marginalization of unpopular views, opinions, or even research results, replacing facts with consensus. That can generate risks to freedom of speech; AI-generated information noise will drown out lonely voices. Another considerable problem can occur if AI is trained mainly on AI-generated data (which seems inevitable in time). Such practice can lead to "model collapse". In such a case, the system forgets rarer elements of its original training data and eventually generates incoherent or nonsensical information (Wenger, 2024; Shumailov, Mireshghallah, Anderson, Anil, 2024). Moreover, many websites and documents consist of machine-translated (MT) materials. After multiple translation steps, the quality of MT data can be very low. Large language models trained on inaccurate translations and AI-generated data can become biased, less fluent, and less accurate, producing many more errors (Thompson, Dhaliwal, Frisch, Domhan, Federico, 2024; Wenger, 2024).

Since the dawn of time, humanity has been struggling with the problem of difficult access to information. Artificial intelligence was supposed to help solve the problem. However, even if AI significantly facilitates and accelerates access to data, it also powerfully amplifies information noise, often covering valuable information. This way, AI creates an entirely new problem. Trend analysis suggests that in the future, not getting the answers to questions will be a problem, but instead verifying the adequacy of the answer. Therefore, together with the development of generative AI, it is necessary to develop powerful AI techniques for data filtration, which is strictly connected with developing systematic literature reviews and bibliometrics.

2. METHODOLOGY

2.1. Utilized AI Embedding Model

Word embedding models (WEMs) technology is based on deep artificial neural networks, a modern artificial intelligence tool. The all-distilroberta-v1 model transforms textual data into 768-dimensional vectors based on the DistilRoBERTa architecture. The WEM has been trained (fine-tuning) on over 1 billion sentence pairs from 21 datasets from diverse sources, including Reddit comments, academic papers, and question-answer pairs, making it highly adaptable for various semantic tasks (promptlayer.com).

During the fine-tuning process, a contrastive approach was utilized. This allows the model to learn how to distinguish valid sentences from randomly selected pairs (hugging face.co; promptlayer.com; dataloop.ai).

The model is particularly effective in applications that require comprehension of meaning and relationships between sentences or short paragraphs. The all-distilroberta-v1 was designed for tasks like semantic search and information retrieval, text clustering/organization, sentence similarity comparison, and semantic analysis across documents (huggingface.co; promptlayer.com).

2.2. Algorithm of the developed method

The first fundamental step in the proposed WEM-based method is to formulate the research problem clearly but in natural language (usually around 50-100 words). This problem description is used as a reference point in the following stages of the investigation. The selected articles are compared to the description. This AI technique makes the proposed approach much more precise than searching a database with keywords. Moreover, using natural language makes it available to everyone (no technical skills like formulating queries with logical operators are necessary) looking for scientific answers to their questions. The method may benefit decision-makers like managers and entrepreneurs but those who need more profound systematic knowledge in specific fields, like doctors, engineers, or scientists. Example descriptions are provided in Section 3, which is about data.

A preliminary, huge publication data set is collected in the next step. The publications are found, e.g., in the Scopus database using specially designed queries that consist of several (usually two) key topics or keywords combined with the AND logical operator. Additionally, if a keyword has synonyms or abbreviations, they are added to the query using the OR operator. Searches are usually conducted based on the title, abstract, or keywords. However, Scopus offers many other criteria (all of them were used in this research). The metadata of all records is downloaded to the spreadsheet in the next step. Example queries are provided in Section 3 about data.

In the following stage, all metadata downloaded for a specific record are combined, creating a description of the record (the most important are the title and abstract). The descriptions are collected in one database. Then, the WEM converts the research problem and specific article descriptions into vector representations. The obtained embeddings allow for measuring textual data semantic similarity using the cosine similarity index. Documents with the highest results are considered the most relevant. The ranking list is generated based on the index. The method can support decision-making, exposing papers similar to the reader's description. The similarity measure between the article description and the research problem is given by equation (1). The index can take values in the range [-1,1]. However, in practice, vector values typically range from [0,1] for most text-processing applications.

$$\text{similarity}(u, v) = \frac{u \cdot v}{\|u\| \, \|v\|} \tag{1}$$

Another widely used metric to describe text diversity is the cosine distance index. The index can take values in the range [0,2], where a distance of 0 indicates identical vector directions (identical text), while a distance of 2 represents the maximum difference (opposite vectors). This relationship is given by equation (2). In this paper, cosine distance is utilized.

$$\text{distance}(u, v) = 1 - \text{similarity}(u, v) \tag{2}$$

A set of bibliometric methods and indicators is used to evaluate the effectiveness of the proposed approach. These indicators examine the degree of relationships between publications. The average number of common keywords and the average number of common references are used as basic measures. The parameters are determined in pairs (comparison of two publications), exploring all possible combinations within the given set of articles. Next, the analyzed set of publications is described using the averaged values of the obtained results and the Jaccard index. In the final step, the values obtained for the whole dataset are compared with values obtained for the selected subset (17 positions with the lowest cosine distance values - highest similarity to the problem description). Indicators describing the number of mutual citations within the analyzed publications are also applied.

The study was conducted using specially prepared, dedicated software written in Python and run in the Google Colab environment. This software enables the automation of the entire process and the calculation of the metrics (a detailed description of metrics is provided in the following section).

The complementing to the calculations part of this research involved visualizing the relationships between articles in the analyzed dataset. For this purpose, the VOSviewer software and bibliometrics package in the R environment are used. The tools allow the analysis of co-occurring (common) words in publication titles and abstracts and the exploration of their interconnections. Both parts of the research complement each other. This way, mathematical precision and unambiguity are connected with intuitive and informative visualization, making the method very small for the user.

The proposed AI-powered method allows for the exact matching of publications to the individual needs of the researcher. Using both parts (calculations and visualization), the researcher can quickly identify the most relevant articles and their relationships. Additionally, ordering the positions from the most relevant ones facilitates the decision-making process and planning of their reading.

2.3. Indicators

Evaluating the suitability of selected papers to user needs cannot be performed in the same way as traditional machine learning (Szymanik, 2022). Therefore, traditional SLR bibliometrics have been used for this purpose. Two leading bibliometric indicators, common keywords and common references, verify the method's effectiveness. The common keywords index is a primary indicator of similarity in the

research subject. A common bibliography, on the other hand, allows the identification of the most important works and thematic groups (Kleminski et al., 2022; Small, 1973).

The intersection (common part of two sets) of references in each possible pair of publications (i,j) is given as |Ri ∩ Ri|, where R represents the set of references in the specific record (publication) and n is the number of records in the set of publications. The average number of common references (AR) is given by formula (3).

$$AR = \frac{\sum_{i<j}|R_i \cap R_j|}{\binom{n}{2}} \tag{3}$$

The Jaccard index measures the similarity between two sets. It is calculated as the size of their intersection divided by the size of their union. Equation (4) gives an average Jaccard Index, which is calculated for each pair (i, j), similarly to (3), and then averaged.

$$AJR = \frac{\sum_{i<j}\frac{|R_i \cap R_j|}{|R_i \cup R_j|}}{\binom{n}{2}} \tag{4}$$

The next metric is the average number of common keywords (AK), which is calculated analogously to (3) and given by (5), where *K* is a set of keywords in the specific publication.

$$AK = \frac{\sum_{i<j}|K_i \cap K_j|}{\binom{n}{2}} \tag{5}$$

The Jaccard Index can also be calculated for keywords. The averaged Jaccard Index is given by formula (6).

$$AJK = \frac{\sum_{i<j}\frac{|K_i \cap K_j|}{|K_i \cup K_j|}}{\binom{n}{2}} \tag{6}$$

The selected metrics enable the identification and description of similarity or diversity areas. Using the averaged value of common elements and the averaged Jaccard index, it is possible to demonstrate the scientific trends under study and eventually prove the method's effectiveness.

Additionally, to complement fundamental bibliographic indicators and to make the evaluation of the model more reliable, six other parameters were used:

1. Number of pairs that have at least one common reference – the total count of article pairs sharing at least one reference in their bibliographies.
2. The number of unique references in common in at least one pair – the total number of distinct references that appear in the intersection of references for at least one pair of articles.
3. Sum of intersection sizes (common references) for all pairs – total number of 'duplicate' references between all pairs of articles.
4. Number of pairs with common keywords – the total number of article pairs that share at least one keyword.
5. Number of keywords that occur together a minimum of 2 times – the count of distinct keywords appearing in at least two different articles.
6. Number of articles cited in references (cross-references) – the count of articles from the dataset cited by at least one other article within the same dataset.

As mentioned earlier, VOSviewer is utilized to visualize the indicators in this study. The obtained maps visualize networks of relationships (bibliographic coupling, common citations, or common keywords). This allows for identifying key thematic clusters and similarities between publications. The visualization is supplemented by the Bibliometrix (R) package. The library enabled the calculation of additional statistical indicators and the examination of word co-occurrences in titles and abstracts. Such procedures not only reveal genuine research trends within the dataset but also point to potential gaps and opportunities for further exploration. All these measures and methods are used to determine the thematic convergence of the articles.

3. DATA

The method was tested on four cases. Each case is discussed in detail to help the reader better understand the methodology.

3.1. Case 1: Impact of CSR on consumer behavior

The research problem:	Does corporate social responsibility (CSR) influence consumer behavior? With growing social and environmental awareness, companies increasingly invest in corporate social responsibility (CSR) activities. However, the question arises whether these CSR initiatives translate into consumer behavior, influencing their purchasing decisions or brand loyalty.
Scopus query:	(‘CSR influence’ OR ‘Corporate Social Responsibility influence’) AND ‘consumer behavior’)
Number of found records:	597

3.2. Case 2: The impact of AI on customer experience

The research problem:	How does artificial intelligence impact the customer experience, and to what extent does its use in companies' marketing efforts improve customer satisfaction and loyalty? While the integration of artificial intelligence in marketing is expected to improve the customer experience, positively impacting the experience, questions remain about potential drawbacks, such as limited human interaction and concerns about data privacy
Scopus query:	(‘Impact of Artificial Intelligence’ OR ‘Impact of AI’ OR ‘Impact Artificial Intelligence’ OR ‘Impact AI’) AND ‘Customer Experience’)
Number of found records:	1 564

3.3. Case 3: gamification in marketing

The research problem:	How is gamification used in marketing activities? Does gamification affect consumer loyalty and engagement? What specific gamification mechanisms are most commonly used in marketing campaigns? The use of gamification mechanisms in marketing activities and their impact on consumer loyalty and engagement.
Scopus query:	(‘gamification’ AND ‘marketing’)
Number of found records:	14 302

3.4 Case 4: BlockChain's impact on customer loyalty

The research problem:	Does BlockChain affect customer loyalty? What dimensions of Blockchain technology support the building of customer loyalty? How does Blockchain affect trust and transparency in various loyalty tools, including loyalty programs? In the context of building customer loyalty, Blockchain can be used in a number of ways - not only for loyalty

	programs but also to make business processes more transparent, protect data, and ensure transaction security.
Scopus query:	(‘blockchain’ AND ‘customer loyalty’)
Number of found records:	1 995

4. RESULTS

4.1. Arithmetic Mean of Bibliometric Indicators

The averaged indicators of the number of keywords and references in a pair of articles are utilized to compare two tested sets of publications. According to the bibliometric theory, if publications in the collection are more thematically related, they have more common references and keywords. The results obtained for two tested sets are presented in Fig. 3. The first set contains all publications returned from Scopus as an answer to the query. The second is based on a ranking list prepared using the embedding model (17 with the lowest cosine distance (2) – most similar to the problem description). In Fig. 3, results obtained for four different cases are presented.

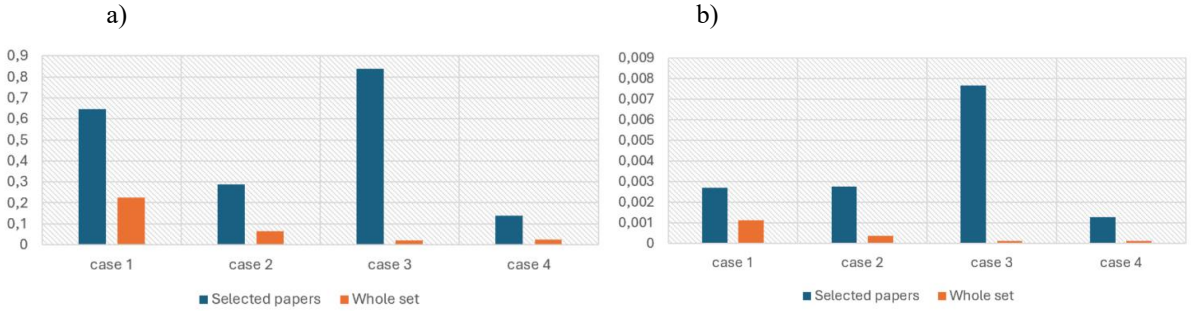


Figure 3. Averaged number of common; a) references AR, b) keywords AK
Source: own elaboration.

For each tested case (Fig. 3), the set with selected publications obtained many times better results. The publications in this collection are more related to the research problem but are also thematically similar. This observation proves the high effectiveness of the utilized method. Moreover, there is a clear difference between both indicators (keywords and references), which confirms the purposefulness of using several indicators simultaneously.

4.3. Jaccard Index of Bibliometric Indicators

The other typical indicator is the Jaccard Index. The index measures the similarity between two publications, calculating the intersection of two records divided by the size of their union. Fig. 4 presents the results of the averaged Jaccard Index obtained for four cases and two metrics (keywords and references).

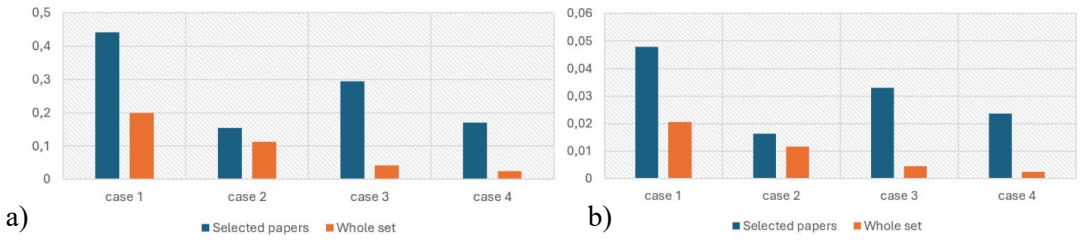


Figure 4. Averaged Jaccard Index of: a) references AJR, b) keywords AJK.
Source: own elaboration.

The results presented in Fig. 4 are less clear than those in Fig. 3. The differences between the metrics are also less straightforward. Nevertheless, this index proves the method's effectiveness in each case. In all cases, results obtained for filtered publications are significantly better than for the whole set. The publications with a lower cosine distance method exhibit greater terminological consistency. High Jaccard index values for keyword co-occurrence suggest that the selection method effectively extracts articles focusing on similar aspects of the research problem, confirming its usefulness in systematic literature reviews.

4.4. Additional Bibliometric Indicators - References

Table 8 presents fundamental bibliometric indicators related to joint publication references.

Table 8. Bibliometric indicators related to joint publication references (model: all-distilroberta-v1)

	Number of pairs that have at least one common reference	**The number of unique references in common in at least one pair**	**Sum of intersection sizes (common references) for all pairs**
Case 1	37	59	88
Case 2	25	19	39
Case 3	43	64	114
Case 4	14	19	19

Source: own elaboration.

Table 8 shows the number of publication pairs with at least one common reference, the number of unique sources cited jointly in at least one pair, and the sum of intersection sizes. These data illustrate the extent to which the publications are interlinked through their references. Low values (e.g., in Case 1) may suggest weaker bibliographic links in this particular set of publications.

4.5 Additional Bibliometric Indicators

Following the methodology described, several indicators relating to keywords and cross-citation were collated from the publications studied.

Table 9. Bibliometric indicators related to keywords/cited publications (model: all-distilroberta-v1)

	Number of pairs with common keywords	**Number of keywords that occur together a minimum of 2 times**	**Number of articles cited in references (cross-references)**
Case 1	49	9	6
Case 2	15	2	19
Case 3	37	5	4
Case 4	20	4	5

Source: own elaboration.

The information presented in Table 9 is used to assess the thematic overlap (based on keywords) and citation intensity. Lower numbers can suggest a minor degree of keyword overlap (e.g., Case 2 compared to Case 1). A high number of pairs with common keywords, combined with a modest number of cited articles in Case 3, may suggest more substantial thematic similarity but a more petite body of shared cited literature. Table 9 also indicates Case 4's moderate thematic similarity and a moderate level of mutual citation in the publications.

The data presented in Table 8 and Table 9 shows that in each case, the number of publication pairs with common references, the total number of unique citations, and the sum of shared references differ across the sets. This indicates some variation in the level of bibliographic connections. Certain groups of publications exhibit more extensive citation networks, whereas others reveal a smaller scope of shared sources. Meanwhile, Table 9, which addresses shared keywords and cited articles, shows differences in the degree of thematic overlap and the intensity of citations.

In each of the examined cases, clear bibliometric connections (common references, keywords, or publications) can be observed, confirming that the selected groups of articles are thematically coherent. All sets demonstrate a certain degree of consistency and interlinkages, which attests to the effectiveness of the publication selection method proposed in this article.

4.6. Bibliographic Coupling Maps

Fig. 5 shows a sample bibliographic coupling map. Due to the large amount of data, this and all other maps are presented and discussed in the example of Case 2.

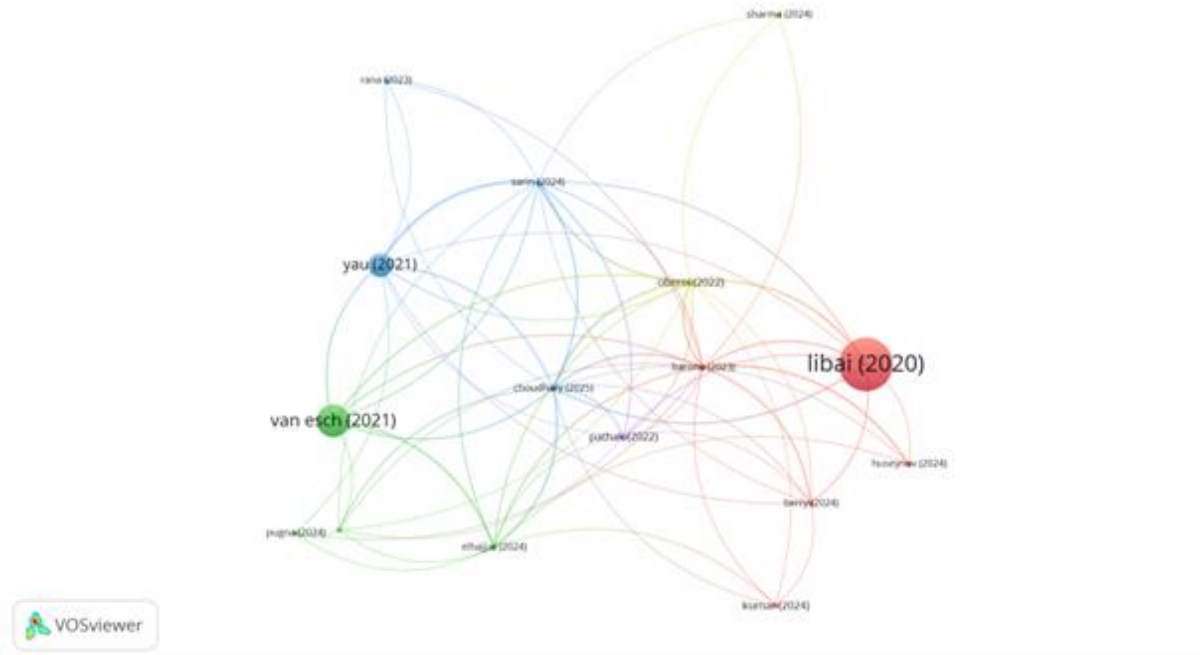


Figure 5. Bibliographic coupling map for 17 Case 2 articles
Source: own work in Vosviewer software.

In the map presented in Fig. 5, several clearly defined groups (clusters) of publications can be observed. Each cluster links articles that share a similar approach to the investigated issue (since they cite similar sources). For example, the red cluster marked with ‘Libai (2020)’ at its center suggests that this publication and its related articles frequently cite similar works, forming a shared literature block. The green cluster around ‘van Esch (2021)’ indicates a different research trend whose authors refer to their specific bibliographic corpus. The lines connecting individual nodes represent the intensity of the relationships; the thicker and more pronounced the line, the more bibliographic items these articles have in common.

4.7. Co-Citation Analysis Maps

Example co-citation maps are presented in Fig. 6.

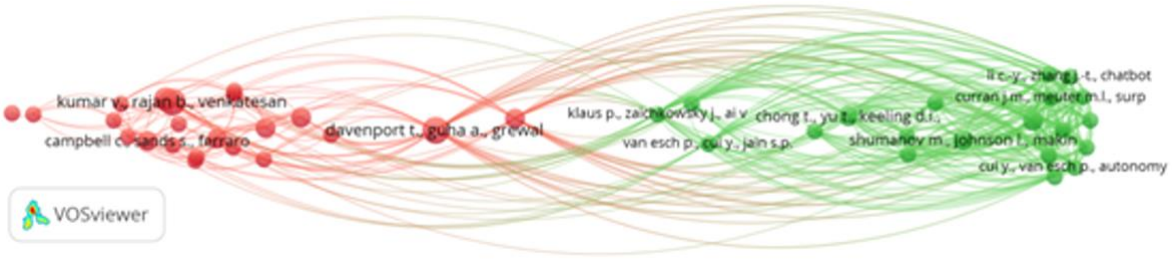


Figure 6. Link analysis of co-citation references for 17 Case 2 articles
Source: own work in Vosviewer software.

On the map of Fig. 6, each node represents cited publications or authors, and the lines thickened accordingly illustrate how frequently these sources are co-cited. The map shows strong bibliographic links between articles.

The left red cluster includes works by authors such as 'Kumar, V.', 'Rajan, B.', 'Venkatesan', and 'Campbell, C.', suggesting that in the publications analyzed for Case 2, sources by these authors (or specific articles) are frequently cited together. The central area, in shades of orange and green, includes references to 'Davenport, T.', 'Grewal, R.', 'Klaus, P.', and 'Sharma, G.', among others. Meanwhile, the right green cluster features sources such as 'Cui, Y.' and 'Van Esch, P.'. Their co-occurrence may indicate that these works serve as a foundation for analyses focusing on the investigated issues.

This type of visualization is used to identify literature sources that are most frequently cited together, thereby highlighting the key publications on a given topic. The largest nodes correspond to the most influential and heavily co-cited works, forming the basis of many of the articles analyzed.

4.8. Keyword Co-Occurrence Maps

In the map of keyword co-occurrence, publications clustered around similar research topics are presented. The thickness and density of the connecting lines reflect the intensity of the relationships between articles. The colored clusters point to various research trends in AI and marketing, highlighting thematic connections. In the example in Fig. 7, all the sets are strongly connected, indicating the effectiveness of the publication selection method proposed in this article.

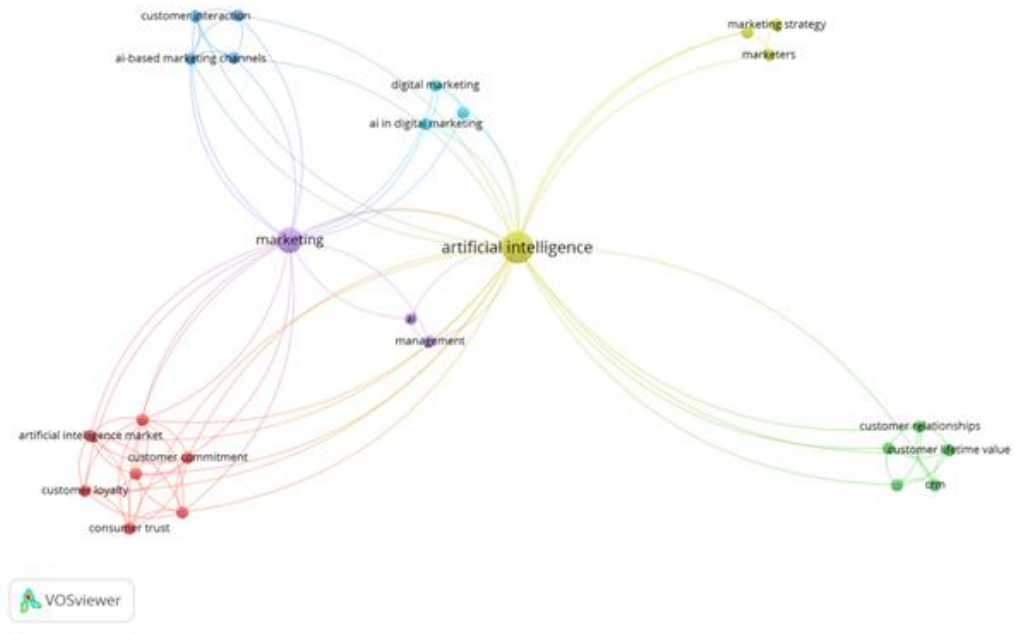


Figure 7. Analysis of co-occurrence of keywords for 17 articles Case 2
Source: own work in Vosviewer software.

In the keyword co-occurrence map presented in Fig. 7, ‘artificial intelligence’ holds the central position, branching out to numerous marketing-related terms such as ‘marketing’, ‘marketing strategy’, ‘digital marketing’, and ‘AI in digital marketing’. Words related to the implementation of AI in marketing channels (‘AI-based marketing channels’, ‘customer interaction’) are in the blue cluster. At the same time, the yellow-green grouping features terms connected to creating customer value (‘customer lifetime value’, ‘customer relationships’, and ‘CRM’). The red area focuses on terms concerning customer trust and engagement (‘consumer trust’, ‘customer commitment’). The thickness and number of connecting lines reflect the intensity of the co-occurrence of these keywords in the reviewed articles. The map shows strong thematic links between articles.

4.9. Title Words Co-Occurrence Analysis

Title word co-occurrence analysis makes it possible to find connections between words extracted from the titles and present them as a map. Fig. 8 presents an example of the map prepared based on massive, many records Case 2.

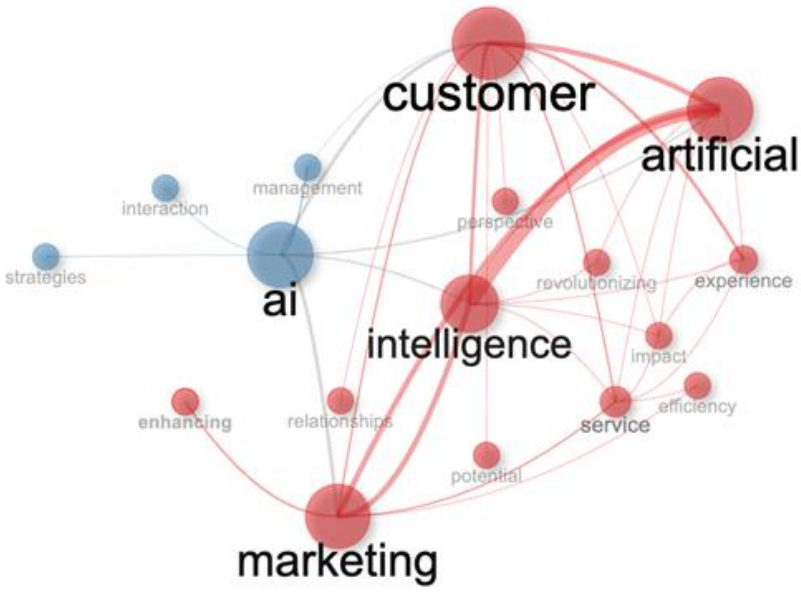


Figure 8. Co-occurrence analysis of keywords extracted from article titles Case 2
Source: own work in Bibliometrix software.

Fig. 8 presents connections between central keywords extracted from titles such as ‘customer’, ‘artificial’, ‘AI’, ‘intelligence’, and ‘marketing’. The nodes (spheres) size suggests that these terms appeared particularly frequently in the publication titles. In the map, strong connections between the following concepts can be easily observed in Fig. 8:

- ‘customer’ and ‘artificial’ – indicating the frequent association of customer-related topics with artificial intelligence themes;
- ‘ai’ and ‘intelligence’ – highlighting the importance of broadly understood intelligent solutions and systems;
- ‘marketing’ and ‘intelligence’ – suggesting an emphasis on the use of intelligent technologies in the marketing field;
- ‘marketing’ and ‘customer’ – drawing attention to the relationship between marketing activities and the customer’s needs and perspective.

Smaller nodes scattered around them, such as ‘management’, ‘relationships’, or ‘experience’, are often linked to the main concepts, forming the context of applying AI and intelligence in customer management and marketing. This co-occurrence map also shows strong thematic links between articles.

4.10. Abstract Co-Occurrence Analysis

The abstract co-occurrence maps present connections between the most important words extracted from the paper's abstracts; an example is presented in Fig. 9.

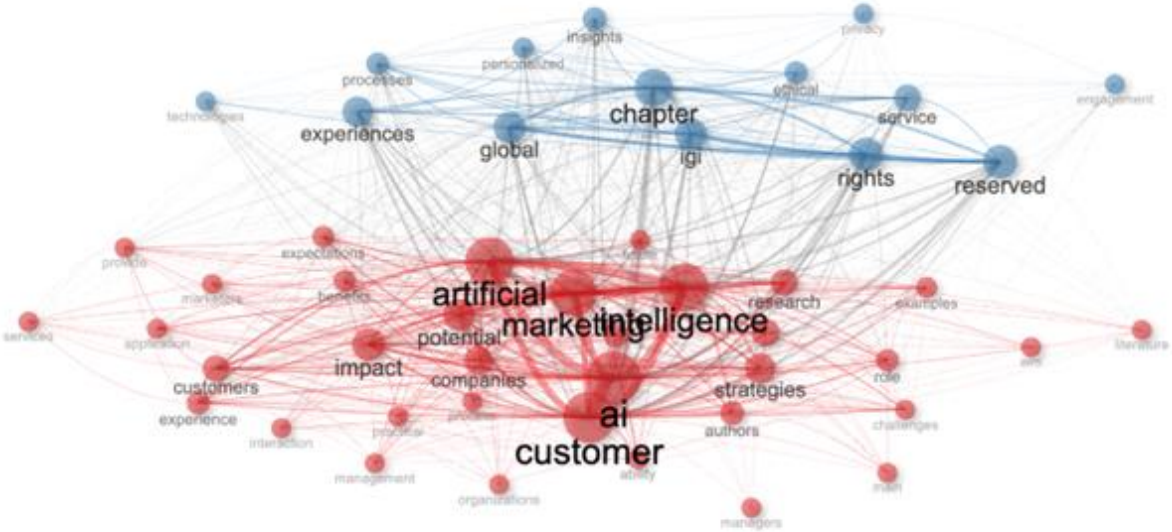


Figure 9. Co-occurrence analysis of keywords extracted from article abstracts Case 2
Source: own work in Bibliometrix software.

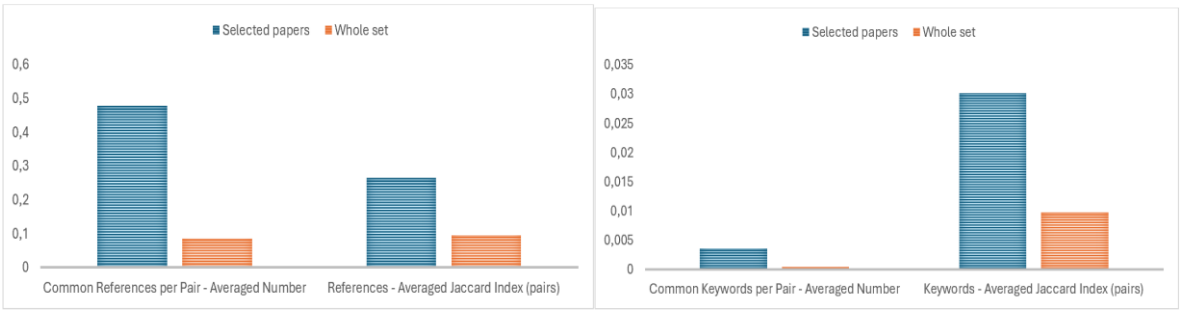
In Fig. 9, a network of strong ties around artificial intelligence (AI), marketing, and customers can be observed. The central positions of 'artificial', 'marketing', 'intelligence', 'AI', and 'customer' indicate their high position in abstract co-occurrence analysis. On the map, we can also observe:

1. A large cluster of red nodes around AI-related terms (e.g., 'artificial', 'intelligence'), marketing, and customers ('customer'), confirming the close association of these topics in the analyzed literature.
2. Blue areas ('chapter', 'global', 'IGI', 'rights', 'reserved') suggest a publishing or legal/editorial context appearing in the abstracts – likely indicating that some publications refer to chapters in monographs published by specific publishers or address copyright issues.
3. A vast network of connections (red lines) among terms such as 'experience', 'impact', 'companies', and 'strategies' shows that many articles describe AI implementations in companies and analyze their impact on customer experience and marketing outcomes.

The arrangement of the nodes and their connections indicate a research focus on integrating artificial intelligence into marketing, with the customer seen as the key recipient of these solutions. The presence of nodes related to management (e.g., 'organizations', 'authors', 'challenges') further underscores the importance of organizational and methodological context in implementing such solutions. Additionally, these keyword co-occurrence maps from both the titles and the abstracts demonstrate that the selected articles are thematically consistent, confirming the effectiveness of the publication selection method proposed in this paper.

4.11. Aggregated results

Analyzing aggregated results for the four research cases allows for assessing the effectiveness of the proposed article selection method. The developed approach has been validated using bibliometric indicators such as common references and common keywords (Fig. 10).

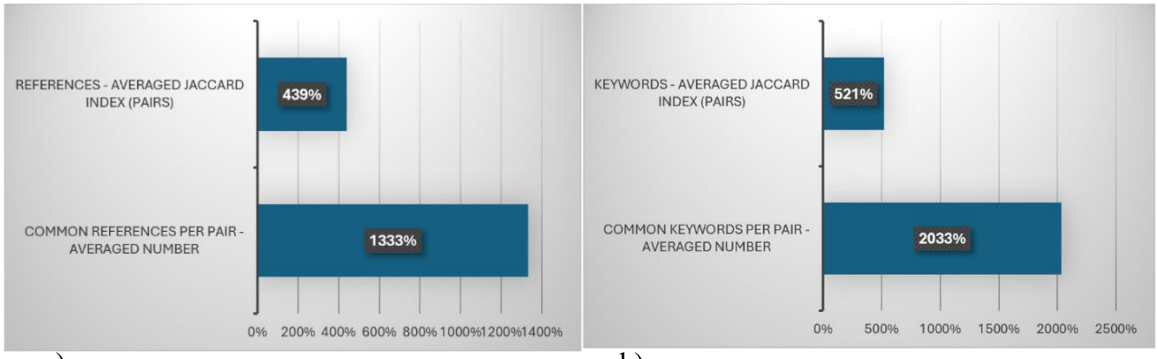


a) b)

Figure 10. Averaged effects of using the embedding model, a) common references, b) common keyword

Source: own elaboration.

The results presented in Fig. 10 prove the high effectiveness of the proposed method. Articles more similar to the given research problem (smaller cosine distance – selected papers) are also closely related thematically. Fig. 11 shows the percentage improvement of the value of indicators in selected papers relative to the value of indicators in the whole set.



a) b)

Figure 11. Improvement of the value of indicators in selected papers relative to the value of indicators in the whole set: a) references, b) keywords

Source: own elaboration.

For the common references, the filtered set of publications has an averaged Jaccard index 439% higher than the whole set (Fig. 11a). In the case of keywords, the result is 521% higher (Fig. 11b). Even better results are obtained for the average number of references and keywords. The obtained values are 1333% and 2033%, respectively (Fig. 11). This means that in the set of selected publications, there are over thirteen times more common references (Fig. 11a) and over twenty times more common keywords than in the whole set (Fig. 11b). All presented in the paper results prove high efficiency of the developed method.

4. CONCLUSIONS

The presented results indicate that AI-powered text embeddings significantly improve the relevance of selected scientific publications. The method is much more precise and effective than traditional keyword searches. Moreover, it allows users to find publications that are much better suited to their needs and are easier to calibrate. Replacing humans in the validation process with bibliometric indexes and semantic indicators makes the process almost fully automated and completely bias-free. Moreover, AI-selected publications had many times higher bibliometric similarity scores (from four to twenty times) than the entire dataset; the proposed selection process does not randomly filter publications but identifies those that share meaningful thematic and citation-based connections. The selected publications addressed similar topics and referenced a more interconnected body of research. The study provides quantitative evidence supporting the effectiveness of the embedding model in literature selection.

Users can use the presented method without technical knowledge of databases or artificial intelligence. The only input is a natural-language description of the research problem. Therefore, the technique may be utilized by professional researchers and anyone who needs access to scientific knowledge or makes decisions based on proven facts. The method can be successfully used, especially in management or business tasks.

The presented AI-driven approach also improves filtering efficiency. For instance, in the case study on gamification in marketing, the embedding model successfully reduced a dataset of 14 302 documents to a manageable and thematically relevant subset of 17 papers. This filtering allows researchers to focus on the most impactful and contextually appropriate studies.

Although the experiments with the all-distilroberta-v1 model yielded promising results, further experiments with other embedding solutions are necessary to confirm the universality and effectiveness of the proposed approach. Additionally, current research must be extended to studies involving a larger sample of publications and a more diverse range of topics. If further experiments prove the effectiveness and universality of the method, it can become an elemental tool in modern systematic literature reviews. However, the presented research should be considered a pilot study for now.

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EFFICIENT AI-POWERED DECISION-MAKING IN SYSTEMATIC LITERATURE REVIEWS USING MULTI-EMBEDDING MODELS

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ABSTRACT

Purpose: *This paper presents a new Artificial Intelligence (AI) multi-model approach for selecting publications that fit researcher needs well. It is the second work in a series of AI-powered systematic literature reviews focusing on replacing the human research team with a multi-model framework.*

Need for the study: *The expected exponential growth of scientific literature generated fully or partially by AI demands advanced artificial intelligence tools to streamline systematic literature reviews. Such a method should filter databases according to the researcher's needs, minimizing the risk of overlooking critical works.*

Methodology: *The technology behind word embedding models (WEMs) powers various AI systems, including ChatGPT. Eight models of this kind were evaluated with bibliometric criteria to select and utilize the four top-performing ones in article selection. Each model independently selects publications that best fit the problem description. Papers selected by the larger number of models are considered more relevant.*

Findings: *Different WEMs are trained on different data, have different architectures, and recognize different publications as the most relevant. Usually, articles selected by more models show higher thematic coherence; however, the number of models in the framework cannot be too large. The process is analogous to a systematic literature review conducted by many researchers with all the advantages and disadvantages of their parallel work.*

Practical Implications: *Our method is less biased and more accurate than a multiple-person systematic literature review (SLR). It allows for a fast examination of the problem from many perspectives and has the same implications as SLR.*

Keywords: Text Embeddings, Systematic Literature Review, Multi-Criteria Approach, Hierarchical Ranking, Bibliometric Analysis, Scholarly Articles, AI-supported decision-making, Agent system

Jel codes: M15; D70; M10

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1. INTRODUCTION

1.1. The Multi-Embedding Method in Comparison to Other Artificial Intelligence Solutions

Word embedding models (WEMs) represent a foundational advancement for artificial intelligence (AI) in natural language processing (NLP). AI tools driven by this technology already dominate all aspects of systematic literature review (SLR) (Fabiano, Gupta, Bhambra, Luu, Wong, Maaz, Fiedorowicz, Smith, Solmi, 2024). WEM models use deep artificial neural networks (ANNs) to convert textual data into n-dimensional vectors. Such vectors are straightforward for digital technology to process and can be used to identify semantic relationships between textual data. Internet users worldwide witness the transformative power of embedding technology through popular generative AI systems such as ChatGPT, DeepSeek, or Perplexity. Models of this kind leverage embeddings to process and understand complex data and generate relevant and coherent content.

The evolution of AI-automated SLR leads from statistical machine learning like the Naive Bayes classifier (van Dijk, Brusse-Keizer, Bucsán, 2013) or histogram features (Pittaras, Giannakopoulos, Papadakis, Karkaletsis 2020), through ANN (Ferreira, Quiles, Nazaré, Rezende, Demarzo 2021), and other machine learning algorithms (Feng, Liang, Zhang, Chen, Wang, Huang, Sun, Liu, Zhu, Pan, 2022) to generative AI based on embedding systems (Fabiano et al., 2024). Table 1 compares machine learning-based methods to the proposed method.

The proposed technique does not use predefined categories and selects publications using the parallel work of many agents, which addresses a significant limitation of machine learning techniques.

Strict categories often fail to adapt to nuanced or evolving research needs. By contrast, embedding models enable dynamic, context-aware retrieval. That makes them particularly valuable not only for researchers (where rigid taxonomies may overlook novel thematic connections) but also for non-experts who need relevant and actual data, such as managers, entrepreneurs, or policymakers.

Moreover, integrating a multi-model framework can significantly enhance the efficiency and adaptability of SLRs. Different models can have different search parameters, which allows the capture of evolving research themes and ensures the retrieved literature remains relevant and up-to-date.

Table 1. A comparison of the proposed system and classic machine learning approach in NLP

	Machine Learning	**Multi-Embedding system**
Learning and validation process	Active – a human is involved in labeling publications from the training set, and the learning process can be time-consuming to create	Passive models are universally trained before the model can be used; during the investigation, there is no need for additional learning; users describe the research problem in natural language
Automation level	Partially automated	Fully automated
Aim	Classify publications into strict categories selected by the user (usually), sometimes rankings	Find publications most similar to user description, which can also be used to do rankings
Validation method	number of models that considered a given publication important, semantic similarities, thematic consistency via bibliometrics	Recall/precision metrics only
Required skills	Knowledge about machine learning	No technical skills required
Matching to user needs	Limited – the method used exact terms	Complete – the method uses natural language
Agent system approach	Usually, a decision is made based on one model	Many different points of view are used to select optimal from user perspective publications
Priorities	Mostly fast processing of huge sets of publications	Matching user needs
Other limitations	Requires labeled datasets for training, which can be time-consuming to create. Performance depends heavily on the	Computationally intensive due to the complexity of transformer models; may require fine-tuning for domain-specific

	quality of training data and feature engineering; limited adaptability to new queries or evolving research topics without retraining	applications; less effective in tasks requiring strict classification without additional layers.
Other advantages	High accuracy if sufficient labeled training data is available; scalability for large datasets; active learning reduces the manual workload by focusing on uncertain cases	There is no need for labeled datasets - embeddings are pre-trained on large data sets, flexibility in handling complex queries expressed in natural language, and superior performance in capturing nuanced meanings compared to traditional machine learning classifiers

Source: own elaboration.

As presented in Table 1, machine learning methods use active learning, which requires human participation at multiple stages and can introduce bias and limit scalability. Moreover, many of these tools focus on expediting processes like screening and data extraction but lack mechanisms for thematic consistency and meeting real user needs. On the other hand, the proposed multi-embedding model offers a fully automated approach (no human participation needed) and guarantees the relevance and consistency of publications utilizing bibliometric validation.

The discussed method can also be considered an evolution of generative models. Generative AI struggles with credibility due to unreliable sources and fabricated references. Models of this type lack scientific rigor, and specific bibliometric indicators are not used in the selection. Even though generative models are more universal and convenient in use, their credibility is much lower than that of a specialized SLR method based on similar techniques (Gwon, Kim, Chung, Jung, Chun, Lee, Shim, 2024; Kacena, Plotkin, Fehrenbacher, 2024). The agent system approach that allows the scanning of publications from many perspectives is also advantageous and improves the quality of recommended publications compared to generative AI.

The proposed method combines the advantages of strict bibliographic scientific rigor with the flexibility and simplicity of generative intelligence. In contrast to machine learning methods, it can be used by anyone, not just AI professionals. Incorporating an agent-based approach further amplifies these benefits by introducing a layer of autonomous adaptation and a more expansive view of the problem.

1.2. Introduction to systematic literature review driven by AI agent system

Systematic literature review (SLR) is a methodology that aims to find and accumulate available but spread knowledge and then transform it into practical conclusions (Clark, Clark, Raffo, Williams, 2021). SLRs reduce bias and ensure a higher level of investigation objectivity and reliability. Therefore, the methodology is considered a crucial element in the early stages of the research (Clark et al., 2021). Unlike narrative reviews, SLR offers a more structured and comprehensive perspective on the state of knowledge and provides a solid foundation for further research (Simsek, Fox, Heavey, 2015; Simsek, Fox, Heavey, 2021). Following a specific, clearly defined algorithm and criteria makes searching for and selecting the most relevant materials faster and more effective (Hiebl, 2021). Moreover, the methodical approach allows other researchers to reproduce the steps and reach similar conclusions (Hiebl, 2021; Hubbard, Vetter, Little, 1998; Combs, Ketchen, David, Crook, Roth, 2011). SLRs are particularly useful in disciplines characterized by paradigm divergence, such as supply chain management (Durach, Kembro, Wieland, 2017).

As mentioned, SLRs are conducted to identify and understand the current state of scientific knowledge (Amjad, Kordel, Fernandes, 2023; Durach et al., 2017; Linnenluecke, Marrone, Singh, 2020; Williams, Clark, Clark, Raffo, 2020) and can be used by researchers, practitioners, decision-makers, and anyone who needs to provide reliable evidence (Amjad et al., 2023; Glass, 1976; Williams et al., 2020).

A typical systematic review procedure includes several elemental steps (Tranfield, Denyer, Smart, 2003; Lenart-Gansiniec, 2022). The first stage is planning the review, when all research questions are formulated and a specific protocol is established.

Next, the search strategy is defined. Key concepts are identified and grouped with their synonyms in the block. The grouped elements are connected with the OR logical operator. Next, the blocks are combined using the AND operator, creating a query to the database. The effectiveness of the search

strategy is tested on key articles to ensure they are included in the results. If the articles are not included, the strategy needs to be modified. Finally, all steps of the strategy are documented.

The following step involves identifying an initial, huge set of publications using clearly defined inclusion criteria. Next, the set is systematically reduced based on previously prepared exclusion rules. Finally, a researcher analyzes the full text of selected publications, extracting and aggregating helpful knowledge from them.

The bibliometric analysis (BA) is an important complement to SLM. Bibliometric metrics represent connections between publications, topics, and researchers numerically, offering clarity, simple relations understanding, and easy comparisons. Moreover, they are invaluable in identifying the most significant publications and theoretical streams in a given field (Zupic, Čater, 2015). The other methods are visualization maps that present connection networks (usually using citations) and tracks of concept evolution (Linnenluecke, Marrone, Singh, 2020). Citation maps and common keyword analyses are also often used to identify research gaps and new areas of inquiry (Simsek et al., 2015).

In research fields similar to management, where studies are often difficult to replicate and conceptual definitions can be inconsistent (Whipple, Wiedmer, Boykin, 2013), SLR combined with BA forms the foundation for building a coherent theoretical base (Durach et al., 2017). The methods can be used not only as an indicator of good practice but also as a catalyst for the further development of the discipline.

SLR usually requires the parallel work of multiple researchers. Such an approach ensures error reduction during SLR and BA and increases the credibility of the obtained findings (Hiebl, 2021). Unfortunately, SLR methods have numerous disadvantages. The most significant are unavoidable bias and time/labor consumption (Matysik, Wiśniewska, Frankowski, 2025). Additionally, other people's participation in the investigation is required to maximize SLM's effectiveness, which is not always possible. According to the authors, all the advantages of the ensemble approach to SLM can also be obtained with the single investigator and the proposed multi-model agent system.

The proposed framework simultaneously reduces the risk of bias to zero, fully exploits the mathematical nature of BA, and allows for more accurate analysis in a much shorter time. Moreover, the diversity of word embedding models (WEMs) and the multi-model approach allows a simultaneous look at the research problem from many different perspectives, miming the effects of teamwork in the investigation group during the SLR. Any WEM model has a different architecture (that can mimic innate skills) and is trained on different data (analogy to different skills and experiences of researchers). However, in contrast to humans, AI agents are fully autonomous and have all the advantages of software.

1.3. Embedding models in content analysis and hierarchization

Modern word embedding models (WEMs) are usually designed as neural networks that convert textual data into n-dimensional distributional representations, which capture semantics (and, in some cases, syntax) context quantitatively (Egger, 2022; Asudani et al., 2023; Gao et al., 2019; Moreo et al., 2021). WEMs enable building information relevance hierarchies by comparing the semantic proximity of vectors (Egger, 2022; Asudani et al., 2023). The models can be used in recommendation systems, topic modeling, or extracting keywords (Asudani et al., 2023). Additionally, the embedding technique also enables matching significant text elements to class labels (Wang, Manning, 2012; Arora, Liang, Ma, 2017; Ren et al., 2019).

The literature research indicates the growing popularity of embeddings in text analysis. A search in the Scopus database for the query "text embeddings" in the titles, abstracts, and keywords of scientific publications showed a growth in the number of publications from 30 in 2018 to 430 in 2024, an increase of more than 1,400%. However, not only researchers are interested in the topic. The Google Trends analysis in 2019–2024 presented in Fig. 1 indicates a significant increase in interest in "Text Embeddings" among all internet users.

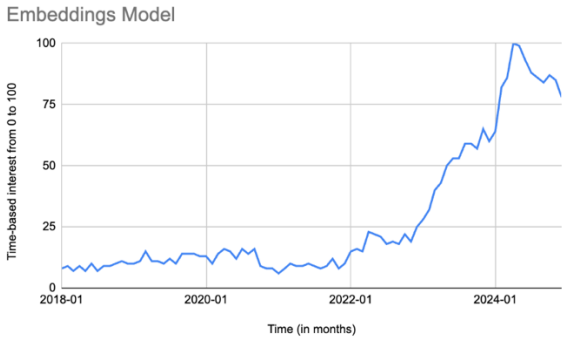


Figure 1. The evolution of Google Trends Popularity Index for the keyword: Text Embeddings from 2018 to 2024
Source: own elaboration based on data from Google Trends.

As presented in Fig. 1, the fast growth of popularity started in 2022, which can be associated with the launch of GPT chat (November 2022) and the key role of this technique in text processing.

1.4. Motivation

We live in the age of information. The daily amount of data uploaded to the internet has reached about 400 million terabytes; yearly, in 2024, it was 147 zettabytes (10^{21}B). It is believed that 90% of the world's data has been generated in the last two years (Duarte, 2025). A massive part of this information is generated by artificial intelligence (AI). Moreover, AI also revolutionized the process of preparing scientific publications and is used in every step of manuscript preparation (Matysik et al., 2025; Májovský, Černý, Kasal, Komarc, Netuka, 2023). Even if AI is not ready to prepare scientific articles alone yet (Kacena et al., 2024), its impact on world science is growing quickly. The trend is clear. The percentage of AI-generated content will grow systematically in the following years. This tendency can have unexpected and dangerous consequences. The first one is that AI usually averages results. Increasing the amount of AI-generated content will deepen the marginalization of unpopular views, opinions, or research results. Another huge problem will occur when AI starts to be trained mainly on AI-generated data. Such practice can lead to 'model collapse'. In such a case, the system forgets rarer elements of its original training data and eventually generates incoherent or nonsensical information (Wenger, 2024). Presented trends suggest that soon, not getting the answers to questions will be a problem but instead, verifying the adequacy of the obtained answer. Therefore, with the development of generative AI and the expansion caused by this AI information noise and nonsensical data, it is necessary to develop powerful techniques dedicated to information filtration. The most popular and effective methodologies used to select relevant publications are systematic literature reviews (SLR) (Matysik et al., 2025).

One of the most important aspects of SLR is the simultaneous work of two or more researchers. People with different abilities and experiences can complement each other with different points of view; the method can also prevent bias, ensure error reduction, and increase the finding's credibility. Therefore, this key element of classic SLR should be adapted by AI-powered, automated SLR. This paper attempts to answer the question of how not only to minimize the amount of human work but also increase the effectiveness of the analysis through more efficient use of bibliometric analysis. The most important element is to find how to obtain the same benefits that in classic SLR are provided by the cooperation of a group of scientists.

2. METHODOLOGY

2.1. The general research model

Eight word embedding models are tested in the first stage of this research. Finding the most relevant papers is described in detail in this cycle's first work (Matysik et al., 2025). Therefore, in this paper, the

description is shortened.

The single test starts with creating a problem description and query in the Scopus database. The prepared query should not be very exact. As a result, thousands of publications potentially connected with the topic are found. A combined title and abstract represent each publication. Embedding models encoded descriptions of the problem and descriptions of the founded papers to n-dimensional real-number vectors (embeddings). This process created a .CSV file containing complete bibliographic data and the cosine distance value calculated for each publication relative to a defined research problem. This parameter enabled the identification of articles with the highest semantic similarity to the analyzed described research problem, even if they were written using different phrasing.

The 17 articles with the lowest cosine distance values are selected from all records in the CSV file, generating a ranking of the most thematically relevant publications. In the experiments, eight different models are used:

1. embed-english-v3-0;
2. all-distilroberta-v1;
3. all-MiniLM-L12-v2;
4. all-mpnet-base-v2;
5. jina-embeddings-v3;
6. nomic-embed-text-v1.5;
7. text-embedding-3-large;
8. text-embedding-ada-002.

The similarities between the description of the problem and the description of each of the founded publications are measured with cosine distance given as (1).

$$\text{distance}(u, v) = 1 - \frac{u \cdot v}{\|u\| \, \|v\|} \tag{1}$$

Where u is a vector made of problem description and v is a vector of paper description.

The 17 most relevant findings (where distance is closest to zero) of each model are used in the following stages of the experiment. Evaluating the suitability of selected papers to user needs cannot be performed in the same way as traditional machine learning (Szymanik, 2022). Therefore, traditional bibliometric metrics are suggested for this purpose. All selected works are assessed using six bibliometric metrics, including:

1. Average number of common (shared) references (single model), the parameter is given as (A);
2. The Jaccard index calculated for the references (single model), the parameter is described as (A');
3. Average number of common (shared) keywords (single model), the parameter is given as (B);
4. The Jaccard index calculated for the keywords (single model), the parameter is described as (B');
5. Number of shared references (between models);
6. Number of unique references (between models).

The first four, called internal, are calculated for pairs of the records in the set selected by a specific model (all possible combinations) and then averaged. The factors show how coherent publications are inside the specific set. The two last metrics (external) are calculated between models. The metrics are described in detail (Matysik et al., 2025). The two last indicators are opposite; one shows how strongly publications of one set (selected by other models) overlap other sets. That index shows the coherence between sets and can mimic the situation when many researchers agree that the publication is relevant. A number of unique publications can also be considered an important factor, but only if all the first four metrics are high. That case simulates when one of the researchers has completely different experiences and points of view than others and finds publications that are not interesting to other researchers. However, eventually, they are valuable for the research. The high index can show that the model is very important or completely useless, depending on the four first indexes.

The advantages and disadvantages of using keywords and reference indicators are discussed in Table 2.

Table 2. A comparative analysis of bibliometric indicators

Indicator	Advantages	Disadvantages
Bibliographic Coupling	• Useful for identifying current research trends; • Minimizes citation lag compared to direct citation analysis; • Highlights shared intellectual heritage among publications	• May not capture very recent references; • Can overemphasize older or more general sources; • Does not directly measure active scientific dialogue
Common Keywords	• Straightforward way to reveal related research concepts; • Helps identify thematic clusters; • Easy to interpret	• Depends heavily on accurate and consistent keyword assignment; • Does not reflect the depth of citation or reference usage; • May overlook nuanced or emerging terminology

Source: own elaboration.

The first experiment showed that the internal metrics obtain the highest value if three or four models select them. The publications selected by fewer or more models are usually less relevant. Results obtained for the tested set are presented in Fig. 2.

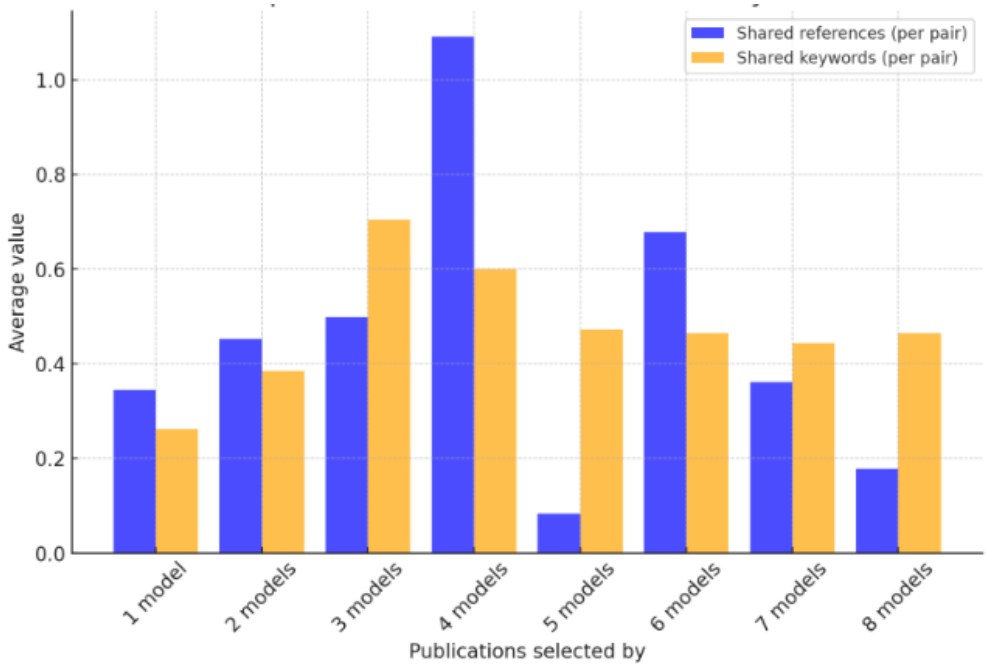


Figure 2. Comparison of averaged shared reference and keywords
Source: own elaboration using the Python library matplotlib.pyplot.

The results were unexpected, so research was repeated on three other research questions. During the experiments, 18,458 publications were retrieved from the Scopus database. Similar results were obtained in each try. The experiments showed that the optimal set of publications (all models) was obtained when only the four best embedding systems were considered. Therefore, only the four best models are used in further experiments. The process is similar to the preliminary selection of the researchers participating in the systematic literature review.

The next step involved hierarchizing the articles using the developed method. The idea of the method lies in the analysis of the overlap of sets of articles selected using a specific model. During the process, which articles are identified by all four models, three models, two models, or only one is tested. Initial experiments prove that papers selected by more models are usually more relevant (if models are preliminarily selected). To select the best WEMs, each model's average position across all six rankings

(A, B, A', B', number of unique articles, number of shared articles) is calculated. These averaged values are then used to create the final ranking of models, highlighting which most effectively and consistently identify publications that are semantically closest to the analyzed research problems.

The method is designed for article prioritization. The publications are divided into groups based on a number of embedding models (from 1 to 4) that recognize them as highly relevant (top 50). The groups are evaluated using internal indicators in terms of shared references and keywords to confirm the effectiveness of the proposed method. Optionally, publications selected by the same number of models (same group) can also be ranked based on internal indicators. Detailed information about this step is presented in the first work of this series (Matysik et al., 2025).

2.2. Word embedding models AI used in the experiment

Different word embedding models (WEMs) have different architectures (which can be compared to the researcher's innate predisposition). They are trained on different data (which can be compared to the researcher's different experiences). Table 3 shows the fundamental differences between popular WEMs. The models from OpenAI and Cohere are proprietary, meaning their internal architectures and training data are not publicly disclosed. In contrast, Hugging Face, Jina AI, and Nomic AI provide open-source alternatives, allowing for greater customization and adaptation to specific tasks (Vaswani et al., 2017).

Table 3. Fundamental differences between utilized embedding models

Model	Source	Architecture	Embedding Size	Context Length	Specialization
embed-english-v3.0	Cohere	Proprietary	Unknown	Unknown	General-purpose text embeddings
all-distilroberta-v1	Hugging Face	DistilRoBERTa	768	512	Sentence similarity
all-MiniLM-L12-v2	Hugging Face	MiniLM	384	512	General-purpose sentence embeddings
all-mpnet-base-v2	Hugging Face	MPNet	768	384	General-purpose sentence embeddings
jina-embeddings-v3	Jina AI	Transformer-based	Unknown	8192	Multi-purpose NLP tasks
nomic-embed-text-v1.5	Nomic AI	Transformer-based	Unknown	8192	Text embeddings optimized for retrieval and search
text-embedding-3-large	OpenAI	Proprietary	3072	8192	General-purpose text embeddings
text-embedding-ada-002	OpenAI	Proprietary	1536	8192	General-purpose text embeddings

Source: own elaboration based on (Cohere; Hugging Face, Jina AI, Nomic AI, OpenAI).

The architectures of the WEMs presented in Table 3 vary significantly. Embedding-based models such as MPNet, MiniLM, and DistilRoBERTa leverage self-attention mechanisms for efficient language modeling (Devlin, Chang, Lee, Toutanova, 2019). However, OpenAI's models (text-embedding-3-large and text-embedding-ada-002) use proprietary architectures optimized for large-scale embeddings (Brown et al., 2020).

Another crucial aspect is embedding size and dimensionality, which impact the richness of semantic representation. More significant embeddings provide more detailed representations, as seen with OpenAI's text-embedding-3-large (3072 dimensions), compared to 1536 dimensions for text-embedding-ada-002. Smaller embeddings, like those in all-MiniLM-L12-v2 (384 dimensions), prioritize efficiency while maintaining strong performance in NLP tasks (Wang et al., 2020).

The following important issue is context length. Some models, such as all-distilroberta-v1 (512 tokens) and all-mpnet-base-v2 (384 tokens), have relatively short context windows, limiting their effectiveness in processing long documents. In contrast, WEMs like text-embedding-3-large, text-embedding-ada-002, and nomic-embed-text-v1.5 can handle 8192 tokens, making them ideal for long-

document retrieval, summarization, and search optimization (Radford et al., 2021).

In terms of specialization, the models cater to different NLP applications. Some, such as embed-english-v3.0, text-embedding-ada-002, and all-mpnet-base-v2, are general-purpose embeddings for various text-based tasks. Others have specific optimizations; for example, all-distilroberta-v1 specializes in sentence similarity tasks, making it useful for paraphrase detection and semantic textual similarity (Reimers, Gurevych, 2019). Meanwhile, Jina-embeddings-v3 is designed for multi-purpose NLP tasks, including search, clustering, and classification.

The selection of a text embedding model depends on the trade-offs between performance, efficiency, and transparency. OpenAI's models provide high-dimensional embeddings with extended context capabilities, making them suitable for complex NLP tasks. On the other hand, Hugging Face models such as MiniLM and DistilRoBERTa focus on computational efficiency. Meanwhile, proprietary solutions such as Cohere's embed-english-v3.0 remain less transparent but are optimized for enterprise applications. Choosing the right model depends on whether the priority is processing long-form text, computational efficiency, or open-source accessibility.

4. RESULTS

3.1. AI-based multi-criteria model selection

The most interesting parameter during the model selection is the number of unique articles the model AI finds. A high value of this parameter is an advantage only if internal metrics are high. The results obtained during the experiment are presented in Fig. 3.

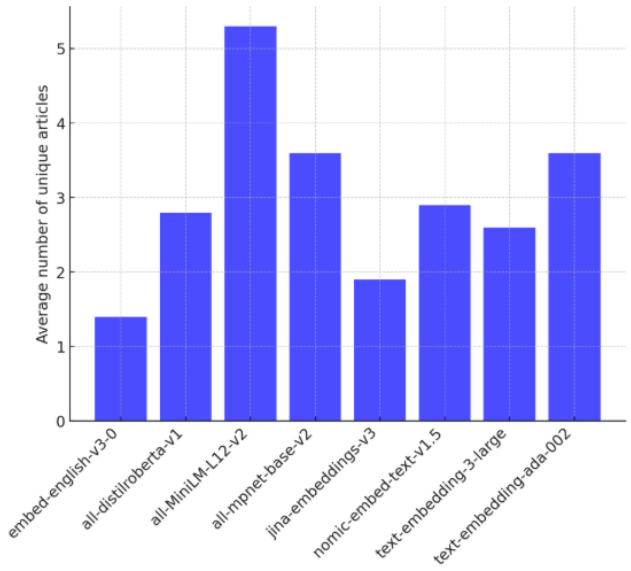


Figure 3. Number of unique articles found by model
Source: own elaboration using the Python library matplotlib.pyplot.

The chart in Figure 3 compares different word embedding models (WEMs). The heights of the bars reflect differences in the model's ability to find unique articles. The highest bars correspond to all-MiniLM-L12-v2 (5.6 unique articles). Slightly worse results are achieved by all-mpnet-base-v2 and text-embedding-ada-002 models (about 3.6 unique articles). Models such as all-distilroberta-v1, text-embedding-3-large, nomic-embed-text-v1.5, and jina-embeddings-v3 are average with 1.9-2.9 unique papers, while embed-english-v3-0 has the lowest value of this parameter (1.4).

The second histogram in Fig. 4 shows the average number of shared (selected by multiple models) articles.

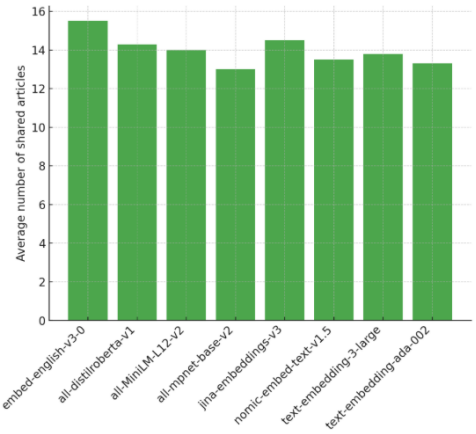


Figure 4. Number of shared articles found by model
Source: own elaboration using the Python library matplotlib.pyplot.

This time, the variation between models is much lower than in the case of unique articles presented in Fig. 3. This observation can be interpreted as models mostly find similar publications.

The graph shows that embed-english-v3-0 has the highest number of shared articles (15.5), followed closely by jina-embeddings-v3 (14.5) and all-distilroberta-v1 (14.3). Slightly lower values are seen for all-MiniLM-L12-v2 (14.0) and text-embedding-3-large (13.8), while nomic-embed-text-v1.5 (13.5), all-mpnet-base-v2 (13.0), and text-embedding-ada-002 (13.3) have the lowest averages in this category.

The results indicate that some models (embed-english-v3-0, jina-embeddings-v3, all-distilroberta-v1) tend to select a more standard set of articles, suggesting higher overlap with other models. In contrast, models such as all-mpnet-base-v2 and text-embedding-ada-002 appear to exhibit a slightly lower tendency to select articles that overlap with others.The quality of the model can be presented on radar charts based on six selected metrics. The evaluation considers arithmetic means (Common references and Common keywords), Jaccard indices (reflecting the degree of overlap in references and keywords), and the number of articles unique to a given WEM and those shared with other models. The visualization allows for precise observation of the strengths and weaknesses of each WEM, as well as a comparison of their coverage (in terms of keywords and references) and their ability to identify unique materials. The shape of the plotted area illustrates which measures the model excels at or underperforms.

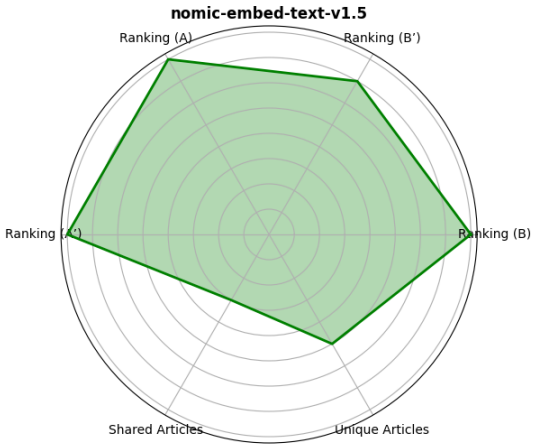


Figure 5. Radar chart for the 'nomic-embed-text-v1.5' model
Source: own elaboration using the Python library matplotlib.pyplot.

The nomic-embed-text-v1.5 model described in Fig. 5 achieves excellent grades in reference-based metrics (A, A') and keyword-based metrics (B, B'). Worse results corresponding to the set of Shared Articles may indicate that while the model effectively links publications, they do not always align with the selections of other models. The level of Unique Articles is moderate on the chart, signaling the model's ability to identify non-repeating entries.

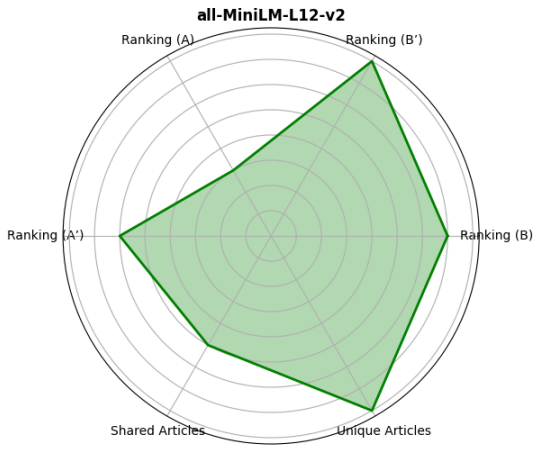


Figure 6. Radar chart for the 'all-MiniLM-L12-v2' model
Source: own elaboration using the Python library matplotlib.pyplot.

The diagram presented in Fig. 6 describes a solid model. The most extensive section of the polygon corresponds to the parameters related to keywords (B, B'). Therefore, it can be assumed that that model selects papers strongly connected thematically. The metrics concerning references (A, A') are smaller. The Unique Articles dimension is high, indicating good performance in finding relevant and unique articles. The Shared Articles area remains moderate, indicating a balanced result overlap with other models.

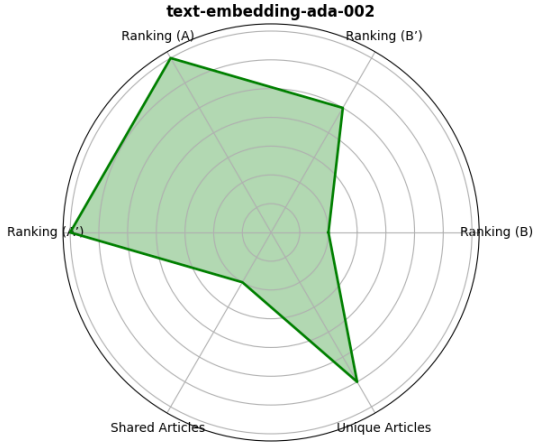


Figure 7. Radar chart for the 'text-embedding-ada-002' model
Source: own elaboration using the Python library matplotlib.pyplot.

The text-embedding-ada-002 model described in the diagram in Fig. 7 is interesting. The model is very good at finding unique publications that have potent relations in references. However, it should be noted that the author keyword metrics for the publications selected by this model are relatively low. The model is suitable for tracking relations and trends, but selected publications may not be connected strongly thematically.

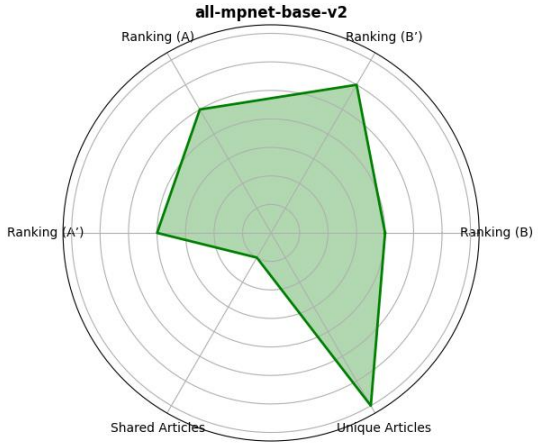


Figure 8. Radar chart for the 'all-mpnet-base-v2' model
Source: own elaboration using the Python library matplotlib.pyplot.

In Fig. 8, the shape of the polygon is relatively balanced, with no distinct maximum in any of the metrics except for unique articles. The reference-based parameters (A, A') and keyword-based metrics (B, B') take on similar, moderate values, which may indicate general but not exceptional versatility. However, an exceptionally high reach is observed in the Unique Articles dimension, suggesting a more significant number of publications identified exclusively by this model. Shared Articles appear relatively low.

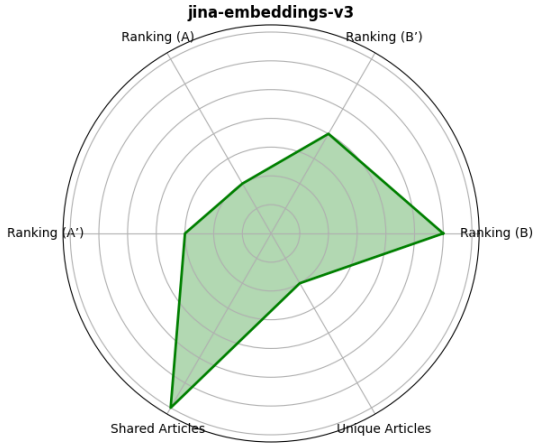


Figure 9. Radar chart for the 'jina-embeddings-v3' model
Source: own elaboration using the Python library matplotlib.pyplot.

Fig. 9 presents the jina-embeddings-v3s polygon as relatively small across most metrics. The reference-based parameters (A, A') and keyword-based metrics (B, B') do not achieve high grades. The dimension of Shared Articles is significantly marked, indicating a high overlap with publications selected by other models. The area for Unique Articles is small. This model's usability in the discussed case is low.

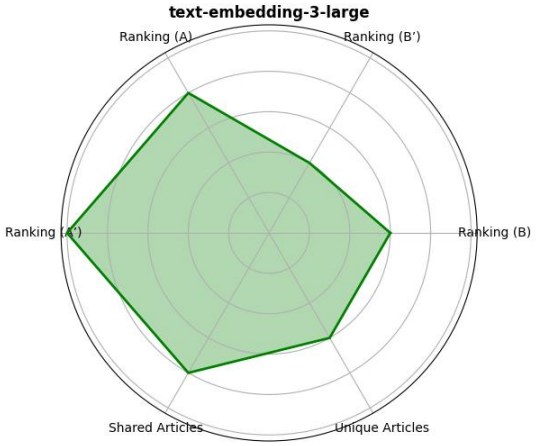


Figure 10. Radar chart for the 'text-embedding-3-large' model
Source: own elaboration using the Python library matplotlib.pyplot.

The shape presented in Fig. 10 is extensive and balanced. The WEM is good at finding publications with common references. The amplitude is comparable across keyword-based metrics (B, B') and the Unique Articles and Shared Articles categories. The best result was achieved in the shared references among publications selected by this model.

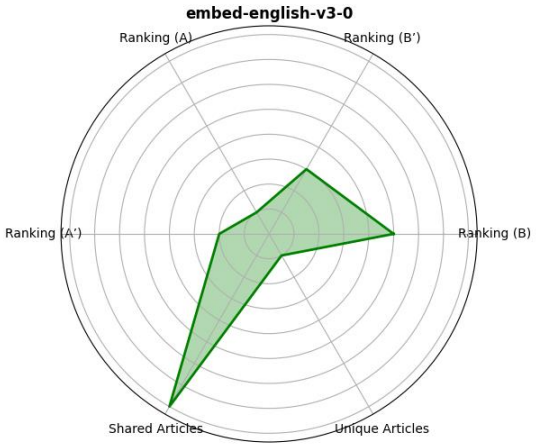


Figure 11. Radar chart for the 'embed-english-v3-0' model
Source: own elaboration using the Python library matplotlib.pyplot.

In Fig. 11, the Shared Articles dimension has a clear outline, indicating substantial overlaps with other models in selecting the same publications. The reference-based parameters (A, A') and keyword-based metrics (B, B') have a low range, suggesting a weak connection between the selected publications regarding keywords and shared references. The Model does not perform well in finding unique results and is not recommended.

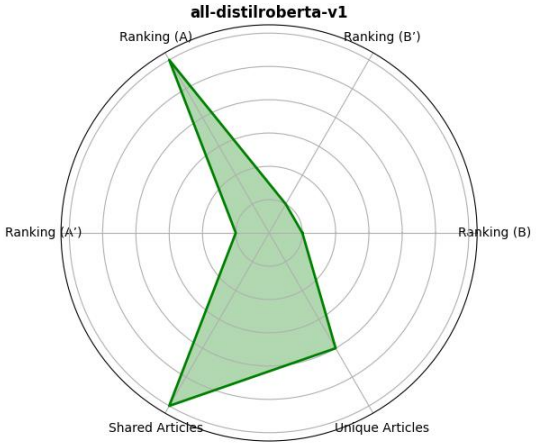


Figure 12. Radar chart for the 'all-distilroberta-v1' model
Source: own elaboration using the Python library matplotlib.pyplot.

The polygon's outline presented in Fig. 12 indicates a high value in the Jaccard index of common references (A') and a low value in other internal indicators. The grades in Shared Articles are high, suggesting some overlap with the results of other models. However, the level of Unique Articles is decent, indicating that the model can suggest interesting publications that do not overlap with those selected by other models.

Table 4 presents the results of a multi-criteria evaluation of eight text embedding models. The four best-performing WEMs retrieve scientific publications most relevant to predefined research problems. The evaluation considered six key factors. Separate rankings are prepared for each of these criteria. Subsequently, the average position of each model across all six rankings is calculated. This allows for identifying solutions that demonstrate the highest consistency and accuracy in recognizing semantic similarities between publications.

Table 4. Multi-criteria Ranking of Embedding Models

Model	Ranking (B)	Ranking (B')	Ranking (A)	Ranking (A')	Shared Articles Ranking	Unique Articles Ranking	Final Average Rank	Final Rank
nomic-embed-text-v1.5	1	2	1	1	6	4	2.5	1
all-MiniLM-L12-v2	2	1	6	3	4	1	2.83	2
text-embedding-ada-002	7	4	2	2	7	3	4.16	3
all-mpnet-base-v2	5	3	4	5	8	2	4.5	4
jina-embeddings-v3	3	5	7	6	2	7	5.0	5
text-embedding-3-large	6	7	5	4	5	6	5.5	6
embed-english-v3-0	4	6	8	7	1	8	5.6	7
all-distilroberta-v1	8	8	3	8	3	5	5.83	8

Source: own elaboration.

The obtained results indicate that nomic-embed-text-v1.5, all-MiniLM-L12-v2, text-embedding-ada-002, and all-mpnet-base-v2 exhibit the highest consistency and accuracy in identifying publications that are semantically closest to the analyzed research problems. As a result, they were selected for future literature reviews and bibliometric studies.

3.2 Selection of the most relevant publications – case study

Four selected, best-performing models were utilized to hierarchize and select the most relevant publications. The method was finally tested on the specific problem presented in Table 5.

Table 5. Research problem tested in the experiments

The research problem description:	**Does BlockChain affect customer loyalty? What dimensions of Blockchain technology support the building of customer loyalty? How does Blockchain affect trust and transparency in various loyalty tools, including loyalty programs? In the context of building customer loyalty, Blockchain can be used in a number of ways – not only for loyalty programs but also to make business processes more transparent, protect data, and ensure transaction security.**
Scopus query:	('blockchain' AND 'customer loyalty')
Number of found records:	1 995

Source: own elaboration.

The presented approach provides a solid methodological foundation for evaluating articles' thematic similarity. Using pre-selected embedding models and multi-criteria analysis of the results ensures a better understanding of the relationships between publications.

In the study, four text embedding models (nomic-embed-text-v1.5, all-mpnet-base-v2, text-embedding-ada-002, and all-MiniLM-L12-v2) were used to analyze 1995 data from Scopus database publications.

The highest number of publications is recognized as most relevant for models. However, many important publications are also detected just by one model. The detailed results are presented in Fig. 13.

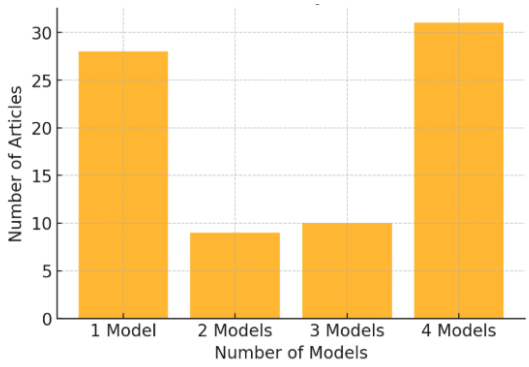


Figure 13. Overlapping of article sets selected by specific models
Source: own elaboration using the Python library matplotlib.pyplot.

The results presented in Fig. 13 show how many publications are included in the set of 50 most relevant by one, two, three, or all four embedding models simultaneously. The largest group of articles appeared on the sets of all four models. That suggests a strong consensus. Regardless of the embedding tool, these publications are always classified as highly relevant to the research problem.

Just one model sees many articles as semantically similar. Such articles can be especially valuable (unique) but also irrelevant; results depend on quality and matching the model to the research problem.

Table 6 presents the arithmetic means of the number of references and keywords per pair in the studied datasets.

Table 6. Comparison of Selected Publications Based on Overlapping References, Keywords, and Embedding Models – Arithmetic Averages

Publications selected by	Common references per pair	Common keywords per pair
1 model	$69 \cdot 10^{-3}$	$344 \cdot 10^{-3}$
2 models	$139 \cdot 10^{-3}$	$472 \cdot 10^{-3}$
3 models	$156 \cdot 10^{-3}$	$222 \cdot 10^{-3}$
4 models	$282 \cdot 10^{-3}$	$434 \cdot 10^{-3}$
2 or 3 models	$258 \cdot 10^{-3}$	$300 \cdot 10^{-3}$
2, 3 or 4 models	$162 \cdot 10^{-3}$	$369 \cdot 10^{-3}$
3 or 4 models	$185 \cdot 10^{-3}$	$360 \cdot 10^{-3}$

Source: own elaboration.

The group of papers selected by all four models includes the largest set of articles and shows the highest average overlap in references ($282 \cdot 10^{-3}$ and a keyword score of $434 \cdot 10^{-3}$). This can be interpreted as the articles chosen by all four embeddings being thematically cohesive and likely central to the research focus (having many important connections).

On the other hand, the group of papers selected by just one model has the lowest overlap of references ($69 \cdot 10^{-3}$) and a low keyword similarity ($344 \cdot 10^{-3}$). These papers are less consistent with each other and may not fit as tightly into the core theme. These two groups are the largest. Therefore, comparing them provides the clearest view of how well the proposed method works in the presented case.

The group selected by the two models has a slightly lower average overlap in reference ($139 \cdot 10^{-3}$) but shows the highest shared keyword score among all the subsets ($472 \cdot 10^{-3}$). These results show that using many bibliometric indicators can be reasonable. The publications in this group may not cite the same references at exceptionally high rates but converge around key topical words or concepts, indicating a notable semantic similarity.

The last group (selected by three models) exhibits a moderately higher overlap ($156 \cdot 10^{-3}$) in reference than the 2-model group but has a much lower keyword overlap ($222 \cdot 10^{-3}$). This pattern implies that these articles share more common bibliographic sources but are less uniform in the specific keywords. That points to a narrower thematic cohesion regarding references but more diversity in how they are described.

The 2-model and 3-model groups present intermediate levels of useability, compared to the groups of 1-model and 4-model. The obtained results, in general, confirm the assumptions about the method.

Table 7 presents the Jaccard Index for references and keywords per pair in the studied datasets.

Table 7. Comparison of Selected Publications Based on Overlapping References, Keywords, and Embedding Models - Index Jacardda

Publications selected by	Common references per pair	Common keywords per pair
1 model	$0.43 \cdot 10^{-3}$	$35.25 \cdot 10^{-3}$
2 models	$1.01 \cdot 10^{-3}$	$54.92 \cdot 10^{-3}$
3 models	$1.79 \cdot 10^{-3}$	$20.82 \cdot 10^{-3}$
4 models	$2.91 \cdot 10^{-3}$	$44.21 \cdot 10^{-3}$
2 or 3 models	$2.03 \cdot 10^{-3}$	$31.96 \cdot 10^{-3}$
2, 3 or 4 models	$2.36 \cdot 10^{-3}$	$44.46 \cdot 10^{-3}$
3 or 4 models	$1.98 \cdot 10^{-3}$	$42.98 \cdot 10^{-3}$

Source: own elaboration.

Table 7 reports Jaccard-based metrics for overlapping references and keywords. The obtained results are broadly consistent with previous findings. The 1-Model group has the lowest joint reference overlap ($0.43 \cdot 10^{-3}$) but a moderate shared-keywords score ($35.25 \cdot 10^{-3}$). This suggests that publications chosen by only one model do not heavily cite the same sources but present some thematic commonalities. The 2-Models group, with a joint-references score of $1.01 \cdot 10^{-3}$, shows the highest shared-keywords score among all subsets ($54.93 \cdot 10^{-3}$). That indicates the articles converge strongly around key topical terms

despite relatively low reference overlap.

The 3-Models group exhibits a higher reference overlap ($1.79 \cdot 10^{-3}$) but a significantly lower shared-keywords score ($20.83 \cdot 10^{-3}$), which implies that while these publications share more bibliographic sources, they employ more varied terminologies. The 4-Models group presents the highest reference overlap ($2.91 \cdot 10^{-3}$) and a relatively substantial keyword overlap ($44.21 \cdot 10^{-3}$).

Like the average numbers of common keywords and references, the 4-Model group shows the most excellent bibliographic coherence. The 2-model shows higher thematic convergence in terms of keywords.

A key comparison lies between the articles selected by only one model and those selected by all four models. In contrast, intermediary groups (selected by 2 or 3 models, 2, 3, or 4 models, and 3 or 4 models) offer additional insights into consistency and variability in model agreement.

The average number of common references per pair can visually present the advantage of the 4-model group over others. The graph is presented in Fig. 14.

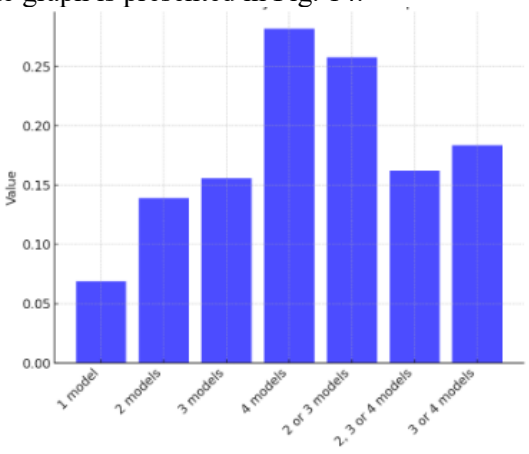


Figure 14. Arithmetic Mean – Common Reference per Pair
Source: own elaboration using the Python library matplotlib.pyplot.

As shown in Fig. 14, the 1-model category exhibits the lowest value. That indicates that articles selected by only one model share fewer references than others. The 4-model group presents the highest value, suggesting that articles consistently chosen by all four models have stronger interconnections regarding shared references. The 2 or 3 models and 2, 3, or 4 models groups exhibit moderate values.

An analogous analysis can be performed for an averaged number of common keywords (Fig. 15).

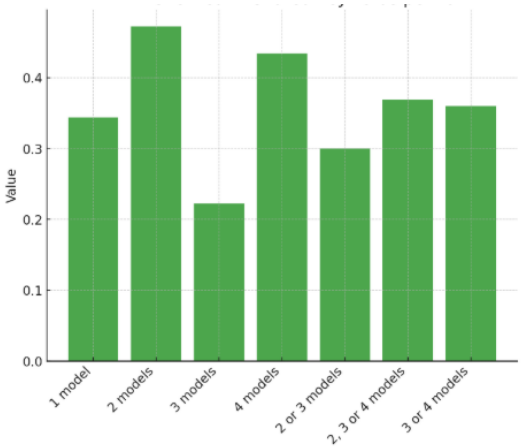


Figure 15. Arithmetic Mean – Shared Keywords per pair
Source: own elaboration using the Python library matplotlib.pyplot.

As shown in Fig. 15, articles in the 1-model group have a moderate proportion of shared keywords. The value is significantly lower than in the case of papers selected by two models and four model groups.

The results obtained for the 4-model group are again the highest, confirming that articles consistently selected by all models tend to share more thematic keywords. The 3-models group shows a noticeable drop compared to the papers selected by the two models. In general, the trend in this category (Fig. 15) is much weaker than in the case of Fig. 14; results obtained across groups are much more difficult to predict in this case.

The averaged Jaccard Indexes for references and keywords are presented in Fig. 16 and Fig. 17.

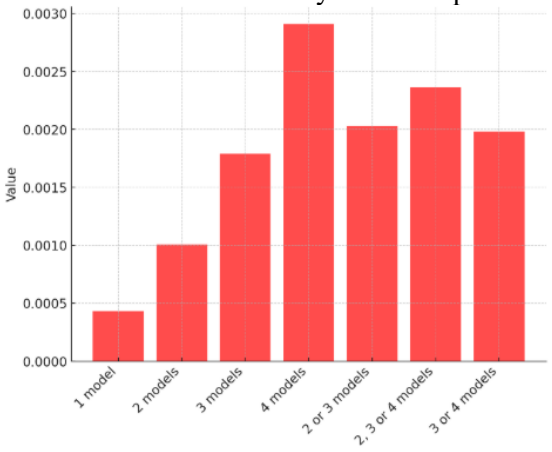


Figure 16. Jaccard Index – Common References per pair
Source: own elaboration using the Python library matplotlib.pyplot.

The results presented in Fig. 16 are analogous to those presented in Fig. 14. However, the differences between groups are even clearer and more linear.

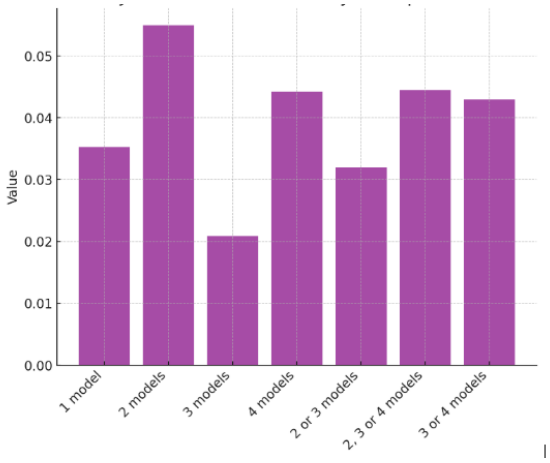


Figure 17. Jaccard Index – Shared Keywords per pair
Source: own elaboration using the Python library matplotlib.pyplot.

The results presented in Fig. 17 are analogous to those in Fig. 15.

Data indicates that articles selected by all four models form the most coherent group in terms of references. In contrast, the single-model group shows the weakest results. Less clear relations are observed in the case of keywords. No significant differences are observed between the averaged Jaccard Index and the average number of common references/keywords.

4. CONCLUSIONS

The AI-based embedding technique finds papers that fit the reader's needs well. It is much more effective in precise searching than classic keyword searching. Moreover, unlike classic methods, it can be used even if authors use different terminology.

The research indicates that using a multi-model approach, combining various word embedding

models (WEMs) can significantly improve the process of selecting publications for systematic reviews. Bibliometric analyses based on various indicators confirm the effectiveness of this approach. Papers selected by four models have significantly more shared references than papers selected by fewer WEMs, especially those selected just by one model. However, experiments showed that this effect is weaker and less straightforward in the case of keywords.

The developed AI-based method is a step toward AI-powered automated systematic literature reviews. The technique reduces the risk of bias almost to zero and improves the effectiveness of using bibliometric metrics, making the process more reliable and accurate. However, the main point of the method is to mimic the actions of many researchers, offering the same advantages as parallel conducted SLR, particularly analysis from many different points of view. The presented pilot study is promising and suggests that its method performs the given task well. However, simultaneous work in SLR brings not only benefits but also disadvantages. Working in a team that is too large may be ineffective. Moreover, not all people are fit for research work. Conducted experiments show the same problems. To achieve optimal results, the number of used WEMs cannot be too large; initial tests have narrowed it down to four. Moreover, not all WEMs fit all problems well. Therefore, preliminary selection may be necessary.

In this work, only pilot studies are presented. Much deeper research is needed. However, the point of the paper is to present the present methodology, allowing the reader to understand it better through a case study and showing initial results together with interpretation. This can be useful both for researchers who need to establish the state of the art in science before empirical research and for entrepreneurs who would like to identify the latest information with a view to making a decision or introducing a new management method. The article is the second in a larger series on the use of AI in literature reviews, and the ideas will be developed in the future.

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APPLICATION OF ARTIFICIAL INTELLIGENCE IN BUSINESS PROCESS OPTIMISATION ON THE EXAMPLE OF INTELLIGENT ENERGY PRICE FORECASTING FOR PHOTOVOLTAIC FARMS

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ABSTRACT

Purpose: *The purpose of this paper is to evaluate the application of advanced artificial intelligence methods in the forecasting of photovoltaic farm electricity prices and to analyse their impact on the optimisation of business decisions and operational processes.*

Need for the study: *With the increasing volatility of energy markets due to unstable weather conditions, dynamic regulatory changes and financial risks associated with long-term PPAs, traditional forecasting methods are proving insufficient. It is necessary to develop state-of-the-art solutions that, through the integration of Big Data and advanced machine learning algorithms, enable accurate energy price forecasting.*

Methodology: *The study is based on a two-stage analysis: a literature review and a conceptual analysis, leading to the formulation of the concept of an intelligent energy price forecasting system. This system integrates data from multiple sources, which are subjected to processes of cleaning, transformation and feature extraction. The resulting hybrid predictive model, based on the LSTM-Transformer architecture, is enriched with adaptation mechanisms that enable continuous updating of the models in the context of optimising business and operational decisions. The approach is validated through an empirical case study on a 1 MW PV farm, using historical data to train the model and evaluate its performance.*

Findings: *The literature analysis and the conceptual analysis conducted show that the implementation of a system based on a hybrid AI model allows for a reduction in energy price forecast errors compared to traditional methods. Adaptive mechanisms allow the model to adapt to changing market conditions on an ongoing basis, resulting in higher forecast accuracy and more effective financial risk management. Furthermore, the case study results confirmed improvements in forecast accuracy, which in turn enhances operational decision-making for the PV farm.*

Practical Implications: *The proposed AI system enables PV farm operators to make data-driven decisions based on reliable data, resulting in optimised sales strategies, energy storage management and stabilised financial flows, thus providing a competitive advantage in the renewables market.*

Keywords: artificial intelligence, machine learning algorithms, management systems, decision support systems, decision optimisation, energy pricing, photovoltaic farms, renewable energy sources, energy price forecasting, economic sustainability

JEL classifications: C53, D81, Q41, Q42, Q48, A1

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1. INTRODUCTION

In an era of rapid technology development and the growing need for efficient management of energy resources, renewable energy systems, and photovoltaic (PV) farms in particular, are becoming a strategic component of the energy transition. The deployment of renewable energy solutions enables the creation of sustainable electricity systems that provide a stable energy supply despite changing weather conditions and market fluctuations (Kanase Patil et al., 2020). However, the efficient operation of PV farms requires not only accurate forecasting of energy production, but also dynamic management of energy prices, which has a direct impact on business decision-making. Traditional mathematical models often cannot cope with the increasing complexity of energy markets, so artificial intelligence (AI) algorithms are increasingly being used for advanced data analysis, system parameter optimisation and energy price forecasting (Lokhande et al., 2022). The use of AI algorithms, such as neural networks, evolutionary algorithms and hybrid deep learning models, allows for accurate forecasting of energy production and market prices, enabling companies to make more accurate operational and business decisions (Kanase-Patil et al., 2020). As a result, PV farm operators can dynamically adjust energy sales strategies, minimising financial risk and increasing operational efficiency of the systems.

In addition, recent research indicates that the integration of hybrid models, combining deep learning with evolutionary algorithms, enables even more accurate energy price forecasting, which is crucial in rapidly changing market conditions (Zhang et al., 2020). The integration of meteorological data with neural network-based predictive models allows for the ongoing adjustment of management strategies, resulting in optimised business decisions (Hou et al., 2024). Furthermore, hybrid optimisation algorithms support decision-making processes by minimising the risk of prediction errors and improving the operational efficiency of energy systems (Krishna Prakash & Singh, 2023).

The aim of this paper is to provide a theoretical analysis of the challenges of forecasting energy prices on PV farms and to assess the role of intelligent management systems based on artificial intelligence technologies in optimising business decisions and operational processes. Forecasting energy prices in the context of PV farms is an extremely complex task due to dynamic changes in weather conditions, fluctuations in demand and market instability. Traditional statistical methods, based mainly on the analysis of historical data, are not able to fully take into account the multidimensionality and complexity of factors influencing energy prices, leading to the generation of forecasts with a high degree of uncertainty. Therefore, it becomes necessary to apply advanced technologies such as machine learning algorithms and neural networks, which, thanks to their adaptability and ability to analyse large data sets, enable the accuracy of forecasts to be improved. The article undertakes a critical analysis of the limitations of traditional forecasting methods and presents a theoretical conceptual framework for intelligent energy price forecasting systems. The proposed model integrates a variety of analytical techniques, including both hybrid approaches based on LSTM-Transformer architectures and adaptive mechanisms to dynamically adjust models to changing operational conditions. This theoretical framework is further validated by a single-case study, which demonstrates the potential implications of AI for optimizing business strategies and operational workflows in a real-world PV-farm setting. The solutions presented have important practical implications – enabling the optimisation of decision-making processes, reduction of operational risks and increased profitability of PV farms. In an era of increasing competitiveness in the renewable energy sector, the implementation of intelligent forecasting systems is becoming a key element in building competitive advantage, providing operators with tools to make decisions based on reliable and up-to-date data.

2. LITERATURE REVIEW

Forecasting electricity prices for PV farms is currently a significant challenge due to increasing market volatility and a number of external factors affecting price levels. The high penetration of renewables in the energy mix leads to increased uncertainty and price volatility, making it difficult to accurately predict future revenues from PV farms (Uniejewski & Ziel, 2025), (Poggi, Di Persio, & Ehrhardt, 2023). The following is an analysis of the scientific literature on key aspects of this issue, including the impact of price volatility and external factors, the risks of long-term PPAs, and the need for improved forecasting methods.

Electricity prices on wholesale markets are characterised by high volatility, which in the case of PV farms is strongly linked to weather factors and market and regulatory conditions. Solar generation depends on weather conditions (insolation, cloud cover), which translates into PV power supply and consequently the spot market price level. Research indicates that the volatility of renewable generation (such as solar or wind) can lead to higher price fluctuations and system balance challenges (Uniejewski & Ziel, 2025). In addition, prices are influenced by macroeconomic and political factors - e.g. increased demand after a pandemic, commodity crises or political decisions. Poggi et al. emphasise that energy prices are influenced by economic activity, political changes, weather conditions and the dynamics of related markets (Poggi, Di Persio, & Ehrhardt, 2023). Also, regulatory interventions, such as the introduction of price caps or changes to the RES support scheme, can significantly alter price formation mechanisms. The complexity of these interdependencies makes price forecasts subject to considerable uncertainty, especially in systems with increasing solar PV.

The regulatory environment and political decisions have a strong influence on energy price formation mechanisms. The rules governing the energy market - such as the market structure (e.g. the existence of a capacity market, RES support mechanisms), the level of price regulation, taxes and subsidies – set the framework within which supply and demand mechanisms operate. Regulatory changes can therefore significantly alter the boundary conditions for price forecasts. For example, the introduction or removal of government subsidies for either energy producers or consumers can change the effective cost of generation or the price paid by consumers, which in turn alters market behaviour (Kojima et al., 2016). In countries where the government keeps tariffs artificially low through subsidies (often at the expense of not compensating state-owned energy companies for generation costs), market prices do not fully reflect production costs (Kojima et al., 2016). Forecasting under such conditions requires tracking government policies and possible adjustments to these support mechanisms.

Another example of the impact of policies on energy prices is climate and environmental regulation. The introduction of emissions trading schemes (such as the EU ETS in Europe) has imposed the cost of CO_2 allowances on power plants, which has gradually raised wholesale energy prices, especially from conventional sources. When policies tighten emission standards or reduce the supply of free allowances, the cost of producing energy from coal or gas rises – and forecasting models need to take these trends into account. As mentioned, in the EU, allowance prices have risen sharply, doubling in the short term, significantly affecting energy price levels (Kojima et al., 2016). Also, energy policy goals, e.g. energy transition (decarbonisation) strategies, indirectly influence the market: announcements of coal plant shutdowns, the development of nuclear power or accelerated investment in RES give signals on how the future supply and cost of energy may evolve. Long-term price forecasts must therefore take into account policy scenarios, such as the implementation of RES share targets, the introduction of a carbon tax, changes in market regulation (e.g. balancing market reforms) (Baird, 2024).

Long-term power purchase agreements (PPAs) are commonly used by PV farm investors to ensure stable revenues, but they come with a number of risks. A key concern is price risk - over the long horizon, market prices may be lower than those agreed in the contract, leading to consumers paying more and producers losing potential profits. In addition, the volatility of RES generation, due to weather variability, results in increased balancing costs and cannibalisation phenomena when oversupply lowers market prices. Regulatory and contractual risks are also important – government interventions, such as temporary price caps, and an increase in the likelihood of parties defaulting on their contracts, further complicate PPA negotiations. Price volatility in the futures market, resulting from backwardation, leads producers to prefer shorter contracts or hedging strategies to long-term contracts. Despite these challenges, PPAs remain an attractive hedging tool, provided they are supported by careful risk analysis and the use of appropriate protection mechanisms (Kapral, Soetaert, & Castro, 2024).

Technological advances and changes in energy generation and consumption patterns introduce dynamic modifications to the market, making price forecasting difficult. The growth of renewables such as solar and wind power is making energy supply highly weather-dependent, resulting in rapid fluctuations - prices fall during periods of oversupply and rise sharply when production declines. Forecasting models must therefore take into account the effect of the so-called ‘duck curve’, illustrating the oversupply of solar at midday and the shortage of capacity during the evening peak (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2017; Nowotarski & Veron, 2018).

Additionally, although the development of energy storage technologies and demand response systems may contribute to market stabilisation in the future, their current impact remains limited.

Changes in demand patterns due to the electrification of transport and increased efficiency of domestic appliances modify the energy consumption profile, which particularly affects prices during night periods (Baird, 2024). Scenario analyses, based on indicators such as the growth rate of electric vehicles and smart home penetration, are a key element in forecasting medium- and long-term price trends. An important group of factors affecting energy price forecasts are sudden, unpredictable external events, known as market shocks. These events, such as geopolitical crises, natural disasters or sudden economic downturns, go beyond typical market volatility and can quickly change supply and demand relationships, causing prices to deviate significantly from historical trends. An example is the armed conflict in Ukraine in 2022, which caused a disruption in energy commodity trade, resulting in unprecedented increases in gas and electricity prices in Europe. As a result of such shocks, forecasting models based on pre-event data often generate erroneous results, highlighting the difficulty of incorporating extreme, rare events into medium- and long-term forecasts (Baird, 2024).

In view of the described unpredictability of prices and market risks, the literature highlights the need to improve energy price forecasting methods for PV farms. Traditional forecasting models, based on historical data and simple statistical assumptions, are increasingly failing in today's highly volatile market (Uniejewski & Ziel, 2025). Hong et al. previously noted that the accuracy of energy price forecasts is limited by the occurrence of abnormal events and rapid market changes, necessitating continuous model refinement. More recent studies confirm that including more inputs (e.g. demand forecasts, RES production, weather) and the uncertainty of these variables can significantly improve the accuracy of price forecasts (Hong et al., 2020). Uniejewski and Ziel showed that integrating probabilistic forecasts of solar and wind generation (rather than just point values) can reduce price forecast error by up to several per cent compared to the traditional approach (Uniejewski & Ziel, 2025). Importantly, more accurate forecasts translate directly into reduced operational and financial risks for PV farms. Better prediction of production and prices enables farm operators to optimally plan energy sales in day-ahead and intra-day markets, reducing costly schedule deviations. It has been estimated that forecasting errors can cause significant revenue losses – Karimi-Arpanahi and colleagues estimated that a 100 MW PV farm can lose up to about 9% of potential annual revenue precisely because of generation unpredictability (Karimi-Arpanahi, Pourmousavi, & Mahdavi, 2023). This is due to the need to buy back the missing energy at high prices or to miss sales opportunities during peak periods.

3. METHODOLOGY

The issue of energy price forecasting for photovoltaic (PV) farms is complex and interdisciplinary – combining elements of economics, energy and management including advanced data analysis methods. Knowledge in this area is developing very dynamically and is sometimes dispersed between different disciplines, making it difficult to keep up to date with the latest developments and to assess the state of the art holistically (Snyder, 2019). Under such conditions, the use of a literature review as the main research method is fully justified. A literature review allows the collection and systematisation of existing knowledge, providing a cross-sectional view of existing research findings and approaches used. This is particularly important for identifying key concepts, trends and possible research gaps in energy price forecasting methods. Furthermore, adopting a formal, rigorous review methodology – rather than an ad hoc approach - increases the quality and credibility of the conclusions obtained (Snyder, 2019).

In addition, in order to provide a theoretical conceptual framework for an intelligent energy price forecasting system, the literature review will be complemented by a conceptual analysis of the collected material. Conceptual analysis is a research approach that involves the precise definition and clarification of key concepts and their interrelationships on theoretical grounds (Furner, 2004). This technique treats concepts as classes of objects or phenomena and indicates the conditions under which a phenomenon can be classified into a given concept. The purpose of applying conceptual analysis in the present context is to better understand how particular concepts related to energy price forecasting are used and defined in the literature (Furner, 2004). Based on this combined framework, a single-case study was undertaken to demonstrate the potential implications of artificial-intelligence methods in optimizing operational workflows and guiding business-strategy decisions. Case study research is widely endorsed as a valid method for examining contemporary phenomena within their real-world context – especially in applied settings where the phenomenon and its context are deeply intertwined. This makes it an appropriate

strategy for studying operational applications of AI in businesses, where technology and organizational context cannot be meaningfully separated (Yin, 2018).

It is worth emphasising that the research strategy adopted (i.e. a combination of literature review and conceptual analysis) is grounded in scientific best practice. In rapidly evolving research areas, the literature review is a recognised method for keeping up with the state of the art and evaluating the collective evidence (Snyder, 2019).

It should be noted that the literature review methodology has several limitations that need to be taken into account when interpreting the results. Firstly, the temporal scope only includes publications available up to 2024, which means that the most recent research may not be included, especially in rapidly developing areas such as AI methods and the energy market. Secondly, publication bias may result in an overestimation of the effectiveness of methods, as papers with positive results are published more often, which may distort the overall picture of achievements. In addition, the heterogeneity of studies, due to differences in assumptions, models, time horizons and error measures, makes direct comparisons of results between studies difficult and requires some simplification when making generalised conclusions.

3.1. Methodological Framework: AI-Based Energy Price Forecasting Models

To meet the challenges of energy price forecasting, researchers are intensively developing advanced artificial intelligence algorithms for energy price forecasting. The trend in the literature in recent years has been to move away from simple regression models towards machine learning and deep learning methods. Neural networks (including deep recurrent LSTMs, GRUs and convolutional CNNs) can capture non-linear relationships between multiple variables (e.g. PV production, demand, weather) and thus often outperform traditional statistical models in accuracy. Chatterjee et al. compared different deep grid architectures (LSTMs, CNNs, CNN-LSTM hybrids) for daily price forecasts and showed significant improvements in accuracy compared to classical methods (Chatterjee et al., 2023). Similarly, other works propose hybrid models that combine signal processing techniques (wavelet transform, feature decomposition) with neural networks to extract hidden temporal patterns. For example, a sequential LSTM model supported by signal decomposition can better represent price spikes than a single network without such preprocessing (Laitsos et al., 2024).

In addition to neural networks, other machine learning algorithms such as vector machines (SVMs), decision trees or ensemble learning methods have been successfully used. The combination of multiple methods in the form of ensembles or model committees has been shown to produce more stable and accurate predictions than single models (Zhou et al., 2019), (Shi et al., 2021). Laitsos et al. (2024) presented a model combining a CNN, a GRU and an attention mechanism that achieved an average MAPE error of ~6.3%, outperforming the accuracy of classical neural models not using an attention mechanism (Laitsos et al., 2024).

In contrast, other studies explore probabilistic forecasting using Bayesian methods and generative networks, providing confidence intervals for prices. This approach helps market participants to assess not only the most likely price scenario, but also the risk of deviation from this forecast, which is particularly important when planning PV farm energy sales strategies.

Three main approaches using AI for energy price forecasting are presented below: machine learning models, neural networks and optimisation algorithms. Their application to the RES market (especially in the context of photovoltaic farms) and the concept of intelligent adaptive predictive systems are also discussed.

Machine learning (ML) covers a wide range of statistical and algorithmic methods that learn relationships from data. Among others, regression models, decision trees (e.g. random forests) or gradient boosting-style ensemble models (Future Bridge, 2024) are successfully used in energy price forecasting. Their task is to look for patterns between variables affecting the price - e.g. energy demand, supply from RES, fuel prices or weather conditions - and predict future price fluctuations on this basis. ML models are able to take into account multiple features (feature vectors) simultaneously and thus capture non-linear relationships better than traditional methods. For example, machine learning algorithms can analyse correlations between various market factors and automatically adapt their models to changing market conditions, which is crucial in a volatile energy market (Pragmile, 2024). This means that when relationships change (e.g. the introduction of new subsidies, changes in weather or consumer behaviour), the ML model can be re- learned on new data or adjusted to still accurately reflect the current

situation. As a result, machine learning techniques provide greater flexibility and accuracy in energy price forecasts compared to the rigid statistical models of the past.

Artificial neural networks (ANNs) are a special class of machine learning models inspired by the structure of the human brain. They consist of multiple interconnected layers of neurons (input, hidden and output), which allows them to model highly complex non-linear relationships between data (Future Bridge, 2024). Deep neural networks, including Recurrent Neural Networks (RNN) architectures and their variations such as Long Short-Term Memory (LSTM), are increasingly used in energy price forecasting. These models are suited to time series analysis - they can remember relevant information from the past and thus capture temporal relationships in price data. Neural networks excel at detecting subtle patterns that are difficult to spot with traditional statistical methods (Pragmile, 2024). For example, they can forecast energy prices based on predicted RES generation (e.g. solar insolation and PV farm production) or predict the impact of weather conditions on this generation - allowing operators to better plan system operation (Pragmile, 2024). Compared to simpler models, deep grids are able to analyse huge datasets from multiple sources (e.g. price history, weather forecasts, demand, sensor data on the grid) and learn from them representations of phenomena affecting price. As a result, they often achieve higher forecast accuracy. The disadvantage can be a 'black box' - the difficulty of interpreting internal weights - but in the context of energy price prediction accuracy, the advantage of neural networks is well documented (Pikus & Wąs, 2024).

The third group of approaches are optimisation algorithms, which support the forecasting process by finding solutions that minimise forecast error or maximise a specific profit. This category includes evolutionary algorithms (e.g. genetic algorithm, GA) and algorithms inspired by natural behaviour (e.g. particle swarm optimisation, PSO). These algorithms are sometimes combined with learning models - e.g. for tuning the hyperparameters of ML/ANN models. For example, the use of a genetic algorithm to optimise the parameters of an LSTM network can improve its price prediction ability through better selection of training settings (Future Bridge, 2024). Another application is the creation of hybrid models: optimisation algorithms can help divide the prediction task into simpler components (e.g. using signal decomposition) or dynamically select a combination of different prediction models to minimise error. For example, the literature describes the use of swarm optimisation (Grey Wolf Optimizer) to tune a random forest model, which significantly improved the accuracy of short-term energy market price forecasts (Zhang et al., 2022). Moreover, the optimisation algorithms are indirectly applicable - the results of the forecasting models can serve as inputs to decision-making algorithms that optimise the operation of the energy system (e.g. planning the use of energy storage, as discussed below). This machine learning and optimisation approach allows not only to predict prices, but also to make the best decisions in response to forecasts.

3.2. Research Instruments: Design of the Intelligent Energy Price Forecasting System

Given the widespread use of AI to optimise business decisions and operational processes in support of PV farm energy price forecasting, the following chapter proposes a system for energy price forecasting to support the optimisation of business decisions of photovoltaic (PV) farm operators, allowing decision makers to support and optimise business decisions and operational processes. The system consists of modules corresponding to the successive stages of information processing – from data acquisition, through data preparation and analysis using artificial intelligence, to adaptive model refinement, application of forecasts to operational decisions and presentation of results to users. Figure 1 shows the designed system, which integrates a variety of approaches and innovative solutions to ensure high forecast accuracy and flexibility in dynamic market conditions.

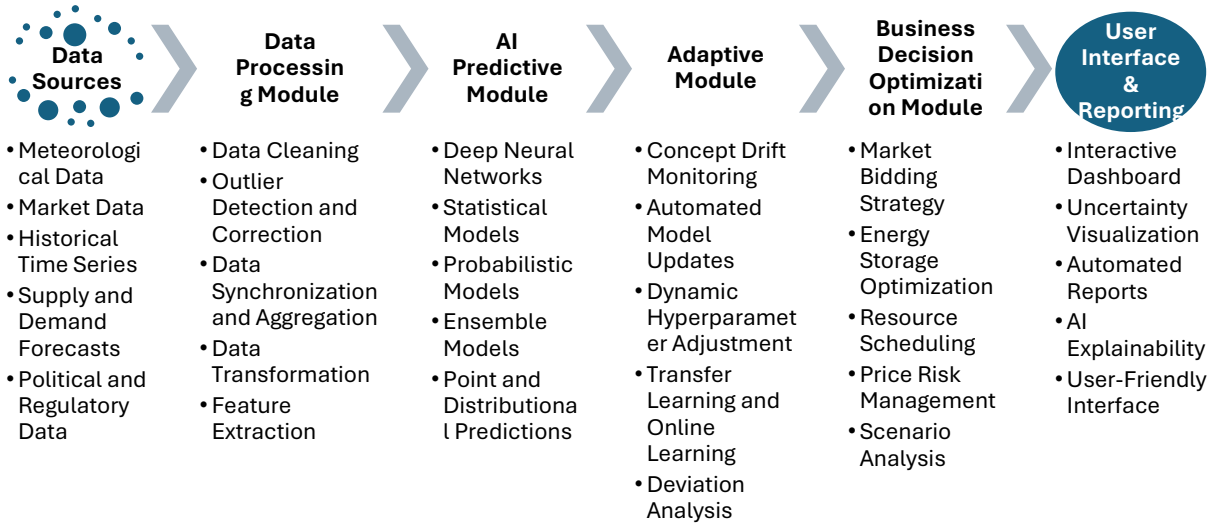


Figure 1. Intelligent energy price forecasting system for PV farms
Source: own elaboration.

Data sources

The energy price forecasting system is based on the integration of data from a wide variety of sources, capturing all the key factors that influence price formation. Among the data used is meteorological information such as sunshine, temperature and wind speed, which affect both renewable energy production and energy demand. Market data, including, among other things, wholesale prices, futures quotes and fuel prices, allow the impact of economic factors on energy prices to be assessed. Equally important are archived time series of prices, trading volumes, generation and past values of weather and macroeconomic variables, which provide a basis for identifying repeatable trends. In addition, supply and demand data – both current and forecast – allow for the identification of the system's ability to meet demand, which has a direct impact on price levels, especially when capacity reserves are insufficient. The inclusion of political and regulatory factors, such as regulators' decisions, legal changes or geopolitical events, on the other hand, allows to reflect the impact of unforeseen events on price dynamics (Singh & Mohanty, 2015; Poggi, Di Persio, & Ehrhardt, 2023). This rich set of data sources allows the forecasting model to learn the complex relationships between weather conditions, demand, fuel prices, and market events, resulting in more objective forecasts based on a broad context.

Data processing module

In the process of preparing data for energy price forecasting, it is crucial to carry out a comprehensive ETL (extract- transform-load) step, which ensures that the input data to the AI modules is reliable, consistent and properly formatted. At the outset, the raw data, extracted from many disparate sources, undergoes cleaning, which involves eliminating errors, gaps and duplicates. Missing observations are filled by imputation methods such as interpolation or moving average, and outliers, detected e.g. by the z-score method, are verified and, if necessary, corrected or removed so that they do not introduce disruptive noise into the model (Mancha Gonzales, Iftikhar, & López-Gonzales, 2024; Khalid et al., 2019). This is followed by data validation and aggregation, which involves synchronising information from different sources that may differ in measurement frequency and time lag. This creates a unified set of features where, for each time interval, demand data, PV and wind generation, reserve status, fuel prices, weather conditions and calendar information, among others, are recorded. The next step is feature transformation and extraction, where the data are normalised or standardised, allowing variables to be scaled to a uniform range and variances to be stabilised. In addition, seasonal components and long-term trends are removed through differentiation or filtering, bringing the time series closer to stationarity. This process results in advanced indicators such as moving averages or rates of change, which enhance the model's ability to detect hidden patterns. Taken as a whole, the implementation of these steps - cleaning, validation, aggregation, transformation and feature extraction - significantly

improves the quality of the data, which is key to the effectiveness of further analysis and forecasting steps using advanced machine learning algorithms.

Predictive AI module

The AI prediction module is at the heart of the energy price forecasting system, responsible for generating forecasts for a set time horizon using advanced artificial intelligence algorithms. Within this module, hybrid strategies for combining different machine learning techniques are used to improve forecast accuracy by synergistically exploiting the strengths of the different methods. On the one hand, deep neural networks such as LSTM, CNN and transformer architectures enable the model to capture complex, non-linear relationships in serial data. LSTM, with its built-in memory mechanism, can effectively model long-term dependencies and trends, which are essential for energy price forecasting, where current values are strongly correlated with historical patterns (Poggi, Di Persio, & Ehrhardt, 2023). CNNs, when used to analyse sequential data, automatically identify characteristic shapes and patterns in the price signal, and a weight- sharing mechanism promotes the generalisation of detected features. Recent solutions based on transformer architectures derived from the field of natural language processing enable parallel processing of entire data sequences, which significantly improves the accuracy of modelling both short-term fluctuations and long-term price cycles (Poggi, Di Persio, & Ehrhardt, 2023).

In addition to deep networks, the prediction module integrates traditional statistical and machine learning models such as ARIMA/SARIMA and GARCH models, which are particularly effective in capturing seasonal components and linear trends. When used in parallel as ensembles, these methods enable the use of different perspectives of data analysis, which allows the reduction of prediction error by combining the results obtained with linear and non-linear models (Poggi, Di Persio, & Ehrhardt, 2023; Lee et al., 2024).

Another important element of the prediction module is the use of probabilistic approaches that go beyond traditional point forecasts. These models generate forecasts in the form of complete distributions, representing confidence intervals, which enables accurate risk assessment and identification of potential price extremes. For example, the distributional forecasting technique, which uses neural networks that learn the price distribution, allows modelling not only the expected value, but also the higher moments of the distribution, which is crucial for managing risk in volatile market conditions (Marcjasz et al., 2023).

By integrating these advanced techniques – a hybrid combination of deep networks, traditional statistical models and probabilistic approaches – the AI prediction module processes the prepared input data and generates forecasts that have high accuracy and reliability. Such a system enables energy companies to make better operational decisions by offering comprehensive insights into possible market scenarios and providing reliable tools for risk management. As a result, the predictive module, through the use of the latest developments in artificial intelligence, provides the foundation for an effective energy price forecasting system, which translates into increased competitiveness and operational stability for companies operating in a dynamic energy market.

Adaptation module

The adaptation module is a key component of the forecasting system, enabling the models to continuously adapt to dynamically changing market conditions. Two main mechanisms are implemented within this module: data drift monitoring and automatic model updating. The first of these, concept drift detection, involves constant surveillance of incoming data, including comparison of actual values with forecasts, in order to detect signals that the statistical properties of the data are changing, which may result in a loss of accuracy of the model trained so far. The system uses advanced detection algorithms that analyse forecast residuals and statistical changes to quickly identify significant deviations, while minimising the risk of false alarms. The second mechanism, automatic model updating, allows the system to adapt through periodic re-learning or incremental learning, allowing hyperparameters and network structure to be dynamically adjusted without full retraining. More advanced solutions use online learning and transfer learning techniques that allow the model to adapt immediately to new trends and changes in the input data. Such continuous feedback, based on analysis of forecast errors and comparison with current observations, allows the system's learning loop to be closed, so that the model maintains high accuracy and validity even in highly changing energy

markets. As a result, the adaptive module provides flexibility and resilience to the system, enabling PV farm operators to benefit from forecasts that reflect the latest developments, such as current fuel prices, new regulations or weather changes, which is key to maintaining a competitive edge in a dynamic environment. (Xiang, Zi, Cong, & Wang, 2023)

Business decision optimisation module

The Business Decision Optimisation module is an integral layer of the system that transforms energy price forecasts into concrete operational actions, enabling efficient asset management and risk minimisation. On the basis of the forecasts generated by the prediction module, which take into account uncertainty expressed in terms of confidence intervals, the module develops bidding strategies, adjusting the amount of energy to be sold on the day-ahead market, the spot market or under long-term contracts. In situations where forecasts indicate an increase in prices, the system recommends selling larger volumes during peak periods and, when prices are low, using energy storage recharge opportunities to sell later at a higher price. In addition, the module enables the scheduling of maintenance work and the coordination of different energy sources within the portfolio, which allows production to be optimised even in a virtual power plant environment. Another important aspect is the use of scenario simulations, which, through what-if analysis, allow the resistance of adopted strategies to forecast deviations to be assessed and recommendations to hedge against price risk to be developed. The results of such analyses, supported by advanced algorithms, make it possible to precisely determine how much energy to offer at auction and how much to leave in storage, which translates into real savings and increased profitability. Such an integrated system, combining forecasting with decision optimisation, allows PV farm operators to make informed, data-driven decisions, respond to changing market conditions and effectively manage risk, a key element in achieving competitive advantage in a dynamic energy environment (Wu et al., 2024; Lee et al., 2024).

User interface and reporting

The user interface and reporting module is the final but key component of the system, allowing PV farm operators to interact with the system, monitor forecasts and receive recommendations and business reports. Through an intuitive dashboard, users have access to interactive charts showing the forecast price curve for the coming hours or days, complemented by visualisations of uncertainty ranges, allowing them to quickly understand trends and assess the reliability of forecasts. In addition, the module presents operational recommendations, such as optimising energy sales or managing storage, in the form of clear messages that enable specific actions to be taken. Reporting takes place both on an ongoing and periodic basis, generating comprehensive summaries of the effectiveness of forecasts and an analysis of savings achieved, which promotes continuous optimisation of operational strategies. A key aspect is also to ensure that the interface is user-friendly even for non-technical people – with responsive visualisations such as charts, icons and clear colours, decision-makers can easily interpret complex data and focus on key information, facilitating both individual and group decision-making. As a result, the module translates the advanced intelligence of the system into added value for the user, enabling effective analysis, communication of results and rapid response to market changes.

The energy price forecasting system presented in this study is characterised by a comprehensive integration of modules that together form an advanced platform for operational decision-making in a dynamic energy market. At the outset, the system collects data from a variety of sources, which are then subjected to rigorous processing – including data cleaning, validation, aggregation and transformation – to guarantee high quality input information. The prediction module, the heart of the system, uses a hybrid architecture that combines deep neural networks (such as LSTMs, CNNs and transformers) with traditional statistical methods to capture complex, non-linear relationships and account for variability in historical and current data. Probabilistic approaches are also used within this module, generating full distributions of forecasts to assess the uncertainty and risk associated with the predictions. Another key element is the decision-making module, which transforms price forecasts into specific operational strategies, such as sales optimisation, energy storage management or maintenance scheduling. The entire system is complemented by a user interface that offers intuitive visualisations and report generation, enabling decision-makers to make decisions quickly and efficiently. A system structured in this way, using approaches ranging from Big Data to advanced AI techniques to decision

optimisation, provides a robust tool to support the operations of energy companies, as evidenced by the results of a study (Wu et al., 2024).

3.3. Case Study: Application of the Forecasting System

Installation Description and Data

A ground-mounted photovoltaic farm with a 1 MW installed capacity, located in southern Poland, is analyzed. The installation comprises PV modules fixed at a constant tilt, producing approximately 1 100 – 1 300 MWh annually (peak in summer, lower in winter). Historical data from 2020 – 2024 were employed, including the PV production profile (measured power/energy in hourly intervals), corresponding meteorological measurements (irradiance, temperature, cloud cover), day-ahead electricity market prices (TGE), and calendar features capturing diurnal and seasonal cycles (hour, time of day, day of week, month, season). Incorporating multiple input variables allows the model to learn complex dependencies – this approach aligns with industry practice, where LSTM networks are trained on a suite of weather and generation variables.

Data Preprocessing

Raw data underwent cleansing: missing values were removed or imputed, and obvious anomalies (e.g., zero generation on a sunny day due to equipment failure) were corrected. Feature engineering then added seasonal indicators (e.g., week number; sine/cosine transforms of day-of-year) and lagged generation and price values to inform the model of short-term trends. All numeric features were normalized (min–max scaling), a standard practice that stabilizes LSTM training. The dataset was split chronologically into training (2020 – 2023) and validation/test (2024) sets, preventing look-ahead bias and reflecting real forecasting conditions.

Forecast Horizon

A 24-hour-ahead horizon was adopted, so the model predicts generation and prices one day in advance, as required by the day-ahead market. This horizon is critical for the operator's planning of SPOT market participation, network load management, and maintenance scheduling.

AI System Implementation

The case study implements an AI system to forecast PV generation and electricity prices using a hybrid LSTM – Transformer architecture. The model ingests past outputs (historical generation), meteorological inputs (irradiance, temperature) and historical price data to capture both temporal patterns and weather impacts on yield. A multi-layer LSTM processes recent observations and extracts hidden trend representations; these are then analyzed by a Transformer encoder with several self-attention blocks, enabling the model to dynamically weight salient features (e.g., morning cloud cover's effect on afternoon output or time-of-day price patterns). Encoder outputs are concatenated and passed through dense layers to produce 24 hourly forecasts of both farm power and price. This multivariate approach supports simultaneous supply-side and market condition forecasting, facilitating operational optimization. The model was implemented in Python with TensorFlow/Keras and trained on GPU hardware. Training minimized mean squared error (MSE) between predictions and actual values while monitoring mean absolute error (MAE) and mean absolute percentage error (MAPE). An early-stopping criterion halted training when validation loss ceased improving, and the model with lowest validation error was selected. Due to its implementation as a simplified case study no parallel ARIMA/SARIMA, GARCH, or CNN models were included – forecasting relies solely on the LSTM – Transformer hybrid. Future work might extend the system with ARIMA or GARCH ensembles (e.g., weighted forecast averaging) and incorporate probabilistic forecasting (Bayesian LSTM or distributional-forecasting networks) to generate confidence intervals alongside point estimates.

4. RESULTS

Within the case study framework, the AI model demonstrated the MAPE of approximately 5 % for daily PV generation forecasts – comparable to leading commercial benchmarks (EPRI reports of 5 – 5.4 % MAPE). Price forecasts attained MAPE of approximately 12 %, within the typical 5 – 14 %

range for day-ahead electricity markets. Given price volatility, this represents a significant improvement over persistence and simple regression baselines.

Projections for 2025 preserve strong seasonality – summer daily maxima near installed capacity on clear days and several-fold lower winter output. Total annual generation is forecast at ~1120 MWh under standard weather assumptions, matching historical performance. Price forecasts foresee continued volatility, including midday negative-price events in spring/summer (–5 to –123 PLN/MWh) on low-demand sunny days, especially on late-spring weekends. Average daily prices are expected between 200 – 300 PLN/MWh, peaking during morning and evening demand surges and dipping overnight and midday.

Based on the generated forecasts, a simulation of the PV farm's operation in 2025 was performed to evaluate three distinct operational strategies (see Table 1).

Table 1. Operational Strategy Simulation

Strategy	Description
SPOT-Only Sales	All generation offered on the day-ahead market. Moderate revenues but high risk from negative prices, which can lead to operator payments to the grid.
AI-Driven BESS Optimization	Utilization of the forecasting model to intelligently control an on-site battery energy storage system.
Fixed-Price PPA	Sale of energy at a predetermined rate under a long-term Power Purchase Agreement.

Source: own elaboration.

Spot-Only Sales ('Merchant' Strategy) involves the farm offering all generated energy on the day-ahead market at prevailing spot prices without any adjustment to its generation profile. The simulation revealed that, while moderate and high prices yield revenues close to market averages, this strategy carries significant risk during periods of energy oversupply. Negative prices pose a serious threat—under extreme conditions, the operator might have to pay for energy injection. The 2025 forecast likewise predicts intermittent negative-price episodes, making a purely spot-market approach potentially less profitable and more volatile in terms of revenue stability. Market evidence shows that merchant projects become less viable without safeguards against price swings.

AI-Driven BESS Optimization Strategy involves equipping the farm with a battery energy storage system (BESS) and using the AI forecasting model to govern its charging and discharging decisions. The model anticipates periods of oversupply and low prices, allowing energy to be stored when sales would be unprofitable and dispatched when prices rise. A simulation using an optimization algorithm (e.g., reinforcement learning) demonstrated a substantial improvement in the farm's financial performance, with annual revenue increasing by approximately 15–20 % compared to the spot-only strategy. This finding aligns with literature reporting up to 20 % profit gains from intelligent storage management. The model avoids selling during negative-price hours—storing excess energy instead—and releases it once prices exceed a predefined threshold. This strategy proved the most financially effective and also reduced revenue volatility, yielding a more even profit distribution and greater resilience to extreme price fluctuations.

Fixed-Price PPA Strategy involves selling all 2025 generation under a long-term Power Purchase Agreement at a predetermined price. This strategy eliminates market risk – revenues remain stable regardless of spot price volatility. The simulation assumed a contract price close to the average forecast market price. Consequently, annual revenue was slightly lower than under the AI+BESS strategy (foregoing high-price gains) but higher than in the pure spot scenario, which suffers during negative-price intervals. The PPA arrangement completely removes negative-price exposure – the operator receives a fixed payment per MWh, avoiding charges for generation. This benefit is underscored by the growing popularity of long-term contracts among PV investors facing market unpredictability. In practice, securing an attractive PPA requires identifying a reliable off-taker and accepting a somewhat lower margin in exchange for reduced risk.

Implementing the AI system enhanced decision-making at several levels. First, BESS management became forecast-driven: precise generation and price predictions allow pre-planning of charge/discharge cycles – storing energy overnight or during anticipated negative-price periods and

selling at evening peaks to maximize profit. Second, the model enables proactive curtailment or storage to avoid negative-price sales, protecting revenue and aiding local grid stability by reducing feed-in during critical periods. Third, continuous comparison of forecasted versus actual generation supports predictive maintenance: systematic under-performance under similar weather conditions signals potential faults (soiling, string failures), enabling timely service interventions before significant losses. Furthermore, knowledge of expected generation guides scheduling of inspections and maintenance on low-generation days, minimizing lost production. Overall, AI integration improved resource utilization (panels, battery, maintenance personnel) and illustrates the added value of advanced forecasting and decision-support algorithms in reducing uncertainty and enabling data-driven operations. As industry analyses note, AI applications in renewables – from forecasting to predictive maintenance – enhance operational efficiency and reliability in variable conditions (delfos.energy). In summary, the AI system delivered measurable economic benefits, reduced operational risk, and facilitated integration of the 1 MW PV asset into the dynamic energy market and grid, thereby increasing project competitiveness.

5. DISCUSSION

Photovoltaic (PV) farms operate in a highly volatile energy production and price environment, driven by weather conditions and a dynamic energy market. The use of artificial intelligence (AI) to forecast energy prices offers a promising solution to these challenges. Accurate AI-based forecasts enable PV farm operators to better plan and make business decisions in real time, resulting in more efficient use of the energy produced and improved profitability (World Economic Forum, 2024). In the context of limited data availability and variability of climatic conditions, it is important to discuss the scope of the model's generalization.

In the following, the key application areas of intelligent price forecasting systems - from production management, sales strategies and risk management to operational cost optimisation and integration with energy storage - will be discussed.

Energy production management

The variability of insolation makes PV energy production intermittent and difficult to control. Although insolation itself cannot be controlled, intelligent forecasting of both PV generation and energy prices can optimally manage the production schedule of PV farms. AI algorithms analysing meteorological data can predict solar production and future market prices with high accuracy (World Economic Forum, 2024). It is worthwhile to emphasize the need for validation of forecasts under varying local conditions and taking into account concept drift. This allows operators to plan operational activities in advance to maximise the use of the energy produced during periods of high prices and reduce losses during periods of low prices. For example, accurate production forecasts make it possible to predict energy surpluses and plan the use of loads or storage during peak generation hours, as well as estimate how much generation will be available for sale under given weather conditions (Rocha et al., 2024). AI thus enables more efficient use of the generated energy and optimisation of plant operating costs, resulting in better farm and grid performance (Rocha et al., 2024). In addition, smart systems can dynamically adapt the generation profile to market conditions, if the flexibility exists. In practice, with forecasts of very low or negative energy prices at certain times, PV farms may consider deliberate curtailment during these periods to avoid selling energy at a loss. However, such decisions require reliable price forecasts - the AI system is able to identify in advance the time intervals when prices will fall below zero and recommend temporarily shutting down some generation Feenstra, 2024). It is necessary to discuss the risks of over-reliance on forecasts and their impact on supply continuity. For example, European spot market conditions have seen an increasing incidence of negative prices during midday hours when there is ample supply from RES. Intelligent algorithms can issue a signal to reduce capacity during such a period, avoiding the costs associated with surrendering energy at a negative price (Feenstra, 2024). Importantly, this type of action should be seen as a last resort – the ultimate goal of price forecasting is to minimise the need to reduce production by better balancing supply and demand. However, the ability to schedule maintenance or technical outages during periods of predicted low prices (e.g. cloudy days with low demand) is also part of optimising the production schedule. AI makes it possible to postpone unavoidable outages to periods with minimal impact on revenue, so that the farm is fully ready at times of peak market prices. Managing energy production in PV farms becomes much more efficient with AI

forecasts. They facilitate generation planning in correlation with prices, ensuring efficient use of resources and optimisation of financial returns even when supply is variable (World Economic Forum, 2024). As a result, the farm can react proactively to changing market conditions, instead of acting reactively ex post.

Sales strategies and energy trading

Intelligent electricity price forecasting is a key support in the development of PV farm power sales strategies. This includes day-ahead and spot market participation, as well as the management of long-term Power Purchase Agreements (PPAs). Having reliable price forecasts for the following days and hours enables PV farm operators to make better decisions on the volume and price of energy offered in day-ahead market auctions, resulting in higher sales efficiency and revenue stability. Trading on the day-ahead market. Traditionally, many RES operators sold energy mainly on the spot market (balancing market), accepting the risk of low prices during periods of oversupply. With AI, however, a change in approach is possible - learning algorithms based on historical price and weather data can predict price profiles in the day-ahead market with a high degree of accuracy, allowing sales bids to be made in advance and a fixed sales price to be secured against adverse conditions (Vinyard, 2024). However, the long-term robustness of these predictions under evolving market regulations and atypical weather patterns warrants further investigation. According to industry analysis, using AI-based recommendations to participate in the day-ahead market can increase a PV project's revenue, as it enables it to hedge against low prices in real time (hedging), while not taking away the opportunity to benefit from potential price spikes (Vinyard, 2024). In other words, the farm, thanks to forecasting, can sell part of the energy in advance at a predetermined price (if oversupply and the threat of falling prices are announced) and sell the remaining part on the spot market when favourable short-term price increases occur. This hybrid approach minimises the risk of revenue loss during periods of price downturns, while at the same time exploiting market opportunities to maximise profits. The trade-off between forecasting accuracy and model complexity should be evaluated to understand the cost-benefit balance of deploying such systems. However, high forecast accuracy is a prerequisite for effectiveness - day-ahead trading becomes virtually impossible without accurate generation and price predictions, as incorrect forecasts can result in penalties for contract defaults or lost profits. AI systems simultaneously integrate forecasts of production (e.g. from weather models) and prices, providing comprehensive recommendations on the optimal sales plan for the next day-ahead. Future research should examine the resilience of automated bidding algorithms to extreme market volatility and data anomalies. As the McKinsey report notes, advanced data analytics in volatile conditions (e.g. the intraday market) can be the deciding factor in making a profit or incurring a loss - the information advantage through AI is key here (Vinyard, 2024). In addition, AI-based trading algorithms can automatically adjust bids and execute trades in a fraction of a second, increasing the speed and efficiency of energy trading and exploiting short-term price fluctuations better than is possible with traditional methods (Montel, 2024a). It remains to be discussed whether reliance on microsecond execution could amplify systemic risks through algorithmic feedback loops.

PPA Management

Many PV farm owners enter into long-term PPAs, selling energy directly to consumers at a fixed price. Intelligent energy price forecasts play an important role in the negotiation and management of such contracts. Firstly, by forecasting price trends in the wholesale market, the investor can better assess the profitability of the proposed rate in the PPA against future market prices. AI analyses huge datasets – historical prices, demand projections, regulatory scenarios - to help estimate whether a given guaranteed price will provide the expected return on investment over the life of the contract, or whether there is a risk of opportunity cost in the event of a sudden increase in market prices. However, the sensitivity of these estimates to abrupt regulatory changes or unanticipated market shocks merits further examination. Secondly, modern business models introduce flexible PPAs in which volumes or prices can be partially indexed to the market. In such cases, AI predictions are essential for deciding when it is more advantageous to deliver energy under a PPA and when to direct it to the spot market. With price and production prediction, a farm owner can, for example, decide to divert surplus (over the agreed PPA volume) to the day-ahead market if forecast prices are higher than the PPA rate, or conversely, increase the volume sold under the PPA when expected market prices are lower. AI also enables ongoing

monitoring of contract execution risks, such as the likelihood of defaulting on deliveries during periods of weaker generation. By integrating weather, satellite and market data, the forecasting system can warn the operator of impending periods of potential undersupply and suggest countermeasures (purchase of missing energy on the wholesale market in advance or activation of reserves) (Montel, 2024a).

It is worth noting that advanced data analytics and AI also improve PPA pricing and management by reducing risk and uncertainty. As studies show, the vast amounts of data generated by RES farms are worthless without proper analysis - AI transforms this data into actionable information, allowing both energy production and prices to be forecast with greater accuracy (Montel, 2024a). This enables farm owners to make informed decisions about future PPAs, choosing their length and price structure, and even renegotiating terms based on hard data rather than intuition. For example, analysis of weather and pricing patterns by machine learning can reveal periods of recurring shortages or surpluses (e.g. cyclical production 'bottoms' in winter and 'tops' in summer) and suggest contract mechanisms to mitigate their impact (such as volume flexibility clauses). In addition, AI supports PPA compliance - continuous monitoring of contract performance and anticipation of potential deviations helps avoid penalties and build a reputation as a reliable partner.

Intelligent forecasting systems significantly improve the trading of energy from PV farms. Both in the short term (day- ahead and intraday markets) and in the long term (PPAs), they provide the data needed to optimise sales strategies and maximise revenues with a controlled level of risk (Montel, 2024a), (Vinyard, 2024). Nonetheless, the comparative effectiveness of AI-driven PPA management versus traditional expert judgment under extreme market conditions remains an open question. The result is a more predictable and stable PV farm business model.

Financial risk management

Entering the energy market involves significant financial risks for PV farm operators, mainly due to high energy price volatility and regulatory uncertainty. Artificial intelligence, through advanced forecasting and data analysis, has become a valuable tool to identify, quantify and mitigate these risks.

Electricity prices on wholesale markets are subject to constant fluctuations depending on weather, demand, availability of other sources (e.g. failures of conventional power plants) or geopolitical factors. For RES generators, this means that revenues are unpredictable – periods of very low prices (or even negative prices) can significantly reduce the profitability of a PV farm. The use of AI reduces this uncertainty by providing more accurate predictions of price trends and market extremes, which in turn allows for pre-emptive hedging actions. For example, with a reliable prediction of a price drop in the coming weeks, a company can enter into forward/futures transactions earlier or increase sales volumes in fixed- price contracts to minimise the impact of a price drop on revenues. AI therefore supports the implementation of hedging strategies - by improving the accuracy and timeliness of price forecasts, it facilitates decisions on when and to what extent to use derivatives (futures, options, swap agreements) to stabilise farm cash flows. The literature shows that advanced analytics and AI improve the effectiveness of hedging strategies, increasing the relevance and efficiency of energy price hedging (Montel, 2024a). Figuratively speaking, AI gives visibility into future volatility – and the lack of such visibility makes volatility particularly threatening to corporate finances (Vinyard, 2024). With better insight into potential price fluctuations (volatility), PV farm management can adjust the financial and operational plan, e.g. maintain cash reserves for periods of expected downturn or, conversely, plan for investment expansion during periods of expected high prices. The implications of delayed data updates on operational decisions should also be critically assessed.

The energy sector is subject to constant regulatory changes (e.g. reforms of RES support schemes, introduction of marginal prices, capacity charges or emission regulation). Such changes can indirectly affect the market price level and the business model of a PV farm. Intelligent forecasting systems can support ‘what-if’ scenario analysis in the context of regulation – for example, simulating the impact of announced regulations on future energy prices and project profitability. In addition, AI facilitates the tracking of political and economic trends and their correlation with the energy market, allowing companies to more quickly adjust trading and hedging strategies in response to new regulations. While predicting policy decisions alone remains difficult, the system can adjust forecasting models on the fly whenever new data becomes available (e.g. the announcement of a change in the CO_2 levy rate or the introduction of price caps) – as a result, price forecasts take into account the most recent regulatory environment, giving managers a better basis for decisions. Moreover, some AI-based platforms

emphasise transparency regulatory – they provide users with information about the regulatory assumptions made in the forecasts, which increases confidence in the models and allows for an assessment of potential risks (e.g. how much performance depends on maintaining a given tax break). According to vendors of such solutions, modern AI tools can improve transparency and understanding of the impact of the regulatory environment on forecast outcomes, enabling more informed management of compliance and market risks (Gupta, 2024). User comprehension of embedded regulatory assumptions and their implications should be empirically studied.

Integration with energy storage

Combining photovoltaic farms with energy storage (e.g. lithium-ion batteries) opens up new opportunities for increased profitability and stability of supply, but fully exploiting the potential of such integration requires intelligent, forecast - based control. AI systems forecasting energy prices play a key role in decision-making: when to store energy and when to release it to the grid. The aim, of course, is to buy (or store one's own energy) cheaply and sell expensively, which, in a competitive market, can significantly increase a PV farm's revenues.

In practice, there are often periods of oversupply of solar energy during the day (e.g. the midday hours of a sunny day), when prices in the market fall, and periods of scarcity (the evening peak of demand, after sunset), when prices rise. An intelligent price forecasting system can identify these periods and their expected prices in advance, so that energy storage can be managed in a way that maximises price arbitrage. This means that when the AI predicts low prices (or even negative prices) in the coming hours, the farm controller switches the system into storage charging mode - the energy produced by the panels is then not sold on the market immediately, but stored in batteries. Then, when forecasts indicate the arrival of high-priced hours (e.g. late afternoon, when the PV is no longer generating and grid demand is high), the system automatically orders the storage to be discharged and the stored energy to be sold. This gives the PV farm higher revenues for the same energy, compared to a scenario without storage, where it would have to sell everything immediately after generation at spot prices (World Economic Forum, 2024). AI can also take into account the technical limitations of the storage (capacity, cycle efficiency, degradation) and optimise its use on this basis – e.g. do not overcharge the battery if the price benefit is small compared to the lifecycle consumption of the battery. Questions remain on how forecast errors propagate through storage dispatch decisions and impact overall profitability.

Integrating AI with a storage system makes it possible to implement fully automated, dynamic energy trading over multiple time horizons. This is described in the literature as AI-enabled trading with storage – the algorithm continuously tracks price changes in intraday markets and signals from the grid, making near-real-time decisions to move energy (World Economic Forum, 2024). The suitability of such high-frequency dispatch in terms of regulatory compliance, market participation rules, and grid service obligations should be critically assessed. This ability to react on a scale of minutes or seconds is crucial, especially in fast-moving local markets or when participating in regulatory services. For example, if a sudden price peak occurs during the day (e.g. due to the failure of a large conventional power plant), the smart system may decide to liquidate some energy from storage immediately, even if the base plan was to sell later - to capture this short-term opportunity. Conversely, in the event of a sudden price collapse (e.g. due to an unexpected increase in wind), the system can pause the current sale and divert energy to storage or leave it for later use. Such flexible, real-time management using AI increases the use of stored energy and maximises profits, while helping to balance supply and demand in the energy system (World Economic Forum, 2024). Indeed, PV farms with AI-controlled storage can act as active participants in the market, providing energy when it is most needed and valuable, and holding back when the market is in surplus – benefiting both themselves and grid stability. However, the broader impact of aggregated AI-driven storage dispatch on system-wide volatility and market dynamics remains an open question.

6. CONCLUSION

Real-world applications of intelligent energy price forecasting systems for photovoltaic farms clearly demonstrate that the implementation of advanced AI technologies brings multidimensional benefits, both operationally, financially and strategically. Accurate price and production forecasts enable operators to make data-driven decisions to dynamically optimise sales strategies by selecting the most

favourable markets and sales moments, negotiating better contract terms and effectively hedging financial risks. By integrating the forecasting system with the management of resources, both generated and stored, efficient use of energy is possible, which contributes to the optimisation of network supply, load reduction during peak periods and the minimisation of operational losses.

In addition, the use of advanced artificial intelligence algorithms, including hybrid models combining deep neural networks with traditional statistical methods, makes it possible to capture the complex, non-linear relationships found in historical and current data. Using techniques such as LSTMs, CNNs and transforms, these models can identify subtle patterns and predict future energy price fluctuations, which is particularly important in the volatile environment of energy markets. As a result, these systems provide operators with the tools to analyse trends quickly and accurately, helping to stabilise cash flows and protect operating margins.

As demonstrated in the case study, the deployment of AI-driven forecasting yielded marked improvements in forecast accuracy. This enhanced precision in predicting solar output, in turn, led to significant financial gains through AI-optimized energy trading and resource management strategies. Furthermore, intelligent decision-making enabled by these advanced forecasts delivered notable operational benefits – from more efficient asset utilization to enhanced grid reliability, ultimately streamlining overall plant performance.

The integration of AI algorithms into energy management systems also opens up new perspectives in operational optimisation – making it possible to link price forecasts to the operational control of energy storage and photovoltaic farms in real time. This approach enables optimal charging and discharging of batteries and flexible adjustment of production to current market conditions, which minimises losses and maximises profits. Further development of AI technologies, including explanatory artificial intelligence (XAI) methods and adaptive model updating mechanisms, will allow for an even better understanding of price drivers and a faster response to dynamic regulatory and market changes.

In the area of energy price forecasting algorithms, future research should focus on the implementation of increasingly sophisticated artificial intelligence techniques that will enable more accurate and stable forecasts. Modern deep learning models such as LSTM networks and transformer architectures, combined with hybrid approaches combining statistical methods with domain knowledge, have the potential to significantly improve forecast accuracy. The development of explanatory artificial intelligence (XAI) methods is equally important, as it increases the transparency of models and facilitates the understanding of the factors influencing forecast prices. Additionally, the standardisation and accessibility of data through the creation of open sets and benchmarking frameworks is a key element in accelerating progress in this field.

In summary, the development of AI in PV farm energy price forecasting will move towards the creation of more accurate and resilient models and closer integration with energy infrastructure, while increasing the transparency of these algorithms. Achieving this, however, requires overcoming a number of challenges - from ensuring high data quality to adapting models to rapidly changing market and regulatory conditions. Interdisciplinary research work (combining machine learning, energy, management and economics) and pilot implementations of new solutions in real-world settings will be key to fully realising the potential of artificial intelligence in energy price forecasting in the PV sector.

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A CONCEPT FOR AN INTELLIGENT TELEINFORMATION SYSTEM TO MITIGATE BOTTLENECKS AND OPTIMIZE SALES DURING RECURRING DEMAND PEAKS.

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ABSTRACT

Purpose: *This study aims to develop an intelligent teleinformatics system to alleviate bottlenecks and optimize sales efficiency during recurring demand peaks at points of sale. The system redistributes workload intensity by shifting selected tasks to periods of lower demand, thereby improving resource utilization and increasing overall transaction throughput.*

Need for the Study: *Recurring demand peaks lead to order congestion, long wait times, and lost sales. Traditional Order Management Systems (OMS) often fail to manage such surges effectively, resulting in customer dissatisfaction and operational inefficiencies. This study addresses these challenges through an ICT-based approach designed to distribute workload more evenly, reduce bottlenecks, and enhance customer experience.*

Methodology: *The research utilizes Business Process Model and Notation (BPMN) for process simulation and optimization. A comparative analysis was conducted between a conventional order processing model and an ICT-enhanced version, focusing on execution time and system efficiency. Data from a high-transaction sales environment were collected to identify bottlenecks, assess process durations, and evaluate the impact of automation.*

Findings: *The ICT-optimized model reduced total process execution time by automating some process steps. This led to an time savings and enabled an increase in processed orders during peak periods. Workload redistribution to off-peak periods further reduced pressure during high-demand intervals.*

Practical Implications: *The system is applicable in retail, hospitality, and event settings where demand spikes affect service delivery. Shifting tasks to off-peak hours improves throughput, reduces congestion, and increases revenue.*

Keywords: Demand Peak Optimization, Business Process Automation, Intelligent Teleinformatics Systems, Workload Redistribution, Bottleneck Mitigation, Retail Process Optimization

Jel codes: M15, L86, C63, L81, O33

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1. INTRODUCTION

The analysis of contemporary order management systems significantly relies on the phenomenon of demand aggregation at points of sale. Sales success relies on an effective order fulfillment strategy amidst ongoing shifts in customer behavior and the rapid advancement of ICT technology in retail.

In selling, forecasting and satisfying demand are increasingly vital competencies. Enhancing procurement methods to achieve greater client satisfaction is essential in this setting. Concerning points of sale, innovative technological solutions, such as sales process automation systems, are increasingly vital for enhancing a supplier's market competitiveness. Such solutions enhance operational efficiency and can substantially impact the improvement of overall financial outcomes. This study emphasizes the necessity of enhancing order control systems. The management of effective demand accumulation mostly relies on advancements in automation and the integration of information systems.

The accumulation of demand at points of sale is a key issue that can affect the efficiency of order management and customer satisfaction. In practice, demand accumulation refers to the phenomenon of significant order growth at specific moments, often generated by specific environmental conditions in which the point of sale operates. This pertains to situations where the accumulation of orders is related to the limited time consumers can allocate for shopping and consuming products. An example includes breaks during sports or cultural events or sales points in schools, where accumulations occur during breaks between classes (Swacha et al., 2023).

Such situations can result in problems with product availability, longer order fulfillment times, and a decrease in the quality of customer service. As a consequence, supplier may experience financial losses and a loss of customer loyalty. Furthermore, it cannot meet the existing demand level due to time limitations. In practice it means that the goods that are provided by merchant may not be sold in quantities corresponding to actual demand. It is caused mainly by time limits, available within the selling slot. Merchant may not provide his goods because the resources that he is able to assign during the short slot time are not enough to deal with the demand peak. That is why some of the customers quit the purchase or are not satisfied with the customer service (Piwowarski et al., 2024). Shopkeeper is loosing clients and his potential profit, because he is not able to serve all requests that could be placed during this short period of time.

On the other hand, in the described environment periods of relative inactivity occurs. Those periods are following the demand peak and are repeating each time customer returns to his main activities like courses or event participation. During those periods resources of supplier are almost completely unburdened. Such a scheme recurs in a cycle. Periods of resource overload alternate with periods of stagnation. The challenge is to balance them in such a way as to distribute the load over time. In this way, the problem of demand accumulation at points of sale can be effectively managed, benefiting both businesses and their customers.

2. LITERATURE REVIEW

Order Management Systems (OMS) play a critical role in modern retail, e-commerce, and logistics by automating and optimizing the processing of customer orders. One of the key functionalities in OMS is the ability to define slots for order collection, which enables businesses to manage order pickups efficiently. This functionality is particularly important in high-transaction environments where a large number of customers place and collect orders within limited time frames. Despite its advantages, slot-based order collection presents several challenges, including capacity constraints, system scalability, real-time synchronization, and fulfillment delays. This reviews the literature on OMS with a specific focus on slot-based order collection and its limitations in high-transaction environments, to apply this tool as a solution for demand peaks in problem that is being studied. The literature offers a variety of critical insights and novel ideas about order management in the context of demand accumulation at points of sale. Efficient order management necessitates a holistic strategy that considers both historical data and market trends, hence facilitating improved resource allocation and cost reduction.

Slot-based order collection refers to the process of allowing customers to choose predefined time slots for picking up their orders, either from a retail store, a warehouse, or a designated pickup point. According to Smith et al. (2021), this system improves operational efficiency by distributing order pickups evenly, preventing congestion, and enhancing customer satisfaction (Niemcewicz, 2023). OMS

may also use predefined rules or AI-driven algorithms to allocate time slots based on factors such as order volume, inventory availability, and fulfillment capacity (Gupta & Sharma, 2022). When the slot set is ready, customers can view and select available slots dynamically, reducing last-minute order fulfillment conflicts (Brown & Lee, 2020). ICT systems may also enhance its usability with a inventory management functions. Such a functionality ensures that only available stock can be assigned to a slot and finally sold, preventing overselling (Zhou et al., 2022).

Another element that may be useful to apply in taken approach and the researched issue are automated notifications and Reminders. Both: customers and sellers receive updates on the orders placed. Customers are notified about the order status so they may keep an eye on the process of their order preparation, to reduce missed pickups (Chen & Wang, 2021). On the other hand supplier will not miss any order placed, because notifications will inform about new updates on the orders list. To prevent and stabilize demand peaks some more custom restrictions may be applied. It was described in a literature as 'Capacity Management' where businesses can limit the number of orders per slot or time based on processing capacity to prevent overload (Rahman et al., 2023).

These functionalities enable businesses to manage high transaction volumes efficiently, but several limitations and challenges persist. A major challenge in high-transaction environments is the scalability of slot-based order collection. As customer demand increases, OMS must dynamically adjust available slots to prevent system overload. However, Kumar & Patel (2022) highlight that many OMS solutions rely on fixed slot allocations, which can lead to bottlenecks during peak demand periods. To address this, some AI-driven slot management systems were being developed to dynamically adjust slot availability based on predictive analytics (Wang & Liu, 2023). However, the adoption of such systems remains limited due to high implementation costs and complexity. A study by Jackson et al. (2021) found that traditional architectures struggle with latency issues, leading to scenarios where multiple customers select the same slot simultaneously, resulting in overbooking.

Another issue that was mentioned in a literature on the subject of online ordering systems is customer no-show and rescheduling problems. Customer behavior is unpredictable, and a significant challenge in slot-based order collection is no-shows and rescheduling. The issue was investigated by Davis & Carter (2022). The authors found that up to 20% of allocated slots go unused due to customer cancellations or delays. To eliminate such situations in current approach results of Robinson & White (2021) research were applied. They described approach of penalty mechanisms, where some businesses introduced penalties for missed slots to encourage timely pickups. However, implementing these solutions requires significant customization of the ICT system, what makes them less accessible to small and mid-sized businesses. There are lots of more solutions on the problems identified by researchers, but despite the promise of these technologies, widespread adoption is limited by cost, integration challenges, and resistance to change within traditional retail and logistics sectors.

The major purpose of this study is to thoroughly identify and analyze the limits of order management systems (OMS) as recorded in the current literature, as well as to evaluate the impact of these constraints within a research environment that is under controlled conditions. The integration of solutions that solve these highlighted difficulties into a compact and cost-effective information and communication technology tool that improves order management efficiency is one of the primary goals of this study. The optimization of OMS performance during times of high demand concentrated within short time slots is the primary focus, but the mitigation of stagnation during off-peak times is also a component of the overall strategy. In addition, although the primary focus of the study is on demand fluctuation management, the research also takes into consideration other recorded difficulties that are, in comparison, less significant. These aspects will be incorporated into the process of developing a conceptual framework with the intention of solving the more widespread inefficiencies that have been noticed in slot-based order gathering systems.

Recent scholarship in the field of intelligent management has increasingly focused on the deployment of intelligent systems, particularly those integrating artificial intelligence (AI), predictive analytics, and knowledge-based decision support, as essential components in optimizing organizational processes. These technologies allow organizations to not only automate but also adapt and self-improve operations, embodying the shift from static digital systems to dynamic, learning-driven infrastructures.

One of the key advances in intelligent management lies in AI-supported decision-making systems, which leverage data from multiple operational domains to optimize planning, scheduling, and resource allocation in near real time. According to Dhar (2020), such systems enhance strategic decision-making

by identifying patterns in historical data and generating prescriptive recommendations under uncertainty. This functionality is particularly relevant in time-constrained operational environments, where demand surges must be addressed quickly and efficiently.

Another significant development is the application of intelligent systems in demand forecasting and workload balancing. As illustrated by Wang and Liu (2023), machine learning models applied to transactional data can anticipate short-term demand fluctuations with high precision. These forecasts allow systems to preemptively redistribute tasks or adjust resource deployment, minimizing congestion and enhancing service delivery – an approach closely aligned with the intelligent redistribution strategy proposed in this study.

Additionally, the integration of process mining and intelligent monitoring tools into business operations has emerged as a robust approach for identifying inefficiencies and dynamically optimizing workflows. As van der Aalst (2016) notes, process-aware information systems (PAIS) that incorporate real-time analytics can continuously monitor system performance and adapt operational parameters based on contextual feedback. These systems align closely with the intelligent teleinformatics model under discussion, where live data from ordering systems could be used to adjust system behavior during peak load periods.

The notion of cognitive automation further expands the role of intelligent systems in management. Unlike traditional automation, which executes predefined routines, cognitive automation mimics aspects of human reasoning and learning. As Baryannis et al. (2019) argue, such systems not only respond to current process conditions but also evolve by incorporating new knowledge, thereby enabling organizations to continuously refine their operational strategies. This is particularly relevant in dynamic environments such as retail and food services, where customer behavior, product availability, and service time constraints interact in complex ways.

Furthermore, intelligent systems also contribute to improving human-machine collaboration, an often overlooked but critical aspect of digital transformation. By delegating routine, high-frequency tasks to intelligent agents, human operators can focus on higher-order functions such as supervision, exception handling, and strategic decision-making. This reallocation of cognitive load supports more sustainable labor models and improves organizational resilience in the face of fluctuating demand (Brynjolfsson & McAfee, 2017).

Another promising direction is the use of digital twins and simulation-based optimization in process management. Digital twins—virtual replicas of physical processes—can be employed in conjunction with AI to test various configurations and identify optimal strategies before deployment in the real environment (Kritzinger et al., 2018). This capability allows managers to evaluate "what-if" scenarios involving different peak demand patterns and determine the most effective workload redistribution schemes without disrupting ongoing operations.

Collectively, these contributions in the literature underline the shift toward systems that do not merely support management but participate in it—an idea central to the paradigm of intelligent management. By embedding learning, prediction, and real-time adaptability into the organizational fabric, intelligent systems transform traditional operational models into responsive, context-aware frameworks capable of achieving continuous optimization. The present study contributes to this discourse by proposing a teleinformatics-based architecture that exemplifies these principles in the context of high-transaction environments.

3. METHODOLOGY

3.1. Concept of a system and its potential benefits

The challenge of peak demand becomes particularly acute in what we term "time-constrained consumption scenarios" - situations where large numbers of consumers must complete their purchasing and consumption activities within sharply defined time windows. These scenarios create severe demand compression that standard retail operations are often not prepared to handle it effectively. Common examples include:

- Intermission periods during sporting events, where thousands of spectators simultaneously seek refreshments within a 15-20 minute window.

- Break periods at educational institutions, where students have limited time between classes to purchase and consume food.
- Time-limited lunch periods in business districts or industrial parks.
- Other similar situations like interval breaks during cultural performances and entertainment events.

In each of these scenarios, the fundamental issue remains consistent: a large customer population with homogeneous time constraints creating synchronized demand that overwhelms service capacity. This synchronization of demand represents one of the most challenging aspects of the research, as it requires maintaining infrastructure and staffing levels designed for peak periods that may represent only a small fraction of overall operating hours. To accurately present the research concept, an analysis of the selling process is essential. This study focuses on the most critical and time-consuming elements of the customer service process in retail environments, particularly those with high transaction dynamics. The following key tasks have been identified and will be examined in detail:

A. Product Range Presentation – this initial phase involves introducing customers to the available product offerings. Customers often require time to familiarize themselves with the current selection and may seek additional information from the merchant regarding product specifications, pricing, ingredients, preparation time, and available options.
B. Order Collection – during this stage, the merchant records the customer's selected items, including quantity, size, and any customization options.
C. Order Summarization and Payment Processing – upon finalizing the order, the merchant calculates the total cost. This is followed by payment collection, which may involve cash transactions requiring change to be provided.
D. Order Preparation – once payment is received, the merchant proceeds to prepare the order according to the customer's specifications.
E. Order Delivery – the final step in the process involves transferring the prepared order to the customer, concluding the transaction.

This streamlined representation of the customer service process provides a framework for analyzing potential bottlenecks and areas for optimization in high-volume retail environments. Further research will explore the implications of these process components on overall operational efficiency and customer satisfaction.

3.2. Research hypothesis

This study proposes the development of a conceptual ICT tool designed to optimize resource utilization by redistributing workload intensity between peak demand periods and low-utilization intervals. The underlying hypothesis suggests that such an approach will alleviate resource strain during high-demand time slots by shifting certain process executions to periods with available capacity, thereby balancing overall workload distribution. To validate this hypothesis, a prototype of the proposed ICT system must be developed, incorporating mechanisms to defer selected process tasks to non-peak time slots. This redistribution is expected to reduce resource congestion during demand surges while scheduling non-time-critical order processing activities for execution during off-peak hours.

The anticipated outcome of this methodology is an overall enhancement in resource efficiency, particularly during short but recurring high-demand periods (e.g., scheduled breaks). By alleviating peak-time workload pressure, the system should enable a higher volume of orders to be processed within constrained timeframes. Consequently, this optimization is expected to increase the number of successfully completed transactions, leading to greater revenue generation for merchants and a reduction in customer dissatisfaction caused by excessive wait times or abandoned orders.

3.3. Analysis of the sales process under conditions of demand accumulation

To illustrate the sequence of execution and the overall process structure, a simplified model was developed using Business Process Model and Notation (BPMN). This model serves as the primary tool within the research methodology, facilitating comparative analysis of process execution times in both traditional and ICT-supported environments. A key focus of the study is to examine resource utilization during short, high-demand time slots. By reducing the number of tasks assigned to human operators and implementing automation through an ICT application, the research aims to quantify potential time savings per process iteration and assess the increased process throughput within constrained timeframes.

The described process tasks have been incorporated into the BPMN model, which is presented in the graphical representation below, illustrating the optimized workflow and automation-enhanced execution.

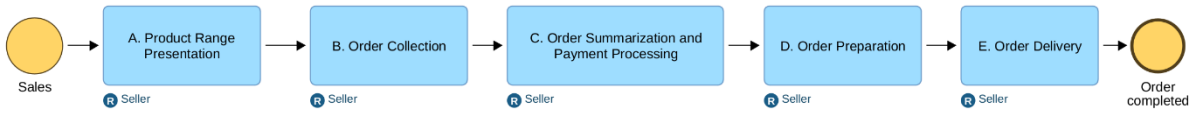


Figure 1. Sales process without integration with an intelligent ICT system, illustrating the sequential steps performed manually by the seller
Source: own elaboration.

One of the key advantages of Business Process Model and Notation (BPMN) is its capability to facilitate execution time analysis, enabling the identification and mitigation of bottlenecks within a given process. The objective of this research is to pinpoint inefficiencies in the original process and explore how they can be resolved through the integration of an ICT-supported solution. BPMN is widely recognized for its effectiveness in execution time simulation and process optimization, as it provides a structured approach to process modeling by visually representing task sequences, decision points, and resource allocations, allowing for a comprehensive assessment of execution times under various conditions (Dumas et al., 2018; van der Aalst, 2016). Simulation-based BPMN analysis enables the identification of process inefficiencies by analyzing real-time performance data, predicting bottlenecks, and assessing their impact on overall system throughput (Mendling et al., 2018). Additionally, BPMN-based simulations support automated bottleneck detection through process mining techniques, which leverage historical execution logs to refine workflow structures (Rozinat & van der Aalst, 2008). This data-driven approach is particularly beneficial in high-transaction environments, where dynamic workload shifts can create temporary bottlenecks, leading to decreased operational efficiency (Reijers & Mansar, 2005). As a result, BPMN serves as a robust analytical tool for optimizing process execution by enabling informed decision-making based on quantitative performance metrics.

To conduct execution time simulations and bottleneck analysis, it is essential to define precise execution times for each task within the process model. In order to obtain real-world execution times for the original process, an empirical study was conducted at a randomly selected retail point within a high school cafeteria. During the observation period, the execution times of individual process instances were recorded, with a particular focus on assessing the number of transactions that could be completed within a single 10-minute break. The study aimed to determine the average execution time of each task within the process, based on empirical data collected during live operations. The findings revealed that the merchant was able to complete transactions for 13 customers within a 10-minute break, with noticeable variability in execution times due to factors such as customer decision-making speed and order complexity. Each task within the selling process was measured individually, and the corresponding execution times were systematically recorded. The average execution time for each task, derived from the collected data, is presented in the table below. These measured times will be incorporated into the BPMN model for further analysis, allowing for a comparative evaluation of the current process versus an ICT-supported alternative aimed at optimizing execution efficiency.

3.4. Empirical observations and bottleneck analysis

The short experiment conducted at a sales point operating without ICT support during a high-demand peak provided critical insights into process efficiency and bottleneck identification. The primary observation from this study is that, within the 10-minute observation period, the merchant was able to complete only 13 transactions, meaning that only 13 customers were served within this timeframe. The most time-consuming task in the process was order preparation, which required an average of 27 seconds per transaction, whereas the total average execution time for a complete process cycle was 47 seconds. This indicates that the order preparation phase accounted for nearly 60% of the total process duration, making it the primary bottleneck within the workflow. Consequently, optimizing this task presents a significant opportunity for overall process improvement.

Table 1. Execution times of 13 sales process instances in a non-ICT-supported model

Task / Process instance	Execution time in seconds													Avg. time (sec.)
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
Product Range Presentation	5	8	1	10	2	3	6	1	7	8	9	9	12	***6***
Order Collection	4	3	3	5	2	3	4	3	3	4	5	5	6	***4***
Order Summarization and Payment Processing	4	8	7	9	4	12	4	4	5	5	10	6	9	***7***
Order Preparation	20	27	16	45	24	28	35	6	16	22	38	37	40	***27***
Order Delivery	2	3	2	4	2	3	3	1	2	3	3	2	4	***3***
Total time (sec.)	**35**	**49**	**29**	**73**	**34**	**49**	**52**	**15**	**33**	**42**	**65**	**59**	**71**	**47**
Total time of 13 processes execution (minutes):														**10,1**

Source: own elaboration.

Other tasks, such as product selection, order collection, and payment processing, collectively consumed an average of 17 seconds per transaction, while the order delivery phase – which involved handing the order over to the customer – was the least time-intensive, ranging between 1 and 4 seconds, with an average duration of 3 seconds. Given these findings, the order delivery task can be classified as a low-impact element in terms of total execution time, whereas the order preparation phase presents the greatest opportunity for time reduction and efficiency gains.

For the purpose of this research, the original process model, reflecting a fully manual execution without ICT support, was used. In this model, all tasks were assigned to the role 'Seller', meaning that the merchant was responsible for every step of the process, following the predefined sequence. Due to this structure, there is limited potential for process reengineering to reduce execution time and increase throughput without introducing modifications to the operational environment.

The collected data not only enabled the completion of the BPMN process model with accurate task execution times but also revealed critical bottlenecks that restrict transaction volume during high-demand periods. To improve the efficiency of the process, certain tasks should ideally be shifted outside the peak demand window. However, such a reorganization is not feasible without the integration of an intelligent ICT system, as structural constraints in the existing manual workflow prevent significant optimization. Even if some process adjustments were implemented within the current environment, their impact on efficiency would be marginal compared to the potential improvements achievable through ICT-enabled process automation.

To illustrate the proposed approach incorporating ICT application support within the process, a second distinct configuration of the model was developed. The first configuration assumes that all process tasks are performed manually by an individual operating a point of sale. In that version, tasks are assigned to the role labeled 'Seller', marked with a responsible for execution blue icon. The second configuration introduces automation by reallocating certain responsibilities to an ICT application. In this model, an intelligent system assists in processing orders by determining how to serve the customer, identifying the scope of tasks, and autonomously progressing the workflow to the next stage when appropriate. Tasks managed by the system have assigned role "App" and are distinctly marked within the process model. The second (ICT-integrated) process includes two additional tasks that facilitate interaction between the seller and the application:

F. Receive and Read Order Preparation Request – in this task, the seller receives a system-generated notification regarding a new order. As the order has already been paid for, the seller's only responsibility is to review the order details, verify the scheduled pickup time, and prepare the required items for collection.
G. Mark Order as Collected – with the ICT system managing order processing, explicit confirmation from the seller is required to update the system's database. Although the system tracks order submissions and communicates relevant details to the seller, it must receive confirmation that the order has been prepared and successfully handed over to the customer. In this step, the seller marks the order status as 'Collected' in the system.

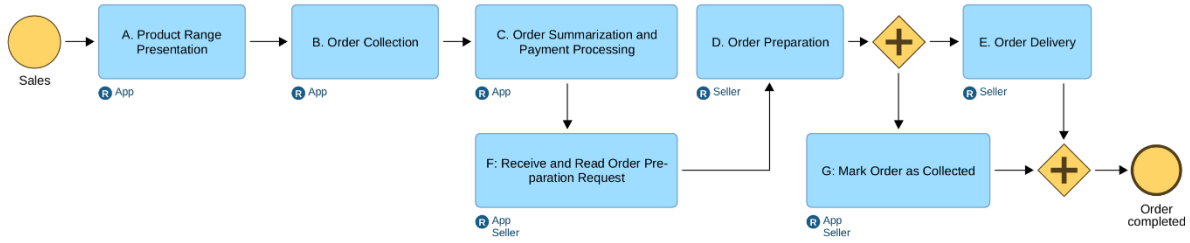


Figure 2. Sales process integrated with an intelligent ICT system
Source: own elaboration.

These two additional tasks are not present in the traditional fully manual process, where customer interaction with the ICT system does not occur. However, to ensure the accuracy of the model, these tasks were incorporated, as they impose additional resource demands and require extra time, which must be factored into the simulation results for a more precise analysis of process efficiency. In the second proposed model, certain time-consuming activities were reassigned to an ICT application, reducing the direct involvement of the merchant in routine operational tasks. This reorganization enhances efficiency by reallocating workload and optimizing resource utilization. Notably, time savings are achieved from the outset of the process, as the initial three steps involve direct client interaction with an intelligent application, eliminating the need for seller intervention during this phase. As a result, freed-up resources can be allocated to other critical tasks, improving overall process efficiency.

To enable automation in the initial phase of the process, the integration of ICT system support is essential. The tasks outlined below can be fully automated within a Business-to-Consumer (B2C) model, allowing the system to handle customer interactions independently, without requiring engagement from the seller. The B2C model refers to commercial transactions in which businesses sell products or services directly to individual consumers. This model has gained significant prominence with the rise of digital commerce, enabling organizations to reach global markets through online platforms (Chaffey, 2022). B2C transactions are typically characterized by high transaction volumes, shorter sales cycles, and a strong emphasis on consumer engagement and personalized marketing strategies (Laudon & Traver, 2021). One of the defining features of the B2C model is the reliance on digital platforms and e-commerce technologies to facilitate transactions. With advancements in internet infrastructure, businesses can engage in omnichannel retailing, integrating physical stores with digital marketplaces to enhance customer experiences (Turban et al., 2021).

3.5. Optimized process model with ICT integration

The second proposed process model minimizes the involvement of the seller in initial transaction stages, requiring their engagement only after an order has been placed and paid. To achieve this, several key tasks have been reassigned to the ICT application, allowing for a more efficient and automated workflow.

A. Product Range Presentation – in this optimized approach, the merchant defines the available products at the point of sale, which are then presented to customers through the ICT system. This method enables a more comprehensive and standardized product display, including detailed descriptions, pricing, images, and multimedia elements such as videos. Customers can review the offerings independently, eliminating the need for the seller to individually introduce and describe products for each client. Compared to the original process, this adjustment significantly improves efficiency by reducing repetitive manual interactions.
B. Order Collection – once a customer selects desired products, the ICT application facilitates order placement. The system allows customers to browse, add items to a virtual shopping cart, modify selections, and finalize purchases at their own pace. This self-service approach removes the pressure associated with waiting in queues and provides immediate visibility into order totals, aiding in decision-making. By shifting this step to a Business-to-Consumer (B2C) model, the process ensures a seamless experience while reducing seller involvement in order processing.

C. Order Summarization and Payment Processing – integrating an automated payment system further enhances process efficiency. In the traditional model, payment collection was one of the most time-intensive tasks. The redesigned approach eliminates this inefficiency by automating order summarization and offering multiple digital payment options, such as online banking, card payments, and mobile wallets. The entire payment procedure is executed by the system, reducing the potential for human errors in transaction processing, change handling, or order total miscalculations. This shift transfers the responsibility of transaction management from the seller to the ICT application, significantly reducing workload.

3.6. Workload redistribution and demand peak management

With these three tasks automated, the seller now receives only pre-processed orders that have already been placed and paid for. This transition addresses previously identified inefficiencies, such as order cancellations due to non-payment or delays caused by indecisive customers. As a result, the seller's role begins at a later stage in the transaction, leading to substantial time savings. To maintain the accuracy of process simulations and workflow analysis, an additional task must be introduced to account for information retrieval. In the original model, the seller obtained order details through direct customer interaction. In the new system, this information is provided digitally via a structured order list. Each entry in the system represents a verified and paid order, allowing the seller to treat it as a work queue and focus exclusively on order preparation.

The preparation phase of the order remains largely unchanged, as the time required to assemble items is not influenced by whether the order was placed manually or digitally. However, a critical advantage of the new model is the ability to shift order placement to off-peak periods. Customers can place orders in advance, allowing the seller to prepare them during low-demand intervals rather than congested peak times. This redistribution of workload reduces bottlenecks and smooths demand fluctuations, aligning with the primary objective of the study.

To enable this optimization, the ICT system includes a time-slot selection feature, allowing customers to specify preferred collection times. Orders originally concentrated in peak periods can now be pre-processed, ensuring that when demand surges occur, the seller is primarily engaged in finalizing and delivering pre-prepared orders rather than managing the entire transaction workflow in real-time. This adjustment effectively reduces resource strain during peak slots by shifting labor-intensive tasks to quieter periods.

To complete the transaction cycle, an additional step is required: confirming order collection. In the optimized model, this task involves marking the order as delivered within the ICT system. This step removes the completed order from the queue and formally concludes the process. While independent from the physical act of handing the order to the customer, both steps can occur in parallel to ensure accurate tracking.

4. RESULTS

At first glance, the redesigned model significantly reduces the execution time required from the seller by transferring multiple tasks to the ICT system, which can simultaneously handle numerous customer interactions. This shift presents considerable improvements in execution time reduction and task distribution over time. To quantify these improvements, calculations were conducted using BPMN-based process models.

For simulation purposes, execution times for the second model were estimated and applied. Tasks fully handled by the ICT system were assigned zero execution time for the seller, as they no longer require manual intervention. Tasks that remained unchanged from the original process retained their initial execution times, ensuring consistency in comparison. For newly introduced tasks, execution times were estimated based on expert knowledge and practical experience. The resulting execution times for each task in the redefined process model are presented in the subsequent analysis.

The total execution time of the order processing workflow decreased from 47 seconds to 38 seconds, primarily due to the elimination of seller involvement in the first three tasks. These activities were fully transitioned to the Business-to-Consumer (B2C) model, meaning that the merchant no longer contributes execution time to these tasks. However, the revised process model introduced an additional task responsible for ICT system communication between the seller and the application. This newly

added task, estimated to require an average of 5 seconds, slightly increased the execution time and reintroduced a minor workload for the seller.

Table 2. Execution times of tasks in a sales process instance with ICT support

Task / Process instance	**Avg. time (sec.)**
Product Range Presentation	*0*
Order Collection	*0*
Order Summarization and Payment Processing	*0*
Receive and Read Order Preparation Request	***5***
Order Preparation	*27*
Mark Order as Collected	***3***
Order Delivery	*3*
Total time (sec.)	**38**

Source: own elaboration.

The order preparation phase, which remains the most time-consuming task, retained its original execution duration, as no modifications were made to its workflow. Additionally, a second new task was incorporated into the revised model to facilitate status updates within the application once an order has been delivered. This task, estimated at 3 seconds, is entirely executed by the seller. Meanwhile, the order delivery phase remained unchanged in terms of duration. Despite the introduction of two additional tasks, the overall process still resulted in an average time savings of 9 seconds per transaction. Based on this improvement, during a 10-minute break, the seller is now expected to serve approximately 16 customers, representing an increase of 23% compared to the initial model. Considering that a typical workday consists of five or more such selling periods, this optimization could result in up to 15 additional customers served per day.

Although the quantitative analysis suggests a notable increase in transaction volume, the primary objective of this model was not solely to reduce process execution time. Instead, the core aim of integrating an intelligent ICT system was to redistribute workload more efficiently across peak demand periods and low-demand intervals. While execution time reduction is an observed benefit, it serves as a secondary outcome, indirectly contributing to overall system efficiency. Due to the limitations of this study, the model has not yet been implemented in a real operational environment, making practical validation of its effectiveness unfeasible. However, theoretical analysis strongly suggests that the proposed approach can significantly improve workload distribution and operational efficiency.

By enabling the process to begin well before demand peaks occur, the model allows key tasks - such as product presentation, order collection, and order preparation – to be executed during low-demand periods, reducing the workload concentrated within peak periods. As a result, during breaks or other high-demand time slots, the seller's primary responsibilities are limited to order delivery and order list management. In the revised model, the workload during demand peaks is significantly lower, while tasks are shifted to periods of resource underutilization, creating a balanced workload distribution over time. Consequently, demand peaks are less likely to create bottlenecks that inhibit transaction throughput.

Furthermore, the new model simplifies operations during peak demand slots. The seller is only required to perform two primary tasks - order delivery and updating the order status in the system - each taking an average of 3 seconds. Since these tasks can be executed in parallel if multiple human resources are available, the per-order execution time could be further reduced. The elimination of bottlenecks in the ordering process is expected to have a positive impact on sales volume. A shorter wait time for customers should enhance the overall purchasing experience, leading to higher customer satisfaction and potentially increased customer retention. Additionally, by serving a higher number of customers per selling period, the model is likely to contribute to a greater overall sales volume and higher revenue generation for the merchant. By combining workload balancing, demand peak management, and ICT-enabled process automation, the revised model not only improves operational efficiency but also creates opportunities for business growth through enhanced service capacity and improved customer experience.

5. DISCUSSION

The proposed ICT-supported system is not merely a tool for process automation; it embodies the principles of intelligent management by enabling data-driven decision-making, real-time process adaptation, and dynamic workload distribution. These characteristics are foundational to intelligent management, where technology acts not just as a passive tool, but as an active agent in managing organizational complexity and resource constraints. Through the integration of automation, workload redistribution mechanisms, and time-slot optimization, the proposed system aligns with the core goals of intelligent management – enhancing operational agility, increasing throughput, and improving customer satisfaction.

From a strategic perspective, the system provides a model for transitioning from reactive to proactive process management. Instead of responding to demand peaks with resource overextension or manual reorganization, the intelligent system anticipates demand patterns and reshapes the workflow accordingly. This temporal redistribution of effort exemplifies predictive resource management, a key tenet of intelligent management. Furthermore, by relieving human actors of repetitive front-end tasks, the system allows personnel to focus on high-value activities, which enhances both job satisfaction and operational scalability.

The system also presents a platform for further integration with AI-based forecasting tools. For instance, incorporating machine learning models could enable automatic adjustment of time-slot availability based on historical transaction data, weather conditions, or event schedules. Such developments would further entrench the system within the intelligent management paradigm, where automation and analytics converge to drive process excellence.

6. CONCLUSION

This study contributes to the field of intelligent management by proposing a teleinformatics-based approach to alleviating bottlenecks and optimizing transactional throughput during periods of peak demand. By automating the front-end stages of the sales process and enabling asynchronous task execution, the model demonstrates how ICT can act as a core component of intelligent organizational systems – ones that are not only reactive to environmental pressures but strategically structured to anticipate and absorb them.

The system's ability to redistribute workload across time, automate customer interaction, and dynamically manage order processing encapsulates the integration of automation, analytics, and process control – pillars of intelligent management. This enables organizations to operate with increased agility, efficiency, and responsiveness to fluctuating demand without compromising service quality. In doing so, it reduces the friction typically associated with peak periods and creates the conditions necessary for sustained operational excellence.

Although the study's findings are currently based on simulated environments, the implications for practice are clear: intelligent systems can transform transactional workflows, particularly in environments where time-constrained consumption limits conventional service models. Further research should focus on integrating AI forecasting modules and user behavior analytics to refine system responsiveness. Real-world pilot programs will be essential to validate scalability, assess human-system interaction, and measure economic impact.

Ultimately, this research positions intelligent teleinformatics systems as vital instruments within the intelligent management toolkit, empowering organizations to move from static operations to adaptive, high-performance service delivery architectures.

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AI AS DECISION SUPPORT IN THE IMPLEMENTATION OF COURIER SERVICES IN SPATIAL TERMS

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ABSTRACT

Purpose*: The purpose of this paper is to present the situation with regard to the use of advanced modern technologies by courier market players and to identify the opportunities offered by AI to courier market players. The paper adopts the following basic research hypothesis: In meeting the emerging challenges in the courier services market, it is essential to identify and implement appropriate AI tools.*

Need for the study*: Decisions to implement state-of-the-art smart mobility solutions can improve productivity, reduce costs and increase efficiency in the operation of the surveyed entities. This article addresses the need to fill the research gap identified in the literature in the area of decision-making regarding the implementation of AI-based tools*

Methodology*: The first part of the article presented a literature review of AI solutions used in the operations of courier operators. This served as the starting point for presenting the results of the study conducted. The survey was conducted in Q1 2024, on a sample of 19 and 21 operators representing the courier services sector. The survey used the expert method, as the issues studied were characterised by the high complexity of the problem, making quantitative measurement impossible. The method used an indirect form of expressions of opinion from experts in the courier services market. The purpose of the article was verified through a CATI survey.*

Findings*: The presented research has shown the differences in the approach to the implementation of AI-based solutions, in the activities of operators operating locally and in the national market. In addition, the authors presented a model solution in the form of a 'roadmap' , which will improve the process of introducing AI-based solutions into the day-to-day operations of courier market operators.*

Practical implications*: The research conducted has identified the broad opportunities offered by the implementation of AI solutions, not only for operators operating in the national market, but also locally. The article also provides practical insights in areas such as route optimisation, predictive analysis of customer behaviour and external events, and integration of AI with IoT technologies and robotic process automation (RPA).*

Keywords: postal market, decision-making processes, artificial intelligence, courier services, sustainable development, network markets.

JEL: O32, O14, L87, L14

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1. INTRODUCTION

The postal sector, broadly defined, is a pillar of the global ecosystem (Budziewicz-Guźlecka & Drab-Kurowska, 2019). It is important to point out that its role is to cross borders, enabling the communication of societies, businesses and institutions, underpinning e-commerce as well as economic resilience. However, the implementation of these activities encounters a number of barriers and challenges, caused both by independent factors, such as pandemic situations, war conflicts, extreme meteorological phenomena, and as factors related to the change of preferences and behaviours of modern society, which has strongly digitised in the last two decades. Therefore, efficient decision-making by the decision-makers of the market under study is essential in this context.

It should be emphasised that the postal market of the 21st century is an inheritor of many diverse concepts and solutions of the past. It is most evident in the aspect of ways and concepts of postal tasks implementation, the scope of which is systematically increasing, the scale of complexity and dynamism of processes is growing, as well as the scope and manner of use and implementation of more and more developed tools, being the effect of technical and technological development in the sphere of operational, tactical and strategic activities in the local, regional and global aspect. Nowadays, in response to the ongoing changes in the global economy, new determinants are emerging, which now, as well as in the future, will determine the direction of postal enterprises (Drab-Kurowska, 2019; Budziewicz-Guźlecka et al., 2018).

One such determinant is the clearly noticeable development of artificial intelligence (AI) in the context of autonomous and rational decision-making. AI is able to make such a decision, through a self-learning module based on information on the internet or databases (Ilieva, et al., 2024) The reactions of society should be particularly noted here. One is curiosity as to how artificial intelligence has the potential to improve the system that has been in place so far, and how this will affect, through the proposed decision-making proposals, the operating costs of the organisation. On the other hand, one can observe a serious fear of replacing a living human being with artificial intelligence. The changes that are taking place in the postal market determine the reconstruction of operators' internal processes and the gradual implementation of AI in analytical and management processes.

Accordingly, AI is becoming the compass of development for operators of the broader postal market, with a particular focus on the courier market, providing the opportunity not only to implement automation and efficiency processes. The implementation of AI creates a platform for highly efficient operations, resulting in a new era of sustainable growth in the context of the market under review. With decision makers deciding to leverage AI capabilities, global operators around the world have the opportunity to collaborate on an unprecedented scale, sharing data, observations and best solutions. Such collaborative initiatives would be a starting point for addressing disparities in the development of the broader postal services at national and international levels. This would allow economically weaker regions to benefit from the digital revolution and provide innovative solutions for cross-border e-commerce. It should be emphasised that generative artificial intelligence models can support the design of sustainable global postal and logistics systems that are resilient to any negative phenomena occurring both globally (pandemic) but also locally (floods). It should be emphasised that close cooperation between operators, supported by state-of-the-art technologies, could redefine the concept of connectivity (Baláž, et al., 2024).

The development of digital platforms, real-time communication tools and advanced data sharing mechanisms has paved the way for global collaboration. These tools are bridging the barriers of geography and time, allowing close collaboration between multiple operators around the world. It is important to emphasise that the situation for operators over the past decade has been put to a demanding test. Unforeseen events, such as the COVID-19 pandemic or the conflict in Ukraine, have significantly affected operators' operations, changing international transport options and accessibility. It is important to stress that in such a turbulent environment, other unforeseen events may arise, which will in all likelihood put operators' resilience to the test. As already emphasised, the postal market studied in this article, with particular reference to the courier market, is currently undergoing a major transformation and will be further transformed by the development of artificial intelligence. Intelligent solutions have already appeared on the market, streamlining and optimising operational work, and the allocation of deliveries or processes related to cooperation with carriers and customer service are already partly automated to the extent that little manual human intervention is required. The introduction of AI-based

solutions makes it possible to decisively accelerate process optimisation – enabling error analysis and early detection of anomalies in the courier service delivery process. This is particularly important in the context of e-commerce, which is growing at a double-digit rate, as well as increasing customer pressure on delivery times. A major challenge for postal market operators, with a particular focus on courier operators, is the problem of the first and last mile. This is largely due to the involvement of the human factor (collection, picking, decompletion and dispatch). In particular, the final stage of the entire logistics process - delivery to the recipient – is the most costly part of the entire delivery process. State-of-the-art technologies, of which AI is one, should be considered as helpful to courier market players. AI thus allows for the activation of advanced analytical methods that produce measurable results, while leaving space for a human to make the final decision. Thus, being at the same time the quintessence of logistics 5.0.

2. COURIER SERVICES AND MODERN TECHNOLOGY- LITERATURE REVIEW

Postal services, from which courier services originated, have been the foundation of global communication and trade since the dawn of time. In the past, postal services focused on the delivery of letters and parcels, functioning as a critical link between individuals and companies (Kováciková, et al., 2023; Drab-Kurowska & Drożdż, 2021). It should be noted that the origins of postal services date back to ancient civilisations, where networks based on couriers and messengers were organised to facilitate the exchange of information. These systems then gradually evolved into more structured and reliable postal networks. As a result, they became the backbone of societies and national economies. Today, postal services have evolved strongly, diversifying their activities beyond traditional mail delivery. The dynamic development of modern technology and the Internet has influenced the development of courier services, which now play a key role in the logistics and distribution of goods. The change in society's habits and the development of e-commerce has led to an intensive increase in the volume of shipments, which has been observed over the last decade. This phenomenon has forced courier service providers to adapt to the new rules of the game in the courier services market. It should also be emphasised that technological advances have been a major driver of change in the courier services market area. The implementation of automation systems and digital technologies has revolutionised a number of areas of courier business from sorting and tracking to customer service and delivery (Drobiazgiewicz, 2017). Automation has had a significant impact on efficiency and the rapid processing of large volumes of parcels. In addition, advanced tracking systems have been implemented, resulting in increased transparency and reliability, allowing customers to monitor their parcels in real time. IoT, in turn, represents a transformative technology for the courier services industry. IoT devices and sensors can be embedded in parcels, vehicles and infrastructure to provide real-time data on location, status and environmental factors (Novák, et al., 2024). This information gives courier service providers the ability to monitor the status of parcels throughout the delivery process, ensuring that parcels are handled in the right way and will be delivered on time. It is important to emphasise that IoT technology increases transparency and accountability and provides the opportunity to receive delivery status notifications.

The implementation of digital technologies has also transformed customer interactions and service delivery in the postal services industry. Online platforms and mobile applications allow customers to easily access postal services, track parcels and manage deliveries. Digital communication tools such as email and SMS notifications keep customers informed about the status of their parcels. These advances improve the customer experience, increasing convenience and satisfaction. Furthermore, digital technologies enable postal service providers to offer value-added services such as flexible delivery options and secure digital mailboxes.

3. CONTEMPORARY TRENDS AS A BACKDROP FOR SERVICE DELIVERY WITH AI SUPPORT

The changes taking place globally in the context of AI development can be defined as "megatrends" of postal market development (Ludziejewski, 2024; Drab-Kurowska & Kuściński, 2023),

Budziewicz-Guźlecka, 2019). They are the result of changes in the global economy (Garretsen, et al., 2025; Kowalska & Syrda, 2024). Megatrends can be defined as constant economic, social, technological, political and cultural trends, phenomena arising in the process of civilisational development of society, with various conditions affecting humanity beyond national borders and continents, encompassing the entire earth globe and conditioning the main directions and goals of the perspective development of humanity (Bujak, 2016) In the postal context, the concept of a 'megatrend' can be defined as a force that fundamentally changes the way postal entities operate, their way of operating, competing, an important direction, trend or force that emerges globally or locally and is likely to operate in the future. It is important to point out that these megatrends have a significant impact on almost every aspect of the functioning of societies and the economy, and in the view considered in the article, megatrends affecting the development of the postal market, which can be presented in two main groups – social (civilisational) and economic-technological, although this division will be blurred and many elements will interpenetrate and complement each other, generating a kind of feedback loop (Przybylski, 2019; Frias, et al., 2023; Nitsche & Straube, 2023).

It should be pointed out that the current digital economy considered in the context of the postal service envisages further digitisation of postal processes using modern technologies that process a huge amount of information, including the Internet of Things, Big Data Analysis and supporting the provision of postal services through the use of robotics and automation and self-learning systems. It should be pointed out that areas of the postal service where people are supported by modern technology have been developing intensively for a long time. Operators have been using automated sorters or parcel machines for another decade, which on the one hand make work easier and faster and at the same time provide a solution to labour shortages. Despite the emergence of new capabilities to improve the Internet of Things and AI, there are constant concerns about data security and the lack of standards for the postal sector. This is the reason why the postal sector is not exploiting the potential brought by the Internet of Things and AI (Mohammad, et al., 2023; Nawaz, et al., 2023; Sulkowski, et al., 2022).

Further perspective analysis shows that in the third decade of the 21st century, human labour is expected to be gradually replaced by intelligent devices or systems through the use of autonomous vehicles and, to a lesser extent, self-learning systems in intelligent supply chains and drones in the role of couriers, although already occurring in this formula, but not on a large scale.

4. OPPORTUNITIES FOR THE USE OF AI IN THE POSTAL MARKET

The apparent increase in customer demands in the context of reducing lead times is resulting in the search for new solutions and decision-making often based on AI (Wang, et al., 2023; Zhang et al., 2023). Among the disruptive market drivers that will have the most impact on the postal sector is delivery personalisation and multi-channel delivery, which is related to the rapid development of the e-commerce industry. It should be borne in mind that the traditional form of delivery at a time and place specified by the carrier no longer meets the requirements of customers, who expect delivery on demand (on-demand delivery) and therefore at any time and place (Wang & Kern, 2021).

An analysis of market and social trends in the postal sector has shown that in the 21st century, one of the important factors, along with multichannel activity and on-demand delivery, is the concept of the sharing economy (Budziewicz-Guźlecka, 2017). The environmental aspect is also a key trend, especially in the context of oil depletion, which has a negative impact on the postal market (car and air transport. It therefore seems necessary to take measures to intensify investment in 'green' postal logistics, based on renewable energy sources, and to seek innovative concepts for energy collection, storage and distribution and alternative modes of transport. It should be pointed out that more and more often business strategies of logistic postal operators take into account, apart from economic objectives, also ecological actions compliant with the concept of sustainable development.

When analysing market trends, it is important to point out that among the main market drivers that are shaping the courier services sector, personalised production and changes in the retail structure and the rapidly developing e-commerce and e-commerce can be highlighted. Examples of AI applications

include recommendation systems, chatbots, speech and image recognition, autonomous vehicles or data analytics systems.

4.1 Warehouse management systems - RPA - robotic process automation

Robotic Process Automation technology is a form of automation that is becoming increasingly common (Wewerka & Reichert, 2023; Herm, et al., 2023; Farinha, et al., 2024). It is software based on artificial intelligence that automates repetitive and simple business processes. It is most commonly used for data entry, transaction processing and report generation based on predetermined algorithms. This work performed by a bot is much more efficient than performing these activities manually. Applications of RPA in the postal sector can be found when processing orders, eliminating the need for manual data entry thereby speeding up the process and reducing the possibility of error (Nielsen, et al., 2023; Pareek & Tailor, 2023; Rajagopal & Ramamoorthy, 2023). The software can generate a signal, in an automated manner, when the correct stock level drops. RPA also supports the invoicing and billing process with automatically generated documents, as well as the shipping process to specific recipients while monitoring payments. The software also allows data analysis by identifying patterns and trends in large data sets. This makes it possible to generate reports, with information used later to optimise logistics processes.

4.2 Optimisation of routes and delivery schedules - autonomous vehicles

Another state-of-the-art technological solution affecting the delivery of courier services is big data analytics. By analysing large amounts of data collected from various sources, postal service providers can obtain valuable information regarding operational performance, customer behaviour and market trends (Janoskova et al., 2021). This information can be the basis for optimising routes, predicting demand and improving resource allocation. AI algorithms can analyse historical data to predict delivery times, identify patterns and optimise processes. For example, AI-based systems can optimise route planning, taking into account factors such as road conditions, weather and delivery priorities. This allows for faster and more reliable deliveries, reducing fuel consumption and operational costs. In-depth data analysis enables the identification of peak delivery times and areas with high delivery volumes. This knowledge allows for more efficient decision-making in the planning and routing of delivery vehicles. In addition, artificial intelligence can be used to automate customer service interactions, providing immediate responses to common queries and freeing up human agents for more complex issues.

Autonomous vehicles are the result of developments in technology and AI that allow for the highest level of efficiency. An autonomous vehicle uses advanced computer systems, artificial intelligence and a large number of sensors (including cameras, sensors, radars) to analyse the environment and respond efficiently to situations on the road (Gamal, et al., 2023; Dabic-Miletic, 2023). Automating vehicles obviously has a number of advantages, first and foremost being the decoupling of driving time from the driver who needs breaks and recuperation, maintaining an economical driving style, replacing drivers who are becoming fewer and fewer every year, fewer road accidents and increasing the fluidity of the flow of goods. In addition to the positive features, disadvantages can be found, which include: high purchase and repair costs, the need for a well-qualified technical background, system vulnerabilities or hacking attacks. Cargo monitoring and tracking - software visibility

The process of monitoring and transporting cargo is crucial for logistics, the transport industry and trade (Zhao & Lee, J2023). It allows for efficient management of deliveries, optimisation of routes and delivery times which ensures transparency in the supply chain. There are many methods to monitor and track cargo, contemporary technologies include GPS, RFID, barcodes and transport management systems. All of these have increased the efficiency of the logistics sector. Nowadays, these solutions are familiar to everyone and widely used. Monitoring and transport systems provide information on the status and conditions of transport, enabling the indication of quality and safety standards for cargo, especially for sensitive loads. Customers and consignees also benefit from the systems by tracking or monitoring their consignments and are made aware of delivery times. Through a special standard number that is assigned by the logistics or production company, the buyer can enter the number via the company’s mobile app or company-owned website and find out

the status of his or her order. There are three different approaches to transport monitoring, including manual, semi-manual and automated monitoring (Lopez-Aguilar, et al., 2023; Cooper, et al., 2023; Sriranga, et al., 2023). The manual monitoring approach is the slowest, least adaptive and most prone to human error. The method uses spreadsheets, emails, faxes or a telephone call. The semi-manual method mainly involves Electronic Data Interchange (EDI), which is based on transferring a large set of supply chain data directly between systems, usually between business partners. Despite its effectiveness, the method does not take full advantage of the capabilities of modern technology. The most effective monitoring method is an automated approach – software that supports real-time monitoring, known as Real-Time Visibility (Kalkha, et al., 2023). Currently, many companies use manual methods of tracking the transportation of supplies and cargo in the conduct of their business. The system has disadvantages such as the creation of delays, errors or increasing customer dissatisfaction. This has led to the development of visibility software, which is designed to monitor the location of loads. It is a collection of functions such as automated workflows, as well as the viewing of quotes and carrier quotes.

5. SURVEY METHODOLOGY

The survey was conducted to obtain the data and information needed to verify the research hypothesis set out in the article. The study was carried out according to the following scenario: 1) Definition of the scope of the study and the target group; 2) Selection and preparation of the survey instrument; 3) Conducting the survey; 4) Summary and analysis of the results; 5) Formulation of conclusions. The survey was conducted in Q1 2024, on a group of 19 and 21 entities representing the courier services sector. The analysis of activity conducted by alternative postal operators indicates that in 2023 62 postal operators indicated that postal activity was conducted exclusively in the courier mail segment. The representatives of the entities taking part in the study are specialists in the application of IT and business solutions. The survey used the expert method, as the issues studied were characterised by a high complexity of the problem, making quantitative measurement impossible. The method used an indirect form of expressing the opinions of experts in the courier services market. The experts were asked to provide answers to questions that were included in a prepared questionnaire containing the issues discussed. It should be pointed out that one of the principles for the selection of experts was their diversity in terms of professional experience. The purpose of the article was verified on the basis of a CATI survey. The choice of this tool was based on the fact that it allowed interviewing the experts, clarifying the questions asked, verifying the answers given, learning about their motivations and identifying other relevant determinants. The selection of experts for the study was carried out by a purposive selection method. The final assessment was carried out by 19 experts representing local actors and 21 experts representing national actors. The specificity of the research problems, which positioned the surveyed entities in a competitive market, required the preservation of confidentiality. The individual indications obtained made it possible to identify indications pointing to the use of advanced IT tools and AI by actors in the courier services market. The questionnaire consisted of 24 questions. When answering each question, experts had the option to choose one answer or provide their own answer. The first group of questions focused on the use of IT tools in the delivery of courier services in the sensitive area of the first and last mile (questions 1-5). The next group of questions attempted to answer questions on the functionality and automation of processes taking place using IT tools in the first and last mile (questions 6-10). The third part (questions 11-16) concerned the use of mobile applications, in the context of effective management of first and last mile processes. In addition, experts were expected to provide information on the scope and context related to their use of mobile applications. In the fourth group of questions (questions 17-24), the questions concerned the degree of interest in the use of AI for the optimisation of sensitive processes at the first and last mile level and the prediction of external phenomena that can significantly affect the courier service delivery process. The aim of the survey was to determine whether the surveyed entities recognise the potential of AI-supported IT tools. Due to limited capacity, the paper presents the answers to the questions of groups one and four.

6. RESULTS OF THE STUDY

Based on the survey, information was obtained on the approach of courier service providers regarding the use of modern technology and AI. During the survey, actors operating at national and local level were identified.

For question 1, the experts indicated (Figure 1) that the organisation uses IT tools in the courier service delivery process, understood as the optimisation, implementation and monitoring of logistics processes especially in the context of the first and last mile. Clear differences can be seen between those operating locally and those operating nationally.

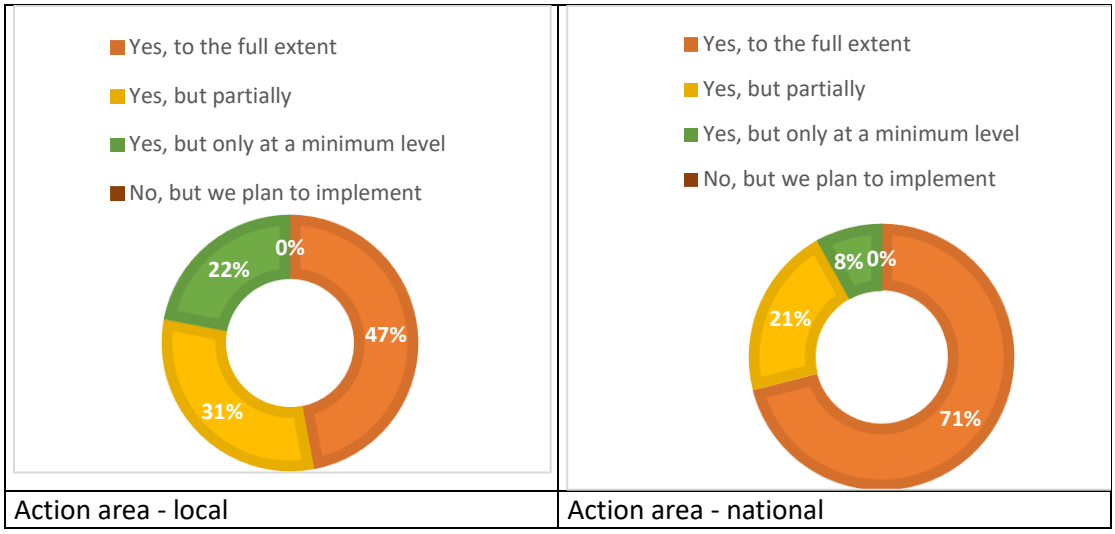


Figure 1. Use of advanced IT tools in the courier service delivery process, understood as optimisation, implementation and monitoring of logistics processes especially in the context of the first and last mile
Source: own elaboration.

It is evident that operators operating at national level use advanced IT tools 24% more often than local operators. For the operators surveyed, operating at a local level, this is only less than half of those surveyed (47%).

Partial use of advanced IT tools in the courier service delivery process is declared by 31% of local operators and 21% of operators at national level. It is worrying that 8% of national operators use advanced IT tools at a minimum level, and the figure is as high as 22% for national operators. This means that the scope of operations has a very strong influence on decision-making regarding the implementation of advanced IT tools. Experts pointed to the lack of need and the cost factor, which at the local level, due to limited economies of scale, would be a burden for the operator.

The next question was about the benefits of using IT tools in the courier service delivery process especially in the context of the first and last mile, as shown in Figure 2. The biggest benefit of using IT tools in the courier service delivery process in the opinion of both local and national operators was the possibility to monitor the route of the parcel (98% of indications of national operators and 97% of indications of local operators).

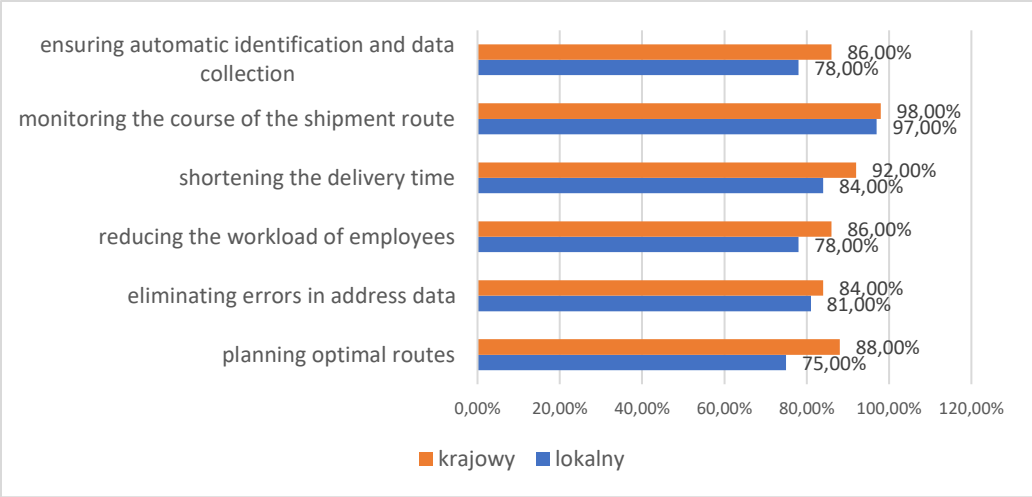


Figure 2. Benefits of using IT tools in the courier service delivery process especially in the context of the first and last mile
Source: own elaboration.

The second benefit indicated by respondents was a reduction in delivery time. For national operators, this benefit was very important (92% of indications). For local operators, it was important to 84% of surveyed operators. The surveyed operators are increasingly paying close attention to optimal routes. This is not solely dictated by economic considerations. It appears that the environmental issue of minimising the carbon footprint is important to them. For 88% of postal operators operating at national level, this is important. In contrast, local operators made an indication of75%. Another benefit shown by operators was the provision of automatic identification and data collection (86% of indications by national operators and 78% of indications by local operators). The same number of indications was the reduction of clerical workload. Respondents also indicated the benefit of eliminating errors in address data (84% of indications from national operators and 81% of indications from local operators).

Another issue analysed in the study concerned the problems and challenges encountered in the courier service delivery process in the context of the IT tools used, as presented in Figure 3.

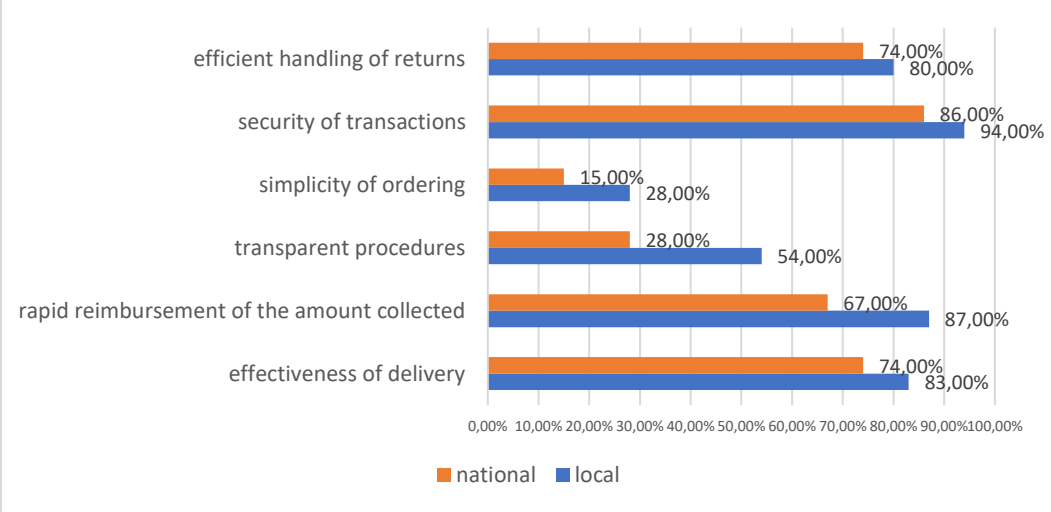


Figure 3. Problems and challenges occur in the process of courier services in the context of the IT tools used
Source: own elaboration.

The biggest problem and challenge, according to the operators surveyed, is the issue of security of the transactions carried out. This issue is prioritized by 94% of local operators and 86% of national operators. A major challenge for operators is also the efficient handling of returns. The parcel return process requires adequate logistics, financing and resources to manage the entire process effectively.

Furthermore, the parcel return process should be as efficient and transparent as possible to ensure a positive customer experience. Operators are aware of this (74% of indications from national operators and 80% of indications from local operators). Next in importance, the surveyed operators indicated issues regarding the return of the collection amount. This is particularly important when paying at the customer's premises (67% of indications from national operators and 87% of indications from local operators). According to operators, a major challenge is the effectiveness of delivery (74% of indications from national operators and 83% of indications from local operators). They expect IT tools to improve efficiency. This is important in terms of timeliness and generating additional costs. IT tools are expected to streamline the process. A less significant challenge in the opinion of operators is the transparency of procedures (28% of indications of national operators and 54% of indications of local operators). These responses show that operators in this area do not need to make major investments. The situation is similar with regard to the simplicity of placing an order for a courier service. According to the operators, customers do not have major problems with this process, which is the result of the high transparency and intuitive layout (15% of indications from national operators and 28% of indications from local operators).

The next question, addressed to the respondents, concerned the plans of the operators, in terms of the implementation of courier services in the perspective of 2 years in the context of the first and last mile, which is presented in Fig. 4. It can be clearly seen that there is a growing awareness of the negative impact on the environment. Operators are looking for solutions that, when implemented, will reduce negative environmental impact and, at the same time, optimise costs. In terms of plans, the answer regarding matching loads to the type of layout vehicle came in first place (98% of indications from national operators and 96% of indications from local operators). In terms of plans for the next 2 years, the surveyed operators indicated two issues. The first was the introduction of the possibility to schedule deliveries in specific time slots, which will increase the effectiveness of deliveries and ultimately reduce the cost of last mile deliveries (87% of indications from national operators and 65% of indications from local operators). The second issue was the simplification of complaint procedures, which will increase customer satisfaction ((87% of indications from national operators and 74% of indications from local operators). Among the plans for the coming years, there is also the very important and relevant issue of reducing fleet costs, which will result from investments in a low-carbon fleet and the use of AI to optimise routes (86% of indications from national operators and 92% of indications from local operators).

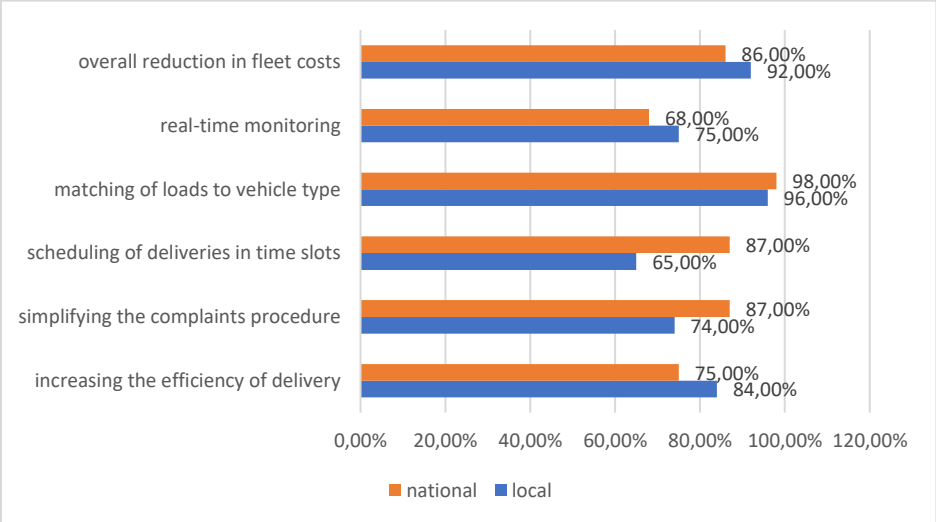


Figure 4. Operators' plans for the delivery of courier services in a 2-year horizon in the context of the first and last mile

Source: own elaboration.

Another group of questions concerned the use of AI in the delivery of courier services. The surveyed entities have high hopes in terms of AI supporting their business (Figure 5).

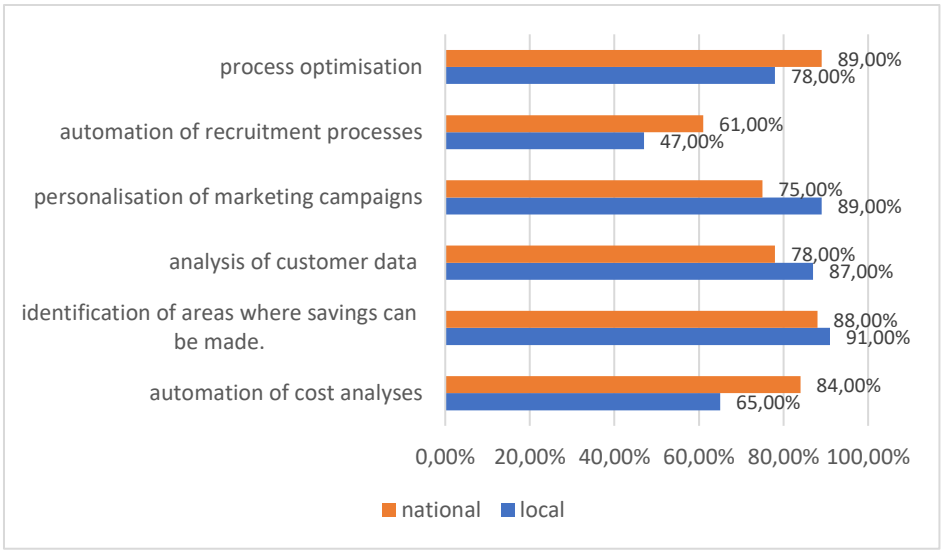


Figure 5. Expectations, in the context of AI solutions, for IT tools supporting the delivery of courier services
Source: own elaboration

An important area that could be supported by AI is the identification of areas where savings could be made. Both national operators (88% of indications) and local operators are strongly interested in this (90%). Operators also point to the possibility of optimising processes within their operations (89% of indications from national operators and 78% of indications from local operators). Closely linked to optimisation and the search for savings is the issue of cost analysis. Operators see the need to automate this process, using AI (84% of indications from national operators and 65% of indications from local operators). According to those surveyed, AI could also serve as a tool to help analyze customer preferences (78% of indications from national operators and 87% of indications from local operators). A better understanding of customer needs and expectations would influence more personalized marketing activities, with the support of AI. It should be noted that there is a high awareness of this among respondents (75% of indications from national operators and 89% of indications from local operators). Human factor issues, i.e. the recruitment process, in the opinion of respondents, could be supported by AI, but only think so (61% of indications of national operators and 47% of indications of local operators).

Subsequently, it was investigated whether actors were using AI to increase operational efficiency, through routing and navigation (Figure 6).

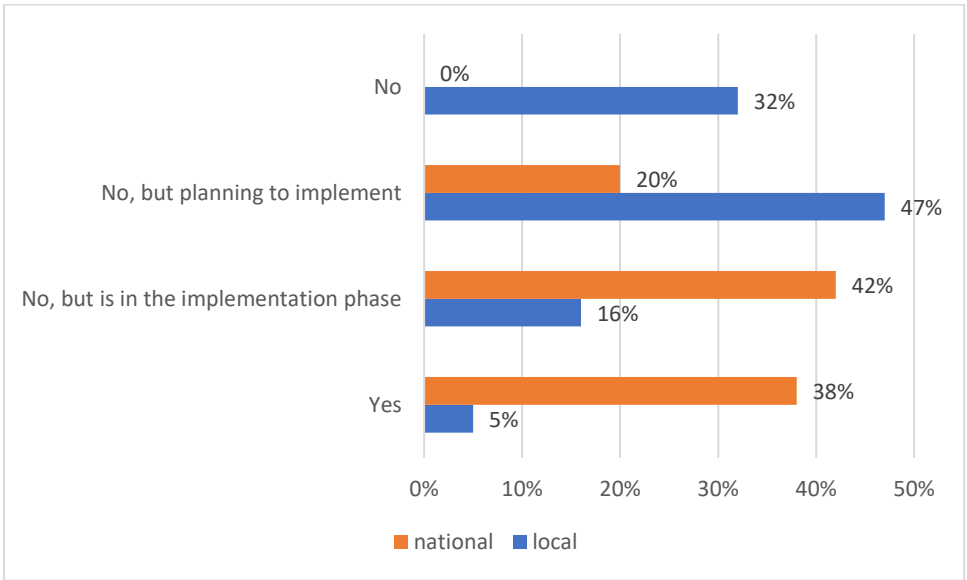


Figure 6. Improving operational efficiency through routing and navigation

Source: own elaboration.

Nearly 40 per cent of national entities have already taken advantage of this tool, 42 per cent are in the process of implementing it and 20 per cent are planning to do so, seeing a number of benefits in the efficient use of both human and physical resources in the entities surveyed, treating it as a strategic element in the entity's digitalisation.

Local operators approach these issues differently. Only 5% support themselves with AI for routing and navigation, and 16% are in the implementation stage. However, seeing the potential of this tool, almost half of the surveyed local entities (47%) are planning such activities in the near future. In contrast, almost a third of the surveyed local entities are not planning such activities.

Another issue that was highlighted in the study was the possibility of using AI to predict external phenomena, such as traffic congestion, unforeseen meteorological phenomena, among others, as shown in Figure 7.

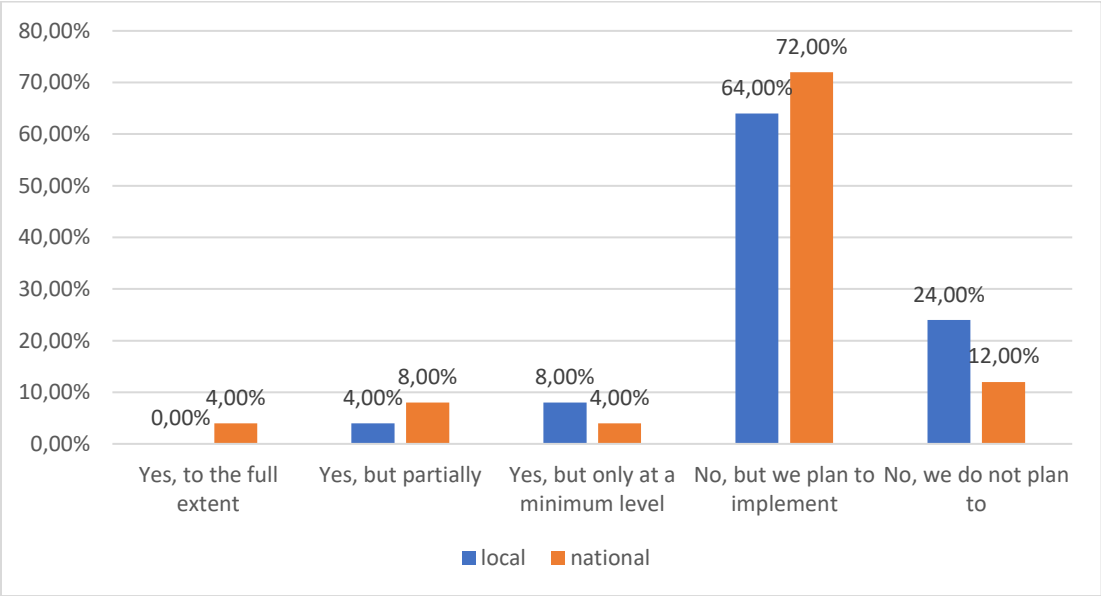


Figure 7. Use of AI to predict external phenomena affecting the delivery of courier services
Source: own elaboration.

It appears that this possibility is only just being recognized by the surveyed operators. Only 4% of the surveyed national operators favour its use to the full extent, 8% partially or minimally. In the case of local operators, none of the surveyed operators have yet used AI to its full extent. 4% of operators indicated that they use it partially or minimally (8% of the surveyed operators' indications). 12% of surveyed national operators and 24% of local operators indicated that they have no plans to do so as of the date of the survey.

However, the growing awareness of AI's potential is reflected in the survey results regarding plans for use. As many as 64% of local operators and 72% of national operators plan to expand the use of AI in the near future to include the prediction of external phenomena negatively affecting the delivery of courier services.

Subsequently, the entities' approach regarding the use of AI to predict customer behavior was verified, as presented in Figure 8.

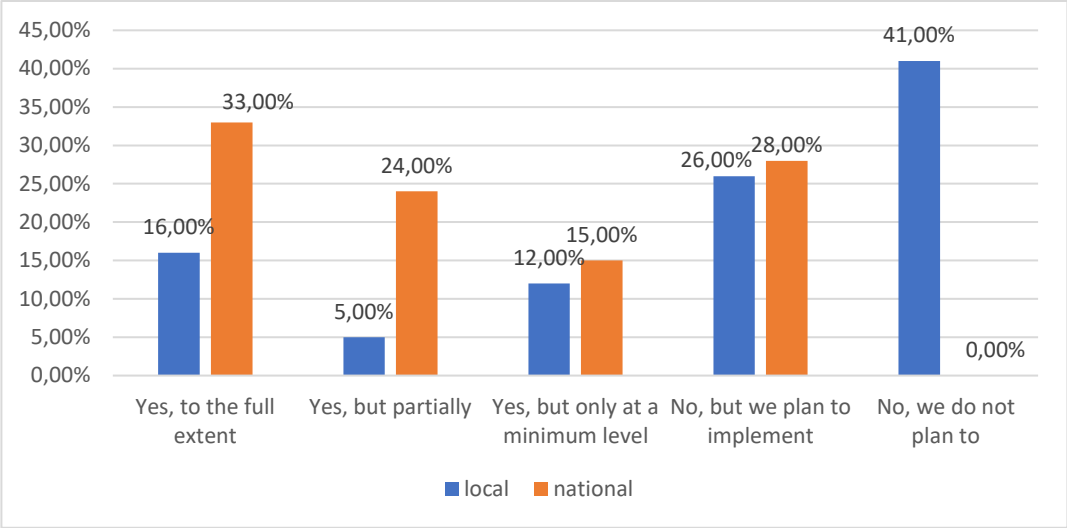


Figure 8. Using AI to predict customer behavior under the influence of external factors
Source: own elaboration.

The results of the survey indicate a high level of awareness regarding customer behavior, hence the need for monitoring. Nearly 70% of the national entities surveyed are using these solutions and the rest are planning to do so. A slightly different approach is presented by local entities. Here, just over 40% of respondents indicated the use of AI to predict customer behavior. There is also a high number of entities, almost 41%, that do not see such a need. This is mainly due to mental barriers, limitations of technological skills and fear of the high costs involved.

The final question explored in this article relates to the need for a 'roadmap', i.e. guidance, guidelines, which would enable the efficient use of advanced modern technologies and AI in managing the entire courier service delivery process (Figure 9).

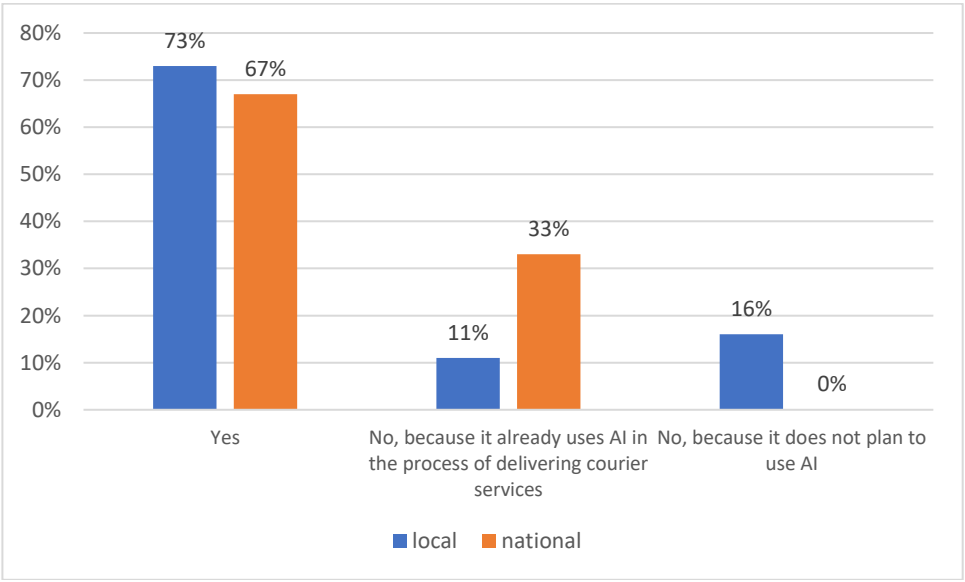


Figure 9. Is there a need for a 'roadmap' in the context of managing the courier service delivery process using advanced modern technology and AI?
Source: own elaboration.

73% of the surveyed local entities declare the need to have such guidelines in place for a smooth implementation of AI. Only 16% have no such need, as they have no plans to use AI. Experts who did not respond positively to this question do not rule out the possibility of using AI to streamline processes, but do not currently find a use for such a solution in their business. This position is influenced by a

number of factors, including the entity's area strategy, the specifics of the AI technologies used and their level of sophistication.

In contrast, for domestic entities, 67% of surveyed domestic entities indicate the need to have a 'roadmap' for AI. This is dictated by the desire to increase the efficiency of the entity's operations. Experts who indicated this course of action indicated that improving the courier service delivery process is a key idea and, at the same time

one of the key activities related to AI.

As with the introduction of any innovation, in the area of the market investigated in the article, AI can carry certain risks - One of these is mistakes made at the implementation and configuration stage of solutions. Incorrect parameters adopted when programming the automatic allocation assumptions, may result in shipments not being sent in the most optimal way, and incorrectly designed response paths, will result in handling bots, instead of reducing the number of contacts, generating more interventions and lowering the level of satisfaction of the end customer. It is therefore crucial to select the right tools and implement them in collaboration with specialists who understand the complexity of logistics processes and have experience in automating them AI is revolutionizing industry after industry, accelerating their technological transformation. However, for the wider postal market, it represents a powerful opportunity to automate and optimise processes. However, it is important to remember that with a highly competitive market, it is important to react to changing trends fast enough. Companies that do not introduce 'smart' solutions in time may lose distance to more technologically advanced competitors.

7. DISCUSSION

Undoubtedly, the incorporation of cost optimisation processes based on artificial intelligence can provide a new approach to optimising cost structures related to the delivery of mail on differentiated routes, especially in the context of the problem of their lengthening. The use of AI will allow to solve the problems related to the efficiency of postal services, which should have an impact on limiting the increase of fees for the services provided. AI's potential for economic efficiency, also comes from determining routes based on their profitability dynamics. AI tools can propose clustering of routes through in-depth analysis based on route profitability models. AI will give the opportunity to apply the right methodology, taking into account the efficient management of routes, by grouping them, taking into account their specific characteristics and operational requirements that ensure the economic sustainability of operators.

As a result, through the use of AI tools, an individual shipment route that might individually appear as unprofitable can become a synergistically aligned element of the network, allowing for economic efficiency. It should also be emphasised that the use of AI makes it possible to identify in advance potential bottlenecks and disruptions occurring in the operator's structures and to propose remedial actions.

AI also improves the sustainability of postal operations (Baláž et al. 2023). Through the use of AI, the reduction of CO2 emissions should be pointed out, in addition to operational efficiency through optimised routes. Effective climate management, in the context of minimising the carbon footprint, should be regarded as a huge challenge for the coordination of operators. Optimisation aimed at reducing CO2 emissions for operator operations is only possible through the use of advanced artificial intelligence algorithms. Furthermore, using the latest IoT solutions, through sensors integrated with AI, operators could access information on CO2 emissions, in real time, at every stage of the delivery process, increasing transparency and environmental awareness. The use of AI can support campaigns highlighting green initiatives, increasing trust and perception of operators. It should also be noted that accurate decarbonization data, validated by AI, can help operators apply for environmental subsidies, which will translate into further investment in green innovation. All the more so as today's institutional customers buying courier services are increasingly paying attention to the eco aspects of their carriers' offerings when finalizing contracts.

Operators using various data aggregation methods and a wide range of data such as, among others, weather forecast, volumes, route times, efficiency, last-mile channels or also geopolitical considerations,

are increasingly interested in engaging AI for estimating risks and recommending management decisions (Zindros, Anagnostopoulou, 2024).

Prediction correlated with operators' operational experience, could definitely reduce problems related to on-time delivery or reduced customer satisfaction.

Another area of impact of AI on operator activity, is the efficient management of resources. In the traditional set-up, many postal operators could use their resource potential (means of transport, warehouses, human resources) inefficiently, which could lead to lower operating efficiency. By using artificial intelligence to forecast demand, operators could more rationally plan the use of resources, adapting them to dynamically changing needs, responding in real time.

8. CONCLUSION

On the basis of the research carried out, it can be indicated that the intended objectives were achieved and the research hypothesis was verified.

In the context of the use of advanced IT tools in the implementation of courier services in the sensitive area of the first and last mile, the entities surveyed are aware of the importance of these tools for the smooth implementation of processes. They largely base it on professional tools. Improving management efficiency and meeting customer expectations are the main benefits of using advanced IT tools.

With regard to the functionality and automation of processes, there is clearly a growing awareness of the continuous modification of processes using IT tools at the first and last mile. The processes of shipment management, quality control and timeliness require continuous adjustment.

In the context of the use of mobile applications, there has been a clear indication of the need to have them, continually modifying and improving them, following ever newer, more user-friendly solutions for end users.

However, the most important issue was to analyse the use of AI to improve the delivery of courier services for the purposes of optimising sensitive processes at first and last mile level and predicting external phenomena that can significantly affect the delivery process. The study showed that the entities surveyed, are attempting to use, whether at a national or local level, routing capabilities, which significantly increases operational efficiency. Another attractive area, strongly emphasised by the surveyed entities, is the possibility of prediction, either of external phenomena affecting the realisation of courier services, or the predictability of customer behaviour, which significantly determine the planning of delivery processes in the courier services market. However, in order to achieve a high level of utilisation of the solutions that AI offers, it is necessary to propose certain solutions, guidelines, which will be a ‘roadmap’ for the courier services market players surveyed, as shown in Fig.10.

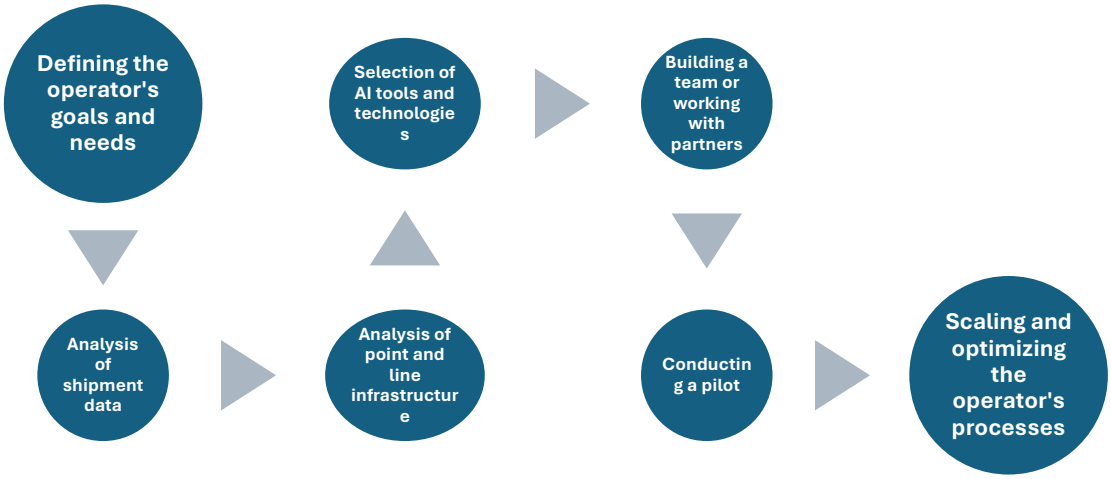


Figure 10. Roadmap for the implementation of AI by courier market players
Source: own elaboration.

Summarising the results of the survey, the following conclusions can be drawn. The entities of the courier services market are aware of the need to use advanced IT tools. Furthermore, it is important to develop functionalities based on modern technologies. The use of advanced IT tools together with AI tools will allow to gain a strong position in the competitive market of courier services.
Additional research is needed into the use of AI by courier market players, indicating which areas need to be developed and which have already reached their optimum.

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28th European Conference on Artificial Intelligence (ECAI 2025)

LARGE DATABASE OF AIS VESSEL TRAFFIC FOR SMART DECISION-MAKING BASED ON AI IN SHIPPING COMPANIES

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ABSTRACT

Purpose: *This study aims to assess the effectiveness of Principal Component Analysis (PCA) in identifying anomalies and improving data quality in AIS (Automatic Identification System) datasets used for maritime monitoring and decision-making.*

Need for the study: *AIS plays a crucial role in intelligent vessel traffic management across the shipping industry. However, despite its widespread adoption, the technology still suffers from issues of data consistency, accuracy, and integrity. These limitations reduce its effectiveness in supporting AI-based decision-making systems. Addressing these shortcomings is essential for improving operational efficiency, safety, and sustainability in maritime transport.*

Methodology: *The research utilizes PCA on a large-scale AIS dataset containing over 800 million records from the Baltic and North Seas. The data underwent filtering and cleaning before analysis to detect patterns, identify anomalies, and evaluate the consistency of variables such as latitude, longitude, draught, and speed. Additionally, t-SNE (t-distributed Stochastic Neighbor Embedding) and UMAP (Uniform Manifold Approximation and Projection) were explored as complementary nonlinear dimensionality reduction techniques.*

Findings: *PCA proved effective in detecting both extreme and subtle anomalies in the AIS data, including implausible draught values, unusual routing behaviors, and spatial inconsistencies. The analysis demonstrated that even mature systems like AIS can yield unreliable data, emphasizing the necessity for rigorous quality control. Furthermore, the study found that nonlinear methods like t-SNE and UMAP hold promise for enhancing dynamic monitoring.*

Practical Implications: *The integration of PCA-based analytics into maritime monitoring systems enhances early anomaly detection, reduces the risks of decision-making based on faulty data, and improves situational awareness. The study advocates for stronger AIS data governance standards and lays the foundation for future use of real-time anomaly detection and AI-driven decision support in maritime operations.*

Keywords: AI-driven decision making, big data, AIS data, smart decision-making, machine learning

Jel codes: C33, C55, C63, C65, C69

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1. INTRODUCTION

Ship operation, a complex and multifaceted domain, presents a unique set of challenges and goals that demand continuous monitoring and optimization to ensure efficiency, safety, and environmental sustainability. The shipping industry faces pressures such as rising fuel and crew costs, strict emission regulations, and volatile market cycles, necessitating innovative approaches to maintain competitiveness. Modern technologies, including automatic identification systems and satellite communication, are driving the need for updated contractual relationships and operational strategies (Rialland et al., 2014). The integration of artificial intelligence and machine learning approaches is crucial for managing complex integrated systems, meeting service requirements, and achieving energy efficiency targets in various maritime communications scenarios (Saafi et al., 2022). The use of machine learning has the potential to improve ship operational efficiency by analyzing voyage parameters, predicting optimal routes, and adjusting engine settings in real time (Wang et al., 2024). A seagoing ship is a self-contained, independent and separate entity, both technically and economically.

In economics, it is even accepted that a ship is a production facility for transport services. Apart from many common features with other production facilities on land, a ship differs fundamentally from any land-based activity. It operates in maritime areas without ongoing access to land infrastructure, utilities, social infrastructure and all the elements of everyday life. The paradigm of independence includes self-sufficiency, independence at a specific time without having to call at a port for any reason other than loading or unloading or major repairs. This results in the crew and cargo having no daily physical contact with interested parties on land. This is the main problem that ship owners have had to overcome for decades in relation to their shipping activities. The need for ongoing monitoring of what happens to and on the ship, itself stems from the natural need for proper ship management based on the best possible knowledge of decision makers. This knowledge should cover both the technical operability of the ship (fault-free operation, ongoing maintenance, current fuel and lubricant consumption, ongoing on-board electricity production) as well as navigational issues (avoiding stormy areas, optimising the route, utilising sea currents, ship trimming, cruising speed, etc.), or economic issues.

Data-driven approaches, which include collecting real-time performance metrics through onboard sensors and data acquisition systems, play a pivotal role in the trade of ship performance analysis and monitoring. Collecting data will allow operators to make better decisions in the lifecycle of the ship from design to redesign and lifetime extension (Hüffmeier & Johanson, 2021). These tools enable the creation of digital twins, which are virtual representations of physical assets, allowing for predictive maintenance, performance optimization, and scenario planning. The use of digital twins enhances decision-making processes by providing real-time insights into the ship's condition and performance, facilitating proactive interventions to prevent failures and improve operational efficiency.

The rise of digitalization in the maritime sector presents new opportunities for streamlining processes, improving decision-making, and enhancing overall efficiency (Gavalas et al., 2022). The temporal changes of marine economic efficiency along maritime routes can be classified as fluctuating, stable, or rising. The maritime industry is embracing new technologies to achieve swiftness and safety (Shaikh et al., 2021). The COVID-19 pandemic amplified pre-existing digitalization and environmental trends, leading to greater acceptance of digital solutions across the industry (Gavalas et al., 2022). Digital transformation can positively affect the maritime transport chain through optimized cargo handling, improved business processes, and minimized environmental impacts (Jović et al., 2022). Digitalizing seaport business processes can also enhance sea-land supply chain performance. Maritime operations stand to gain significantly from meticulous monitoring and optimization, addressing multifaceted challenges and pursuing ambitious goals within the shipping industry. The integration of advanced technologies, such as Artificial Intelligence and Machine Learning, emerges as a pivotal strategy for enhancing efficiency, safety, and sustainability across maritime operations (Saafi et al., 2022). The Automatic Identification System is particularly useful for gathering and exchanging data, offering possibilities for anomaly detection, route optimization, and collision avoidance, all of which improve safety and efficiency at sea (Montiel et al., 2021; Tu et al., 2016). The expansion of global trade, facilitated by initiatives like those of the World Trade Organization, is expected to increase maritime traffic, necessitating innovative solutions to manage this growing complexity while minimizing environmental impact (Montiel et al., 2021; Saafi et al., 2022). The social, environmental,

political, and economic effects of maritime transportation are substantial, as it is the most significant mode of transportation for goods and passengers, accounting for 80% of the volume and 70% of the value of all cargo, and there is a pressing need to meet sustainability standards. The lack of sufficient use of readily available AIS data is the source of the research challenge, which raises the possibility of higher expenses, delays, and risks in the maritime transport chain (Montiel et al., 2021).

2. LITERATURE REVIEW

The application of AI in maritime navigation is particularly promising, providing solutions to complex problems characterized by uncertainty and time constraints (MacKinnon et al., 2020). By leveraging data-driven approaches, AI algorithms can analyze vast datasets to identify patterns, predict potential risks, and optimize operational strategies, thereby enhancing decision-making processes (Wang et al., 2024). This includes tactical decisions related to traffic patterns and vessel encounters, akin to a game of chess where AI algorithms consider multiple moves in advance to optimize outcomes (MacKinnon et al., 2020). Furthermore, the implementation of AI-powered systems can automate routine tasks, freeing up human personnel to focus on more strategic and complex responsibilities. The incorporation of digital solutions and automation has the potential to greatly improve the offshore wind sector's operational effectiveness. AI-powered operations data, for instance, can cut inspection times by up to 50%, lower operating costs, and improve data quality and accessibility (Wang et al., 2024). The integration of AI in offshore wind superstructures has demonstrated the technology's potential for broad use, and progress in data gathering and processing enables real-time decision-making and predictive maintenance, improving the dependability and efficiency of offshore wind farms. The Automatic Identification System is a critical maritime technology designed to enhance safety and efficiency in vessel operations. AIS operates as an autonomous tracking and identification system, utilizing VHF radio waves to transmit data about a ship to other nearby vessels and coastal authorities (Muthulakakshmi et al., 2020). This system is crucial for collision avoidance, traffic monitoring, and search and rescue operations (Bao, 2004). AIS transmits a variety of data, including the vessel's identity, position (latitude and longitude), speed, course, heading, navigational status, and other safety-related information. This data is automatically broadcast at regular intervals, allowing other ships and coastal stations equipped with AIS receivers to track the movement and identity of vessels in their vicinity. The integration of AIS data with other navigational tools, such as radar and electronic charts, provides mariners with a comprehensive understanding of the maritime environment, improving situational awareness and decision-making capabilities. AIS data can be used for various applications, including vessel tracking, collision avoidance, search and rescue operations, and maritime domain awareness. AIS information, including vessel position, speed, and course, is stored and primarily used for vessel positioning. Real-time analysis of AIS data facilitates traffic anomaly detection, route optimization, and collision risk assessment, contributing to safer and more efficient navigation (Tu et al., 2016).

The Automatic Identification System has revolutionized maritime domain awareness, enabling real-time tracking of vessels globally (Šakan et al., 2018). This system, mandated for larger vessels by the International Maritime Organization (IMO, 2020), transmits data such as vessel identity (name, IMO number, MMSI number), position, course, speed, port of departure and arrival, contributing significantly to safety, security, and efficiency in the maritime domain in a regulated way (IMO, 2015). However, the effectiveness of AIS relies heavily on the consistency and completeness of the transmitted data. Although currently we can evaluate AIS as mature tool (Lee et al., 2019), several gaps and threats can be still observed (Lee et al., 2019; Eriksen et al., 2018), which negatively impact of data inconsistencies, further on emphasizing the need for robust data quality management, challenging AIS development in near future (Fournier et al., 2018). It is also crucial for all ship owner in real-time monitoring and supervision of owned fleet, enabling constant and swift responses for optimizing vessel voyages (Di Ciaccio et al., 2019).

Consistent and reliable AIS data is paramount for a multitude of maritime applications:

- Collision Avoidance: Accurate and timely AIS data is crucial for collision avoidance systems, allowing vessels to identify and maneuver in relation to other ships in their vicinity. Data gaps

or inaccuracies can lead to misjudgments and increase the risk of collisions (IMO, 2015; Goudossis and Katsikas, 2019).

- Search and Rescue: In SAR operations, real-time vessel tracking through AIS is vital for locating and assisting vessels in distress. Incomplete or inaccurate data can hinder rescue efforts and lead to delays in providing assistance (IMO, 2015).
- Maritime Security: AIS plays a crucial role in maritime security by enabling the detection of suspicious activities, such as piracy, smuggling, and illegal fishing. Data inconsistencies can create loopholes for illicit activities to go undetected (Aziz et al., 2020; Sciancalepore et al., 2021; AS, 2016; Balduzzi et al., 2018).
- Environmental Protection: AIS data is used to monitor vessel movements in sensitive marine environments, ensuring compliance with environmental regulations and supporting efforts to protect marine ecosystems. Data gaps can hinder the effectiveness of such monitoring efforts (IMO, 2020).
- Traffic Management and Efficiency: Port authorities and Vessel Traffic Services rely on AIS data for efficient traffic management, optimizing vessel routing, and minimizing congestion. Inconsistent data can lead to inefficiencies and delays in port operations (AS, 2016).
- Maritime spatial planning: maritime authorities, regional and national governments are feeded by the data on maritime are used by different stakeholders (Fiorini et al., 2016) and therefore can predict real need for it in the future and to divide areas by types of use in case of such excluding each other.
- Monitoring of vessels' traffic: with the main goal of AIS being to provide real-time vessel traffic data.

Despite its importance, AIS data consistency faces several challenges:

- Technical Limitations: AIS transmission range is limited by factors such as weather conditions, signal interference, and geographical obstructions. This can result in data gaps, particularly in remote areas with limited AIS receiver coverage (Sciancalepore et al., 2021; Fournier et al., 2018).
- Data Manipulation: Intentional manipulation of AIS data, known as "AIS spoofing," poses a significant threat to data integrity. Malicious actors can transmit false information, creating ghost ships or disguising a vessel's true identity and activities (Androjna et al. 2021; Aziz et al., 2020; AS, 2014].
- Human Error: Errors in AIS configuration, data entry, or system operation can lead to inaccuracies and inconsistencies in transmitted data, where intelligent management systems could be applied (John, 2014).
- Data gaps and inaccuracies: there can be observed several gaps in data continuation provided by each vessel, as well as data apparently out of the reality (i.e. speed of 100 kn at sea), which degenerated the outcomes of any analysis made based on the data by looking for trends, exemptions, dominants and other factors being of stakeholders' interest. This has also negative impact on the research performed by using AIS data.
- Data Overload and Management: The vast volume of AIS data generated globally presents challenges for data storage, processing, and analysis. Effective data management strategies are crucial for ensuring data quality and consistency (John, 2014).

To mitigate the challenges to AIS data consistency, a multi-faceted approach is required:

- Technological Advancements: Continuous improvements in AIS technology, such as increased transmission power, enhanced receiver networks, and satellite-based AIS, can enhance data coverage and reduce data gaps (Chen, 2014; John, 2014).
- Data Validation and Verification: Implementing robust data validation techniques, including cross-checking AIS data with other sources and using algorithms to detect anomalies, can help identify and flag inconsistencies (Di Ciaccio et al., 2019; Šakan et al., 2018).
- International Cooperation and Regulation: Strengthening international cooperation and regulations related to AIS data quality, including mandatory data reporting standards and penalties for data manipulation, is crucial (IMO, 2020).

- Data Sharing and Collaboration: Promoting data sharing and collaboration among maritime stakeholders, including governments, industry, and research institutions, can facilitate the development of comprehensive solutions for data quality management (IMO, 2020).

Addressing the challenges to data quality requires a collaborative effort involving technological advancements, robust data management practices, and strengthened international cooperation. By prioritizing AIS data consistency, we can unlock the full potential of this vital system for a safer, more secure, and more efficient maritime domain. In this meaning, the data provided by AIS should undergo permanent improvement. One of the possible pathways is presented by this paper attempting addressing the data validation and verification for further elaboration using method proposed below.

The integration of Artificial Intelligence and Machine Learning offers a promising avenue for addressing the complexities inherent in managing integrated maritime systems, enabling stakeholders to meet service requirements and energy efficiency targets across diverse maritime communication scenarios. The importance of sustainability in maritime activities is heightened by growing environmental awareness and regulatory pressures. This necessitates the adoption of strategies that minimize environmental impact while maximizing operational effectiveness. Operating costs, encompassing crew, maintenance, insurance, and overheads, alongside voyage costs like fuel, constitute a significant portion of a shipping company's expenditures (Tu et al., 2016). Consequently, effective cost management is essential for maintaining profitability and competitiveness in the maritime market. Furthermore, optimizing the operational efficiency of ships is pivotal for curbing greenhouse gas emissions and fostering environmental stewardship within the maritime sector. The incorporation of real-time data analytics and predictive modeling facilitates proactive decision-making, enabling shipping companies to mitigate potential disruptions and optimize resource allocation. Moreover, the industry is increasingly embracing automation and digitalization to optimize operations, reduce inspection timelines, and enhance data quality, demonstrating the potential for achieving climate goals while driving economic growth (Saafi, Vikhrova, et al., 2022; Saafi, Вихрова, et al., 2022; Wang et al., 2024).

Monitoring and optimization of ship operations are pivotal in addressing these challenges and achieving industry goals, necessitating the integration of advanced technologies and innovative strategies. Furthermore, the rise of autonomous vessels introduces additional layers of operational and regulatory considerations, requiring thorough risk analysis and assessment of factors such as human errors, mechanical malfunctions, weather conditions and cybersecurity (Koikas et al., 2019). The integration of artificial intelligence offers a promising avenue for improving safety and efficiency in shipping, providing solutions to navigation problems that are often complicated by information uncertainty, complexity, and time constraints. AI's ability to make tactical decisions by analyzing traffic patterns and predicting vessel encounters mirrors strategic games like chess, where anticipating future moves is crucial (MacKinnon et al., 2020). The reliance on readily available Automatic Identification System data is paramount for improved route prediction and optimization of seaport operations, which can effectively reduce undesirable events such as collisions and congestions, thereby mitigating delays and associated costs (Montiel et al., 2021). The proactive application of AI can significantly reduce inspection timelines, potentially by up to 50%, lower operational costs, and improve data quality and accessibility (Wang et al., 2024).

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

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3. DATA AND METHODOLOGY

3.1. AIS database

The analyzed AIS database was acquired on a commercial basis from the S&P Global data provider, specifically within IHS Markit. In its entirety, the database comprises over 8,225 indicators that describe a ship, with data being (or at least expected to be) sourced from the vessel registration authority.

In total the authors had at their disposal the database of 828,942,961 records, whereof 324,785,448 were selected for initial revision covering vessels being reported in the region of North Sea and Baltic Sea during last 15 years. The database has been prepared structured by 13 characteristics listed in the Table 1. As such, the commercial database is provided by the AIS operator for any ship owner demanding real-time data on the vessel/fleet status.

Table 1. AIS data and their definition

Head of column	Description
LR IMO Ship No	Unique ship identifier (seven-character number allocated by IHS Maritime).
Call Sign	Callsign. An Alpha numeric identifier used for radio communications. Each flag authority has a designated call sign range, from which the national radio authority issues a call sign for each vessel in that fleet.
Destination	Destination as entered by personnel on board the ship.
Draught	Draught of vessel in Meters, as entered by the personnel on board the ship
ETA	Estimated Time of Arrival to the destination as entered by personnel on board the ship.
Heading	True heading if present else course over ground.
Latitude	Used to express how far north or south the position is, relative to the equator. Values given in decimal, valid range 90 to +90.
Longitude	Location shown in a east-west direction relative to the Greenwich meridian. Values given in decimal, valid range -180 to +180.
MMSI	Mobile Maritime Station Identifier (MMSI) is a 9-digit number used to identify vessels in VHF radio communications. The first three digits denote the country of registry. When a flag change is affected, this number will also change.
Movement Date Time	Date/time where/when the movement was recorded.
MoveStatus	Navigational Status (moored, under way, not under command, etc.).
Ship Name	Vessel Name in English format, as recorded by the vessel's registration authority. To avoid problems with fonts and characters sets the name may use nearest equivalent English character.
Speed	Maximum vessel Speed in knots when the ships engine is running at Maximum continuous rating (MCR).

Source: AIS Database: www.maritime.ihs.com.

The database is supported by the Microsoft SQL Server 2022 engine, all data for the Baltic Sea basin is located in one database, in one table, in which all columns are of the basic text type varchar(50).All processing attempts consisting of automatic conversion (SQL language functions and Microsoft SQL Server engine) from text type to the type consistent with the purpose (dates, numbers) for the entire database failed, due to unsupported ranges and existing values. Since the research intended to use only data for the selected period and selected units, a different approach was used. First, the desired data was filtered and exported from the database to a CSV file and then, using the Python conversion function from text type to dates with time (datetime.fromisoformat) and numbers (float, int), the data was converted and validated.

A total of 100,000 records were selected from the AIS database for 10 selected ships operating regularly on the route between Świnoujście and Trelleborg or Ystad in the date range between 2023-04-

07 and 2024-12-31. The selection was made according to the MMSI column for the following ships: 209183000 (m/v Copernicus), 209867000 (m/v Gryf), 210174000 (m/v Varsovia), 311000330 (m/v Mazovia), 209864000 (m/v Polonia), 209911000 (m/v Skania), 209869000 (m/v Wolin), 265866000 (m/v Tinker Bell), 210425000 (m/v Epsilon), 210095000 (m/v Galileusz).

Data analysis was therefore carried out on data after conversion and validation, saved in CSV files.

3.2. PCA method

Principal Component Analysis (PCA) is one of the fundamental machine learning techniques used for dimensionality reduction. It is particularly useful for visualizing complex datasets and for preprocessing data for machine learning models, as it helps reduce redundancy and noise while preserving important information. By transforming the dataset into a new coordinate system, PCA enables also detecting anomalies by indicating points that are far away from typical cases (i.e. the main cloud(s) of points).

PCA techniques have already been used in the context of AIS database, but mainly in problems related to the analysis of ship trajectories and collision detection (Jao et al., 2018). The PCA algorithm relies on numerical data represented by p variables (X1, X2, ... Xp) measured for n statistical units:

No.	X_1	X_2	...	X_p
1	x_{11}	x_{21}		x_{p1}
⋮	⋮	⋮	⋮	⋮
n	x_{1n}	x_{2n}	...	x_{pn}

These data may be represented by a matrix X of dimensions n × p. The first step of the algorithm is to standardize X, producing X^std, by subtracting the mean from each column and dividing by its standard deviation:

$$X^{std} = (X - \mu)\Sigma^{-1} \tag{1}$$

Here, μ represents a matrix of the same dimensions as X, where each entry corresponds to the mean of its respective column. Similarly, Σ is a diagonal matrix containing the standard deviations of the corresponding columns.

Dimensionality reduction using the PCA algorithm is achieved by introducing a new set of variables, $Z_1, Z_2, \ldots, Z_p$, where each successive variable captures a smaller proportion of the variance in the original data. Reduction is then performed by discarding the least influential variables, allowing the analysis to focus on a smaller subset that is easier to visualize and more suitable for applying other machine learning algorithms. The newly introduced variables are linear combinations of the original ones:

$$\begin{aligned} Z_1 &= a_{11}X_1^{std} + a_{12}X_2^{std} + \cdots + a_{1p}X_p^{std} \\ Z_2 &= a_{21}X_1^{std} + a_{22}X_2^{std} + \cdots + a_{2p}X_p^{std} \\ &\vdots \\ Z_p &= a_{p1}X_p^{std} + a_{p2}X_2^{std} + \cdots + a_{pp}X_p^{std} \end{aligned} \tag{2}$$

Here X_k^{std} denotes *k*-th column of X^{std}.

It is useful to form a matrix Z containing columns Zk from the above equation. Then the above set of equations can be reformulated as

$$Z = XA^T, \tag{3}$$

where A is a matrix of coefficients to be computed to obtain principal components. The way to compute matrix A is to start with the correlation matrix

$$C_X = (X^{std})^T X^{std} \tag{4}$$

and then to compute its eigenvalue decomposition

$$U^{-1}C_X U = \Lambda \tag{5}$$

It can be shown that $A = U^{-1}$ (i.e. it is a matrix containing eigenvectors of the correlation matrix for our data).

The consequence of Λ being diagonal (which is an essential part of eigenvalue decomposition) is that the principal components are orthogonal. Thus, we can think of them as independent coordinates describing our data. The eigenvalues in matrix Λ correspond to the variance explained by the principal components. Therefore, we can reduce a complex dataset to only the most essential variables (i.e. those which explain most of the variance).

4. RESULTS

In this analysis, Principal Component Analysis (PCA) was applied to explore the interrelationships between four key numerical variables: Latitude, Longitude, Draught, and Speed. The primary objective was to identify two new variables Z_1 (Principal Component 1) and Z_2 (Principal Component 2), which are linear combinations of these four variables and explain the maximum possible variance in the dataset.

All the computations were performed using Python 3.10.12. Implementations of PCA and t-SNE algorithms were taken from package scikit-learn v. 1.6.1, while packge umap-learn v. 0.5.7 was used when UMAP algorithm was considered. Visualisations were made using matplotlib v. 3.10.1.

One significant challenge in this analysis arose from the fact that these variables are measured on different scales and in different units. Latitude and Longitude are expressed in degrees, Draught is measured in meters, and Speed is given in knots. To account for these differences, each variable was standardized, meaning it was transformed to have a mean of zero and a standard deviation of one (cf. Data and Methods).

This standardization process allows each variable to contribute equally to the analysis, ensuring that no single variable dominates due to its scale.

By applying PCA, we reduced the dimensionality of the dataset, creating a two-dimensional representation that is easier to visualize. The algorithm estimated, based on the data, formulae for the principal components:

$$Z_1 = 0.6528 \times Latitude - 0.5530 \times Longitude - 0.0405 \times Draught - 0.5161 \times Speed$$
$$Z_2 = 0.1413 \times Latitude + 0.3016 \times Longitude + 0.9177 \times Draught - 0.2166 \times Speed$$

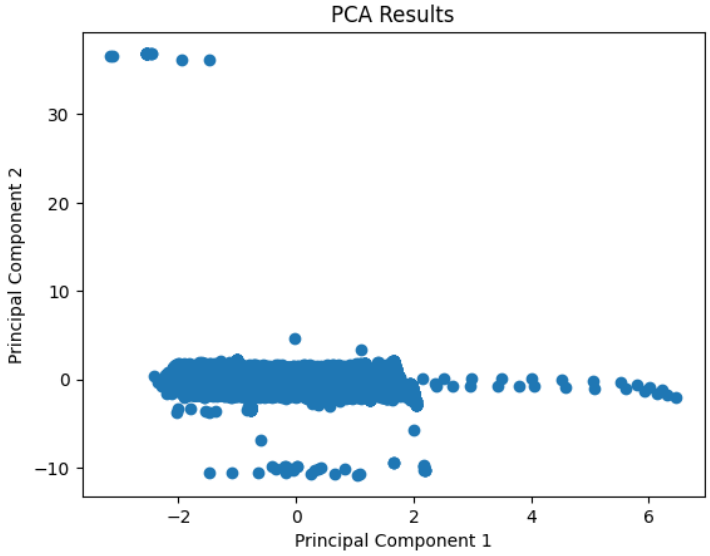


Figure 1. Visualization of principal components computed for the whole dataset
Source: own elaboration.

The visualization of principal components presented in Figure 1 reveals that most data points cluster within the ranges $Z_1 \in [-3,3]$ and$Z_2 \in [-3,2]$, with several distinct outliers identified outside these ranges. These outliers likely represent atypical combinations of the original variables, which can be seen more clearly after the dimensionality reduction process.

The current analysis offers a static view of ship positions at a specific time. However, a potential next step would be to extend this analysis to consecutive ship positions, thus creating a higher-dimensional dataset that may uncover more nuanced patterns in ship movement dynamics. This approach could yield further insights into the factors driving atypical ship behavior over time, enriching our understanding of maritime movement.

A prominent set of outliers in the data corresponds to cases where $Z_2 > 30$. Based on the formula for Z_2, it appears that Draught is the most influential variable in determining the values of this principal component. Consequently, we expect that these cases may differ from typical data points in terms of Draught. Our investigation confirms this expectation.

Upon examining these outliers, we observe that all the data points originate from a single ship. The last two data points in this set are from a different passage of the same ship, as evidenced by the difference in their MovementDateTime. Upon further inspection, the primary issue with these records lies in the Draught variable - its value exceeds 20m for each data point. As anticipated, the typical values for Draught do not exceed 10m, a pattern which is clearly illustrated in the following boxplot. This anomaly in Draught suggests that these outlier points deviate from the expected behavior, contributing to their unusual position in the PCA plot.

On the other hand, we anticipate that cases with exceptionally low Z_2 might correspond to unusually low Draught values. This pattern is indeed evident in the data itself – the values were about 0.5 m. The data points exhibiting these unusual values come from a variety of ships. However, many of them appear to originate from a single voyage of the m/v Galileusz ship, with the remaining data points seeming somewhat incidental.

In the PCA results plot on Figure 1, we observe a distinct "tail" of points with Z_1 values greater than three. Upon further investigation, we find that these points originate from two ships: m/v Varsovia and m/v Epsilon.

Since we are focusing on Z_1 we can reasonably conclude that the anomalies observed here are unlikely to be related to Draught. Instead, we suspect that they may be associated with the ships' positioning. As shown in Figure 2, both m/v Varsovia and m/v Epsilon appear to have followed atypical routes.

It is possible that these ships were traveling near Denmark. However, the database entries for these routes seem somewhat erroneous, possibly due to missing data points. In the tables below, we have examined the entries for m/v Varsovia and m/v Epsilon. Notably, the data points furthest from Denmark begin at seemingly arbitrary locations at sea. This is probably another error in the database that was discovered.



Figure 2. Unusual route discovered during analysis of the database using the PCA method
Source: own elaboration.

Follow-up PCA

After removing the previously identified outliers, we performed another PCA to refine our understanding of typical and atypical data points. This approach allows for a clearer distinction between normal variations and genuine anomalies, as per visualization in the Figure 3.

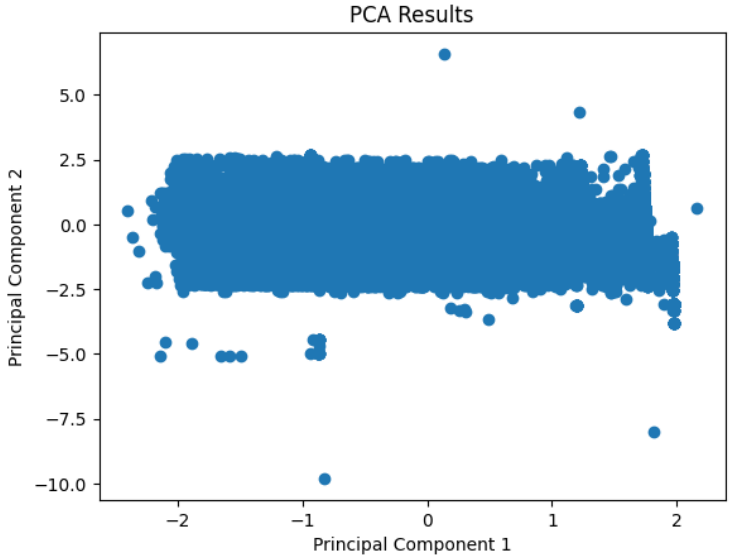


Figure 3. Results of the follow-up PCA after removal of the most significant outliers
Source: own elaboration.

The updated principal component formulas are as follows:

$$Z_1 = 0.6537 \times Latitude - 0.5461 \times Longitude - 0.0083 \times Draught - 0.5238 \times Speed$$

$$Z_2 = 0.2079 \times Latitude + 0.3233 \times Longitude + 0.9186 \times Draught - 0.0921 \times Speed$$

The values remain largely consistent with the previous results. However, the most notable change is the lower coefficient for Speed in Z_2 which is expected since outliers can significantly influence the computation of principal components.

Despite the removal of major outliers, some anomalies remain. The most interesting cases might be those that are relatively close to the main data cluster, as they may provide additional insights. Meanwhile, the extreme values of Z_2 are likely still linked to incorrect Draught measurements. To verify this, we investigated records with values greater than 3 or less than -7.5. Records satisfying this condition have Draught values around 2.5m (for those at the lower end of the distribution) or around 8m (for those cases at the upper end of the distribution) indicating these are somewhat atypical values.

Another set of points of interest comes from a small cluster with values around -4. The corresponding records, along with two cases from the previous table, are presented below. Most of these data points originate from two passages of the ships m/v Galileusz and m/v Gryf. A closer inspection of their coordinates reveals that they correspond to locations in Zalew Szczeciński, which is an unusual route for most ships in our dataset. These ships were likely flagged due to their slightly lower Draught values.

Additionally, two other records identified in this analysis (also appearing in the previous table) belong to m/v Skania and m/v Galileusz. The coordinates for m/v Skania correspond to a port in Świnoujście, while those for m/v Galileusz point to a port in Trelleborg in this case.

5. DISCUSSION

The current analysis offers a static view of ship positions at a specific time. However, a potential next step would be to extend this analysis to consecutive ship positions, thus creating a higher-dimensional dataset that may uncover more nuanced patterns in ship movement dynamics. This approach could yield further insights into the factors driving atypical ship behavior over time, enriching our understanding of maritime movement.

As we pointed out this type of PCA-analysis may detect "static" errors - e.g. due to incorrect locations, draught. However, if we are interested in the dynamics, we might perform this analysis on the consecutive values of the variables (e.g. consecutive locations). This requires casting data to time series format for each ship individually.

We performed some work in this direction by applying the above PCA-analysis for the records from ships with the largest numbers of records. We did not dig into the outliers just as before, but we just present the PCA plots for ships: m/v Tinker Bell, m/v Skania and m/v Mazovia. As we can see in the above plots, some outliers are visible - they require further investigation.

It is important to underline that this approach is exploratory in nature – we do not construct a model of the data that needs to be validated on a separate dataset. The only validation that was performed involved manual investigation of the detected outliers and their verification based on our knowledge of the vessels.

5. 1. m/v Tinker Bell



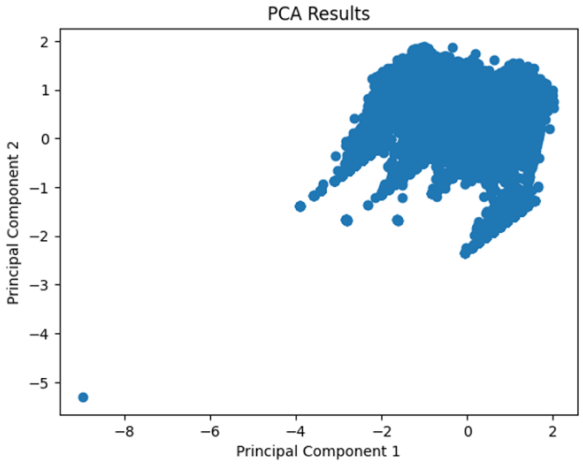


Figure 4. Results of PCA performed based on records on m/v Tinker Bell (lower panel) and locations of the ship registered in the database (upper panel)
Source: own elaboration.

5.2. m/v Skania

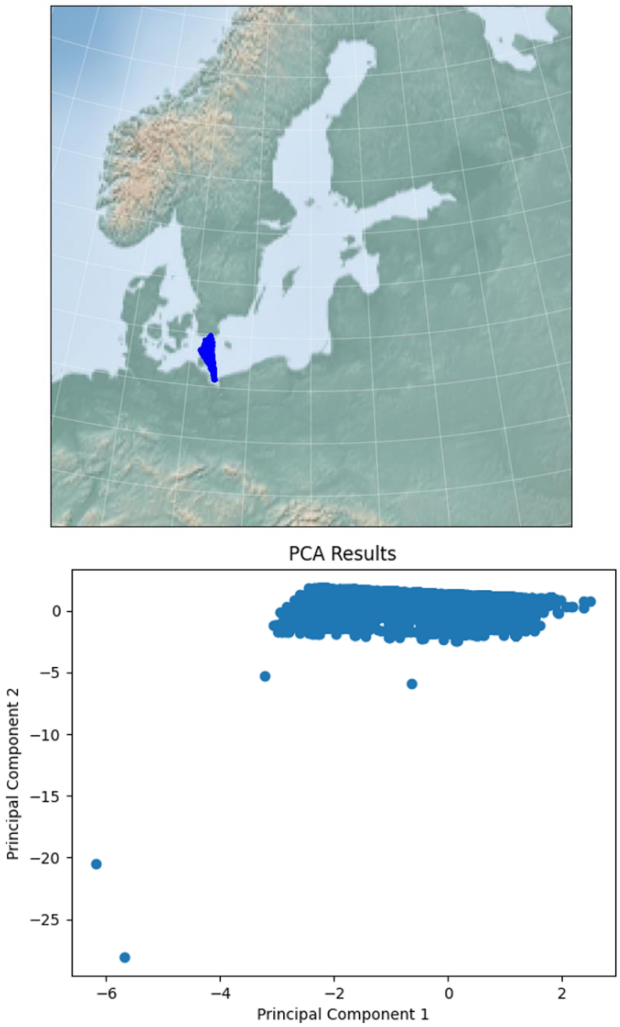


Figure 5. Results of PCA performed based on records on m/v Skania (lower panel) and locations of the ship registered in the database (upper panel)
Source: own elaboration.

5.3. m/v Mazovia

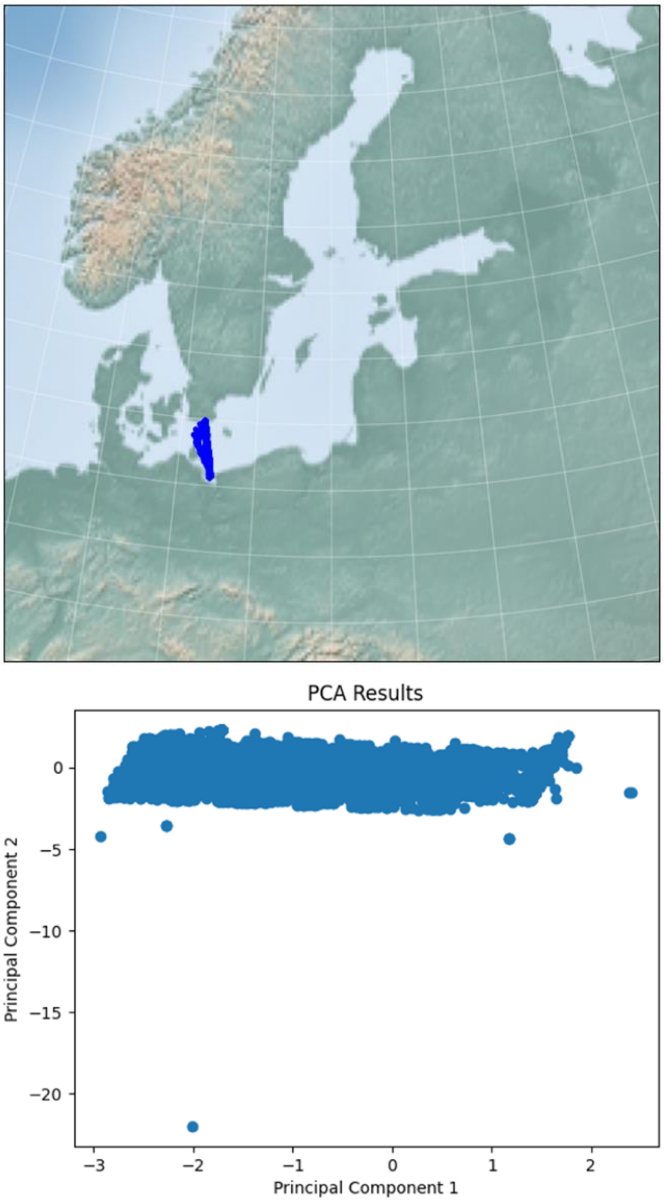


Figure 6. Results of PCA performed based on records on m/v Mazovia (lower panel) and locations of the ship registered in the database (upper panel)
Source: own elaboration.

5.4. T-SNE and UMAP algorithms

T-SNE and UMAP are algorithms that allow us to perform an analysis like PCA. They are, however, nonlinear algorithms which allow us to perform more nuanced analyses. They, however, have multiple hyperparameters to adjust. And are not as interpretable as PCA-components.

Here, we present some examples (performed for m/v Mazovia), to point out that (after some work) these algorithms might be useful in detecting anomalies in the database.

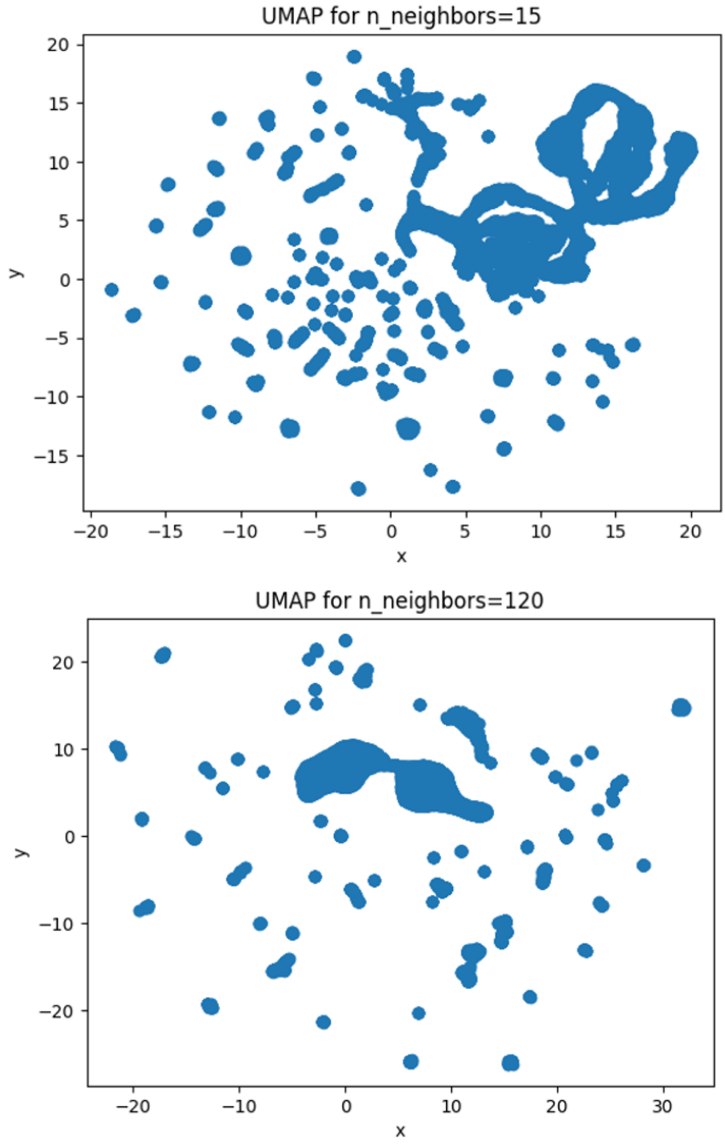


Figure 7. Results of UMAP dimensionality reduction based on records on m/v Mazovia. Two values of hyperparameter n_neighbors were selected: 15 (upper panel) and 120 (lower panel). The parameter controls the number of neighbouring points considered by the algorithm
Source: own elaboration.

As we can see, pictures we get for different values of hyperparameter n_neighbours is somewhat different. However, the general trend is still visible (we can see the main "bulk" of data surrounded by multiple groups of outliers. These need further investigation.

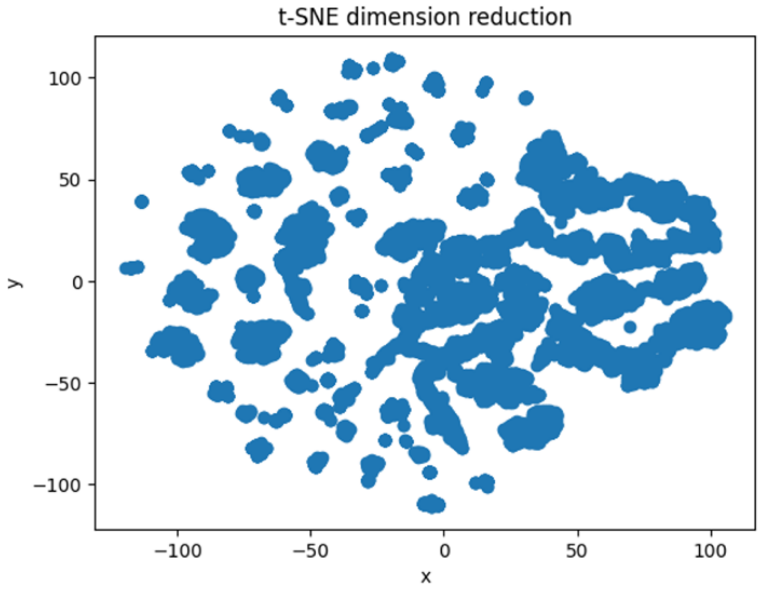


Figure 7. Results of t-SNE dimensionality reduction based on records on m/v Mazovia
Source: own elaboration.

Above we presented t-SNE plot for the same part of the dataset (m/v Mazovia). The picture we got this time is different. This algorithm still requires hyperparameter tuning, and some simple clustering need to be performed to see what the groups of points really mean.

The application of PCA to AIS data has proven effective in identifying both clear and subtle anomalies in ship movement data. This aligns with previous studies where PCA was used in trajectory simplification and collision detection (e.g., Jao et al., 2018), yet our approach focused more broadly on data validation and quality assurance within a real-world, large-scale dataset. The insights gained from this analysis have important implications for both academic research and practical maritime operations.

One of the key strengths of the PCA approach is its ability to compress multivariate data into easily interpretable visual representations, which can help stakeholders—such as fleet operators, port authorities, and maritime administrators—quickly identify vessels or voyages that deviate from standard behavior. These deviations may result from data input errors, unusual operational decisions, or technical malfunctions. As such, PCA could serve as a first-step screening method in more comprehensive vessel monitoring systems or be embedded into early warning systems to trigger closer inspection of suspicious AIS signals.

Moreover, the results suggest that some anomalies—particularly those relating to ship draught—may systematically affect specific vessels or routes. This raises questions about data governance in the maritime industry, including the need for better onboard data entry standards, real-time plausibility checks, and cross-verification mechanisms. The reliance on self-reported variables like draught and destination exposes AIS to human error, which, if not corrected, undermines the utility of such datasets for high-stakes applications like route optimization, congestion forecasting, or environmental enforcement.

While PCA offers significant advantages in interpretability and speed, its linear nature limits its capacity to capture complex, nonlinear relationships in maritime data. As demonstrated in our exploratory application of t-SNE and UMAP, nonlinear techniques may offer additional insights by revealing hidden clusters or transition zones in ship behavior that are not evident through PCA alone. However, the lack of interpretability and sensitivity to hyperparameters make them less suitable for operational use without further standardization. A hybrid approach, where PCA is used for broad anomaly detection and nonlinear methods for deeper pattern discovery, may represent an optimal solution.

Additionally, this study has focused on a static cross-sectional snapshot of ship behavior. While useful for identifying anomalous states at given points in time, future work should explore temporal modeling—treating AIS records as time series. Time-aware PCA, recurrent neural networks, or

transformer-based architectures could reveal not just what is anomalous, but also when and how such anomalies develop over time. Such models could help distinguish between short-term deviations (e.g., weather avoidance maneuvers) and systematic problems (e.g., miscalibrated sensors).

From a data governance perspective, the results underscore the urgent need for improved international standards on AIS data quality reporting. The presence of records showing implausible speeds or starting "mid-sea" highlights gaps in both data validation and satellite reception coverage. Developing shared protocols for automated anomaly detection, along with penalties or technical feedback loops for recurring issues, may significantly enhance the reliability of AIS-based systems in both civil and commercial domains.

Finally, it is worth acknowledging the limitations of this study. Although PCA revealed meaningful patterns, the focus was limited to four numerical variables and a subset of ships and voyages. Extending the model to include categorical data (e.g., vessel type, flag state, navigational status) or integrating external data sources (e.g., weather, sea state, port traffic) could enrich future analyses and support the development of more comprehensive maritime intelligence platforms.

6. CONCLUSION

This study has demonstrated the significant potential of Principal Component Analysis (PCA) as a method for assessing and improving the quality of Automatic Identification System (AIS) data in the maritime domain. By applying PCA to a large, real-world dataset consisting of millions of AIS records collected in the North Sea and Baltic Sea regions, we were able to detect both technical and operational anomalies in vessel movement data. Specifically, we focused on key numerical variables—Latitude, Longitude, Draught, and Speed—and successfully transformed these into new, uncorrelated components (Z_1 and Z_2) that preserved the most relevant variance in the original data.

The results revealed that PCA not only facilitates dimensionality reduction and visualization of complex maritime datasets but also serves as a robust tool for anomaly detection. The identified outliers, particularly those with extreme values of principal components, were traced back to specific inconsistencies—such as implausible draught measurements exceeding typical operational ranges, abnormal positioning data likely caused by signal or reporting errors, and navigation patterns deviating significantly from standard routes. These issues, if not properly addressed, can severely compromise the validity of analyses based on AIS data, leading to erroneous conclusions in operational monitoring, traffic forecasting, or maritime spatial planning.

Furthermore, we demonstrated that removing clear outliers and reapplying PCA leads to more stable and interpretable results, supporting the use of PCA as an iterative data-cleaning and exploratory analysis tool. Even after the exclusion of extreme cases, some subtle anomalies remained, suggesting that AIS data quality issues are not limited to egregious errors but may also include marginal cases that require more nuanced detection methods. These findings highlight the necessity of implementing continuous validation and verification mechanisms when dealing with large AIS datasets, especially as they increasingly support AI-driven decision-making in maritime navigation, logistics, and safety systems.

The discussion also touched upon the potential of dynamic and nonlinear extensions of PCA, such as time-series PCA, t-SNE (t-distributed stochastic neighbor embedding), and UMAP (Uniform Manifold Approximation and Projection). These techniques allow for the exploration of temporal behavior, local structure preservation, and more complex anomaly patterns, which are particularly valuable in scenarios involving route prediction, traffic density analysis, or automated vessel behavior classification. Although these methods require more tuning and computational resources, they provide a promising path forward for future research into high-resolution, real-time maritime data analysis.

Importantly, this research reinforces the notion that AIS data—despite being a mature and widely adopted technology—still faces critical challenges related to data integrity, transmission gaps, and potential manipulation. Ensuring the quality and consistency of AIS data is essential for unlocking its full potential in domains such as environmental monitoring, vessel traffic services, collision avoidance systems, and maritime domain awareness. By showcasing how PCA can contribute to this effort, the study paves the way for more systematic, transparent, and data-driven practices in the maritime sector.

In conclusion, PCA proves to be a valuable methodological approach for maritime data analysis, offering practical benefits for anomaly detection, data quality assessment, and exploratory visualization. Its integration into maritime analytics pipelines can substantially support operational efficiency, safety management, and sustainability objectives across the global shipping industry. Future studies should aim to combine PCA with other machine learning techniques and investigate its utility in dynamic, real-time environments where decision support systems depend heavily on the quality of streaming maritime data.

The complexity of events that vessels may encounter during a voyage, as highlighted in this article, will, in the authors' view, increasingly require not only further improvements in data collection through the AIS system, but also support from AI-based tools. The integration of artificial intelligence is expected to significantly enhance maritime traffic management across various levels, including:

- between shipowners and individual vessels within their fleets (fleet management),
- between vessels operated by different shipowners (alerts regarding unusual phenomena, such as pirate activity or canal blockages),
- between vessels and specialized maritime services onshore (e.g., reporting abnormal situations like damage to underwater energy infrastructure caused by another unit),
- and between vessels and port authorities (in relation to abnormal situations in access channels or within ports – such as spills, collisions, or groundings).

Funding: The analyzed database was purchased on a commercial basis from the company S&P Global data provider. The database consists of more than 225 indicators describing a ship, where data is sourced from the vessels registration authority. The database purchased for the study was selected by the region of ships' appearance with the limitation to the Baltic Sea and the North Sea in the time frame of 2011 – 2024, where each unique record related to the unique (in time at least) ship's position. This research was partially supported by National Ministry of Science in Poland as part of the statutory activities of the University of Gdansk.

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ANALYSIS OF SUPPORT FOR THE DEVELOPMENT OF INNOVATION IN HYDROGEN TECHNOLOGY SECTOR ENTERPRISES IN THE REGIONS BASED ON EMPIRICAL RESEARCH - DECISION PROJECT

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ABSTRACT

Purpose: *Energy and hydrogen technologies are considered to be technologies of the future, forward-looking and highly innovative, and therefore fit perfectly into the concept of smart specialisations implemented in the regions. The article analyses the current decisions regarding measures taken in regions for innovation development, with a particular focus on the importance of building innovation potential (RIS3 strategies).*

Need for the study: *The market for hydrogen technologies is increasingly supported by regions interested in innovation, and these technologies are or are now becoming priorities for EU energy policy. Therefore, it seems interesting to identify and evaluate decisions regarding their public support in innovation policy at the regional level.*

Methodology: *The study used logistic regression, which is a statistical method of analysis used to model the probability of a binary event. The purpose of using this type of regression was to identify and assess the significance of the determinants of the performance of the companies studied.*

Findings: *The approach to supporting the development of innovation in hydrogen technology companies has recently undergone a transformation. The results of the analyses help to identify challenges in the perspective of future pro-innovation decisions, updating approaches, and improvements in influencing the technological potential of companies.*

Practical implications: *The conclusions developed allow new decisions to be taken or existing ones to be revised toward public support, which in turn should foster modern solutions to stimulate innovation in regional economies.*

Keywords: Smart specializations, innovation, energy, hydrogen technology, public support, regional development, public sector governance

Jel codes: 031; O32; L21; R11

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1. INTRODUCTION

To maximise its innovation potential, Europe is investing in innovative areas through a number of support mechanisms. In Poland, various solutions are taken into account in the context of innovation development, including the so-called smart specialisation (*Smart Specialisation Strategy*). The identification of smart specialisation at the regional level through the identification of technologies and innovative solutions increasingly relates to energy policy priorities. However, in Poland, unlike other European countries, there is a visible gap with regard to hydrogen technologies. The deployment of FCH technologies should be supported by regions interested in innovation, as these technologies are or are now becoming priorities in EU energy policies. Furthermore, FCH technologies are innovative and thus fit perfectly into the concept of smart specialisation proposed by Prof. Dominique Foray (Foray et al., 2012) , and which currently seems to be the basis for major European initiatives to support innovation.

The current structure of public support in the regions concentrates most of the efforts on the system of financing enterprises within operational programmes. The system of financial support alone for the purchase of new technologies by enterprises is becoming insufficient in the context of the need to build a whole ecosystem of links between enterprises, public administration, and business environment institutions. Public action should create a favourable environment for innovation, stimulate research and development, and foster rapid technological challenges. In light of the above, it is interesting to analyse the key benefits and needs of business innovation development, using the example of hydrogen technology companies, to identify the decision-making challenges that are most relevant in the near future.

The paper will identify and analyse the forms and effects, as well as the subject and scope of the public support functioning system to influence the development of innovation in hydrogen technology companies. The purpose of the article is to formulate conclusions and provide information on current decisions about actions taken in regions for the development of innovation, with particular emphasis on the importance of building the innovation potential (RIS3 strategies).). The changes taking place in the environment of contemporary enterprises, related to the constant competitive struggle, force a change in the way of looking at the current standards of public management and generate new challenges in this area. Changes in support systems require the application of the principles of smart governance - one that can adapt public policy to the rapidly evolving hydrogen market. Smart governance in a policy context, often understood as smart governance, refers to the use of technology and innovation to improve the efficiency, transparency and effectiveness of decision-making by public bodies. The use of regional smart specialization strategies, illustrates the need for smart governance to support innovation at the regional level. In the context of the defined research objective that indicates the evaluation of the importance of public decisions and actions in the development of innovativeness of enterprises that implement hydrogen technologies within the framework of the so-called smart specialisations, it should be stated that companies that implement new technologies perceive the need for continuous verification and updating of the functioning support mechanisms.

In identifying the research gap, it was assumed that the deployment of hydrogen technologies is certainly one of the promising activities to be supported by regions interested in innovation, as these technologies are beginning to play a dominant role in the energy policies of many countries. Hydrogen-based technological solutions have many potential applications in the industrial, transport, construction and, in particular, energy sectors, which have very ambitious goals and operate in a dynamically changing environment. Energy and environmental safety issues are constantly being redefined here.

Hydrogen technologies, and hydrogen itself, are also essential to meet the EU's commitment to achieve carbon neutrality by 2050, while aiming for zero emissions. Investments in hydrogen will contribute to sustainable economic growth and job creation. Hence, it is often stressed that a breakthrough in the development of hydrogen technologies is needed, based on new investments, a favourable regulatory framework, new lead markets, sustained research and innovation in breakthrough technologies (Hydrogen Strategy..., 2020). Although, increasingly in practice, hydrogen technologies are creating new conditions for companies operating in traditional regional arrangements, forcing change and operating within networks, there is a lack of analysis in the literature linking and describing these phenomena. On the one hand, it can be seen that hydrogen technologies create innovation potential and are becoming the main focus of smart specialisation strategies in the regions, but on the other hand,

they are new enough to be well established as the subject of separate studies on stimulating their development as specialised industries in innovation-supporting regions.

The regional enterprise support system was evaluated based on the results of a quantitative survey conducted on a sample of 150 enterprises in the energy sector related to the development and deployment of hydrogen technologies. The study used logistic regression, which is a statistical method of analysis used to model the probability of a binary event. A key reason for selecting and using this type of regression was its feasibility and usefulness in identifying and assessing the significance of the results obtained from the companies surveyed.

2. LITERATURE REVIEW

Smart growth and sustainability are directly correlated and the concept of innovation is a factor integrating them (Dziedzic et al., 2015, 2016). According to Dziedzic et al. the support provided by public actors is particularly important as they can combine their efforts within national and regional innovation systems to develop technology and support research. Cooperation between the world of science and the world of business supports the commercialisation of knowledge and technology (Dziedzic et al., 2015). However, it becomes crucial to verify whether the implemented support meets the needs of entrepreneurs (Kogut-Jaworska & Ociepa-Kicińska, 2020). The focus on innovation and technology per se is to identify how the transition to sustainable economic development relates to changes in the economy and society in general, and public policy in particular.

Public policy issues are now treated as a significant socio-economic challenge. Public policy is mission-oriented and argues that major challenges such as sustainable growth, climate change, energy transition will require the adoption of new ways of cooperation (especially between public and private actors) (Gifford & McKelvey, 2019). Besides, innovation and new technologies only contribute to sustainability goals if they become more accessible in the larger socio-technical system (Gifford & McKelvey, 2019; Köhler et al., 2019). Current knowledge of how to achieve such goals is inadequate, so it is necessary to invest in the development of new technologies and new scientific knowledge (Gifford & McKelvey, 2019). The result of this combination can be a Regional Innovation Strategy (RIS3), prioritising the achievement of competitive advantage by developing and combining strengths in research and innovation with business needs. The concept of smart specialisation is central to defining the path of innovative growth in the regions. Although the principles and implementation of regional smart specialisation strategies (RIS3) are widely discussed in the literature, the effectiveness of these policies depends on the willingness and ability of the beneficiaries to use them (Gemma & Bulderberga, 2017). As Grillitsch and Asheim argue, in order to address any emerging opportunities, businesses should be impacted in a coherent way, while avoiding any duplication or fragmentation of efforts (Asheim et al., 2016; Grillitsch & Asheim, 2018b, 2018a). On the other hand, Gianelle and Guzo point out that regional decision-makers may lack the capacity and resources necessary to manage efficiently the innovation support system set by smart specialisation strategies (Gianelle et al., 2020).

RIS3 aims at economic development through regional priorities that correspond to efficiency, research and innovation in the knowledge economy. According to (Bevilacqua et al., 2019; Kangas & Aarrevaara, 2020) the main point is to allocate resources to research and innovation to strengthen priority areas of regional funding, governance and regulation, creating a regional policy mix (Kangas & Aarrevaara, 2020). This corresponds to what is probably the largest attempt yet at a structured, transnational innovation strategy, which, according to Grillitsch and Asheim, stimulates economic growth through economic diversification and the development of a new pathway, e.g. diversifying the economy into technologically more advanced activities that make progress towards more complex knowledge compared to its current level in the region (Grillitsch & Asheim, 2018b).

Smart specialisation can be seen as a key solution to avoid the dispersion of research funds and focus research, human and financial resources on those sectors that have innovative potential, are highly productive, strategic from a socio-economic perspective, environmentally friendly and attractive to investors (Rusu, 2013). Public impact is justified and advisable especially when the complex interactions that take place between the different organisations and institutions involved in innovation do not work smoothly (Coenen et al., 2017). EU strategy documents and other claims in the literature (Gifford & McKelvey, 2019; Köhler et al., 2019; Schot & Steinmueller, 2018; Uyarra et al., 2020) have an

important impact on the current discussion on smart and sustainable development, especially based on smart specialisation strategies.

Recently, it has been noted that the link between business support policies and hydrogen technologies is increasing. This is the view of Ortiz Cebolla, Rafael & Navas, Carlos, among others. (2018), arguing that economies are moving away from hydrocarbon-based energy and that hydrogen is an effective alternative for them, of interest to policy-makers creating innovation support policies. In addition, the use of hydrogen technologies in modern economies, mainly energy or transport, aims to halt the progressive greenhouse effect and is part of many policy documents (among others, it forms one of the pillars of the implementation of the European Green Deal, which aims for Europe to achieve climate neutrality by 2050).

In summary, it should be assumed that contemporary approaches to stimulating innovation potential are based on the 'logic of regional innovation systems' (Weidenfeld, 2018) and focus on the interrelationships and complementarities between industries and sectors. Innovation systems in regions should consist of a knowledge generation and dissemination subsystem, which includes R&D organisations, educational institutions and technology transfer agencies, and a knowledge application and utilisation subsystem, which includes firms and clusters located in the region. Here, there is an intensive flow of knowledge, resources and human capital, which is important and underpins systemic innovation.

3. METHODOLOGY

The identification and evaluation of public support decisions for innovation policy at regional level, with a particular focus on EU innovation policy and hydrogen technologies was the subject of a study conducted in the second half of 2023. The intention of the overall research project was to collect and present data on the effectiveness of the management of innovation based on energy sources and hydrogen technologies in the implementation of regional innovation strategies (RIS3). In particular, the research assumption was to identify progress in the implementation of smart specialisation strategies and, consequently, to define guidelines and recommendations to increase the effectiveness of management, including decision-making of applied public support mechanisms.

As a first step, documents in force in the regions concerning support for innovation, including in particular the RIS3 strategies, were analysed. This research intention was analysed by means of a qualitative structural content analysis. The information contained in the strategies was compared with the guidelines of the national and European documents that were in force in the period 2020-2025. Based on the conclusions drawn, a quantitative study was designed and a survey questionnaire was prepared. The survey used the CATI (Computer-Assisted Telephone Interview) and CAWI (Computer-Assisted Web Interview) survey techniques. The questionnaire developed consisted of a total of 12 closed-ended and semi-open-ended questions, with single or multiple choice. For the clarity of the survey, the questions were grouped into sections of metrics and pertinent questions.

The database was created for the survey and consisted of 200 records, and during the survey process it was extended by 50 records in order to reach the desired number of respondents, i.e. n=150 business entities representing the energy sector (according to PKD) operating in industries related to hydrogen technologies. The research sample was selected from data contained in the Kompass International and Business Navigator databases (the indicated databases contained data on enterprises from all over Poland). Entities meeting the criteria for conducting the study were selected from the databases, and due to the definition of the group of respondents in terms of business activity, the sample was selected on the basis of the identification of the leading PKD code (selected sections: Section D - production and supply of electricity, gas, steam, hot water and air to air conditioning systems; Section C - industrial processing, G - wholesale and retail trade, repair of motor vehicles, including motorbikes; M - professional, scientific and technical activities).

Consequently, the survey generated a sample of 150 enterprises with knowledge of the concept of smart specialisations. The enterprises participating in the study represented all voivodeships in Poland. The largest number of respondents came from Pomorskie Province n = 26 (17.33%) and Mazowieckie Province n = 21 (14.00%). The smallest number of respondents conducted their business activities in the Opolskie Province n = 3 (2.00%) and Podlaskie Province n = 2 (1.33%). The characteristics of the

companies in relation to their sector of activity were as follows: the group of companies operating in the renewable energy sector (RES) was n = 69 (46.00%), to which n = 54 (36.00%) companies came from the heating, industry and transport sector and n = 27 (18.00%) companies operated in the combined heat and power (CHP) sector. In addition, the surveyed sample consisted mainly of companies operating on the market for several years, with a geographical concentration in the Pomeranian and Mazovian Voivodeships. The dominant group were companies operating in the RES sector, which may indicate an increased interest in the green economy and the development of innovation in this field in the near future. The survey covered companies with different market seniority, which made it possible to observe the dynamics and development trends also in the context of the companies' time on the market.

The results of the study were constructed using logistic regression, which is a statistical method of analysis used to model the probability of binary events. The use of this type of regression allowed the identification and assessment of the significance of the determinants of the surveyed companies' performance. The analysis was carried out at a predetermined level of alpha (α) = 0.05, which determined a 5% risk of Type I error. The normality distribution of the numerical variables was assessed using the Shapiro-Wilk test. A backward stepwise algorithm based on the Bayes Information Criterion (BIC) was used to select the independent variables for the logistic regression model. This algorithm at a later stage allowed the modelling process to start with a full model, including all potential independent variables, and then iteratively eliminated those variables whose removal led to the greatest improvement in the BIC value. Variables whose coefficients were not statistically significant at the α=0.05 confidence level were candidates for removal. Analyses were performed using the statistical language R (version 4.3.1; R Core Team, 2023) on Windows 10 Pro 64 bit (compilation 19045).

4 RESULTS

The assessment of public support within the framework of stimulating the development of innovation of hydrogen technology enterprises is a multi-threaded issue and can be the subject of broad decision-making analyses. The conducted research focused on key decision-making aspects, i.e. the effects, object, scope and forms of public support within the framework of the implemented innovation policy and implemented innovation stimulation strategies (RIS3).

The expected benefits from the implementation of smart specialisations may relate to the innovative development of enterprises, increasing their competitiveness in markets or, in a broader context, fostering the development of sectors and industries. Among the benefits related to the development of the innovativeness of enterprises are increases in production, income or employment. In turn, the impact on the competitiveness of enterprises is associated with the flow of technological thought from areas of smart specialisation to others, the innovative activation of entities and their employees directly related to the smart specialisation of the region. The mobilisation of innovative attitudes of suppliers, collaborators and competitors of companies in smart specialisation areas may also favour the development, of markets. Public support provided to stimulate the development of innovation in the regions may also contribute to influencing the demand for smart specialisation products. The characteristics of the distributions of the variable on past support for innovation development of the surveyed firms in the regions are presented in Table 1.

Table 1. Evaluation of public support to date in stimulating innovation development in the region

Characteristics	**N**	**Total sample** n (%)
Contributes to the development of company innovation	150	40,00 (26,67%)
Increases the competitiveness of the company on the international market	150	23,00 (15,33%)
Promotes the development of the energy sector in the region	150	16,00 (10,67%)
Promotes the development of the renewable energy sector in the region	150	16,00 (10,67%)

Characteristics	N	Total sample n (%)
Promotes the development of the hydrogen market and technology in the region	150	29,00 (19,33%)

Source: own elaboration.

The survey shows that public support is perceived by respondents as a factor contributing to the development of business innovation. It should be noted that 26.7% of the surveyed enterprises consider it as an important element of the system stimulating the development of innovativeness. On the other hand, the indicator, however, shows that the majority of surveyed enterprises do not perceive a direct impact of the support on their propensity to create or implement innovation. The suggestion here is that decisions need to be made to intensify pro-innovation activities or to better adapt existing forms of public support to the needs and market conditions of enterprises.

An evaluation of public support to date in stimulating the development of innovation in the regions, reveals that support to increase the competitiveness of enterprises on international markets is only perceived by 15.33% of the surveyed entities. This may mean that pro-innovation activities offered by the public sector at the regional level may not be globally relevant enough or are insufficiently promoted to companies with international aspirations. The importance of development projects that increase competitiveness in international markets may also stem from the need to create a sustainable co-operation-friendly ecosystem. It should therefore be important to take measures to support the cooperation of entrepreneurs, business environment institutions and research and development units, going beyond regional borders.

The analysis shows that support conducive to the development of the energy sector and the renewable energy sector in the region is assessed by respondents at a similar level. 10.67% of the responses indicate an even perception of the impact of support on both areas, which may indicate a balanced approach to the different energy fields. Nevertheless, it should be noted that the results have low percentages. The results may suggest that public support provided at regional level is not sufficiently felt by energy companies, or that these companies expect a more specific and targeted impact on markets, including specific technologies. An indicator illustrating support favouring the development of the hydrogen market and technologies may confirm this. 19.33% of respondents see the need for such measures, which is relatively the highest score. This indicates the potential emphasis of pro-innovation policies on this market segment, which may result from global trends and priorities in the field of green energy.

The distribution of variables characterising the potential and technological readiness of companies in the hydrogen economy value chain to develop innovation provides interesting results, as shown in Table 2.

Table 2. Assessment of the potential and technological readiness of companies in the hydrogen economy value chain

Characteristics	N	Total sample n (%)
Part of the hydrogen economy value chain	150	
Distribution		40,00 (26,67%)
Storage		17,00 (11,33%)
Production		76,00 (50,67%)
Application		17,00 (11,33%)
Form of activity in the context of technological readiness	150	
Supplier of hydrogen technology		91,00 (60,67%)

Recipient of hydrogen technology	59,00 (39,33%)

Source: own elaboration.

The results obtained from the analyses in Table 2 indicate that there is potential for a dynamic development of the hydrogen production sector. The obtained results are a signal for policy makers and companies to focus on the development of other elements of the value chain. Simultaneous support for innovation and technological competence in hydrogen storage and application may prove crucial for the sustainable development of the hydrogen economy. Building synergies between suppliers and consumers of hydrogen technologies through initiatives that support knowledge and technology transfer can significantly contribute to accelerating technology readiness along the value chain.

Among the respondents, the largest proportion of companies (50.67%) point to production as the main element of the value chain for which they see an increased need to mobilise public support. Indeed, technological development in this area, seems to be advancing more each year, suggesting that hydrogen production could be a key area for investment in innovation. Distribution is the second largest segment, with 26.67% of respondents specifically indicating innovation potential in this area. It can be concluded that, in the context of the need to efficiently deliver hydrogen to consumers, influencing the development of innovation can be very successful here. The elements of the value chain in the hydrogen economy that were much less noted by respondents were hydrogen storage and use. The representativeness of the responses here is much lower at 11.33% each, which may indicate that they are perhaps supported under other disciplines than hydrogen technologies or require additional investment in research and development.

When analysing the forms of enterprise activity in the context of their future technological readiness, it should be pointed out that the majority of enterprises surveyed (60.67%) identified hydrogen technology suppliers as the main group of public support. This may indicate maturity and technological readiness in this area, as well as companies' perception of business opportunities in developing products and solutions based on new technologies. On the other hand, 39.33% of respondents point to recipients of hydrogen technologies as key beneficiaries of public support. This shows that there is also a significant number of actors ready to implement new solutions, which may favour the rapid adoption and development of the hydrogen technology market.

Creation of a strong institutional system of innovation support may refer to structures set within regional innovation systems (including development strategies of voivodships together with regional innovation strategies) or structures created at the national level (within selected fields of innovative activity). The integration of the management system for the development of innovation, apart from financing pro-innovation projects, should serve the development of new cooperation and strengthen the already existing network connections, and not only be a response to the needs of public administration. A system functioning in this way should create conditions for the development of specialisation and ensure its proper infrastructure, access to information for entrepreneurs on technological or economic opportunities and threats, standards and norms of activity, as well as sources of financing, etc. The task of public decision-makers should therefore be to create individualised support tailored to the needs of a specific area of specialisation within the resulting innovation ecosystem.

The results of the study point to the need to review and adapt impact strategies for innovation development at national and regional level. Public policy makers should focus on increasing the effectiveness of programmes by better adapting to the specific needs of businesses including those in the area of hydrogen technologies. An integrated approach should be key to ensure coherence between actions at different levels of government and to create a strong ecosystem to support innovation and competence development in the hydrogen sector.

Table 3. Importance of public support for smart specialisations to the company's business (on a scale of 1 to 5, where 1 means "not at all important" and 5 means "very important")

Characteristics	N	Overall sample[1]
Support at national level - within the framework of National Intelligent Specialisations (NIS) - supporting more often the construction of the "supply side" of hydrogen technologies, e.g. within complex hydrogen economy value chains for company operations	150	3,00 (2,00, 3,75)
Support at Regional level - within the framework of Regional Intelligent Specialisations (RIS) - supporting the building of the "demand side" for hydrogen technologies (e.g. subsidies for the purchase of hydrogen vehicles)	150	3,00 (2,00, 3,00)
Sum of scores for the above questions	150	6,00 (4,00, 7,00)

[1] *Mdn* (*Q1*, *Q3*)

Source: own elaboration.

Analysing the data obtained, it is important to point out that support at the national level, under the NIS, shows a median significance rating of 3.00 with a quartile range from 2.00 to 3.75. This indicator shows a moderate rating of the importance of national support, which may suggest that companies perceive some benefits from NIS initiatives, but this level is not rated as critical to the companies' operations. It is likely that companies expect more specific or direct assistance that would have a greater impact on their business. On the other hand, support at the regional level, under RIS, also received a median score of 3.00, but with a narrower quarterly spread from 2.00 to 3.00. This is a signal that, although regional support is perceived as equally important as national support, expectations of it are more homogeneous among respondents. The sum of the scores for both types of support is 6.00, which, with an average score of 3.00 for each type of support, indicates a symmetrical perception of the importance of both levels of public influence on innovation development.

The surveyed entrepreneurs did not indicate significant shortcomings in the context of full integration of the innovation development management system. Apart from activities in the area of financial support, where respondents indicated full integration of the system, there is a need for improvement in other areas. Respondents perceive the need for integration of regional innovation ecosystems that bring together enterprises, research and development units and business support organisations. Respondents had a similar response to the issue of cooperation with local authorities. This may be due to reasons related to the short time of establishment and immaturity of some structures, as well as quite dynamic changes, evaluation or updates within the designated smart specialisations.

As the survey shows, grants, financial instruments and expert and advisory services are perceived as moderately effective (mean of 3.00), with some businesses rating them as more effective (upper quartile at 4.00). In contrast, vouchers for specialised services appear to be perceived as less effective (lower quartile at 1.00), suggesting that some businesses may be experiencing difficulties in using these support instruments effectively in their business. The assessment of the effectiveness of the forms of support offered under smart specialisations is presented in Table 4.

There is a widespread perception that the grant system is more popular among entrepreneurs than the repayable support system provided in the form of loans or guarantees. It is often pointed out that repayable instruments are less attractive than non-repayable financing in the form of grants, due to the time and manner of capital involvement. This is mainly important in the case of large investments requiring several years of planning, where the risk of success increases and, consequently, the prospect of achieving the set objectives is more difficult to realise. The use of repayable instruments requires entrepreneurs to make rational decisions based on sound economic accounts, to carry out well-considered actions and to use the funds put at their disposal within the framework of public support in a balanced and effective way. The advantage of grant instruments, as opposed to repayable instruments,

is their relative cheapness (no interest costs) and flexibility (possibility to refinance the capital remaining in the company). These instruments are a convenient form of support for investment in modern technologies, conducting research in a broad sense of development, which in turn has an impact on increasing income, improving competitiveness and increasing the value of enterprises.

Table 4. Evaluation of the effectiveness of the forms of support offered under smart specialisations from the point of view of meeting the needs of the enterprise (on a scale of 1 to 5, where 1 means "very ineffective" and 5 means "very effective")

Characteristics	**N**	**Overall sample[1]**
Grants	150	3,00 (2,00, 3,00)
Financial instruments (e.g. soft loans and credits)	150	3,00 (2,00, 4,00)
Expert and consultancy services	150	3,00 (2,00, 4,00)
Vouchers for specialised services (e.g. to be selected from the Development Services Database)	150	3,00 (1,00, 3,00)
Cooperation and collaboration (e.g. within cluster initiatives, hydrogen valleys and other institutional)	150	3,00 (2,00, 4,00)
Sum of scores for the above questions	150	15,00 (13,00, 16,00)

[1] *Mdn* (*Q1*, *Q3*)

Source: own elaboration.

Cooperation, collaboration, co-generation of demand for smart specialisation products within cluster initiatives and hydrogen valleys involves strengthening the development potential of entities forming a given cooperation network, including strengthening human resources, financing R&D infrastructure, financing activities supporting the professionalisation of research services, creating a system of research vouchers. The commissioning and implementation of R&D projects is often linked to the use of grant incentive systems consisting in the funding of programmes, research works or the purchase of research infrastructure. In addition, a popular activity is the organisation of meetings of representatives of the world of science and enterprises focusing on the specific sector of the economy identified as a smart specialisation (smart labs, technology workshops, good practices, exchange of views and working standards), which leads to a reduction in transaction costs of activities within the framework of the established cooperation networks. According to the survey, the vast majority of surveyed companies feel the benefits of this type of support system. The importance of business environment institutions in the context of building a public support system and developing smart specialisations is illustrated in Figure 1.

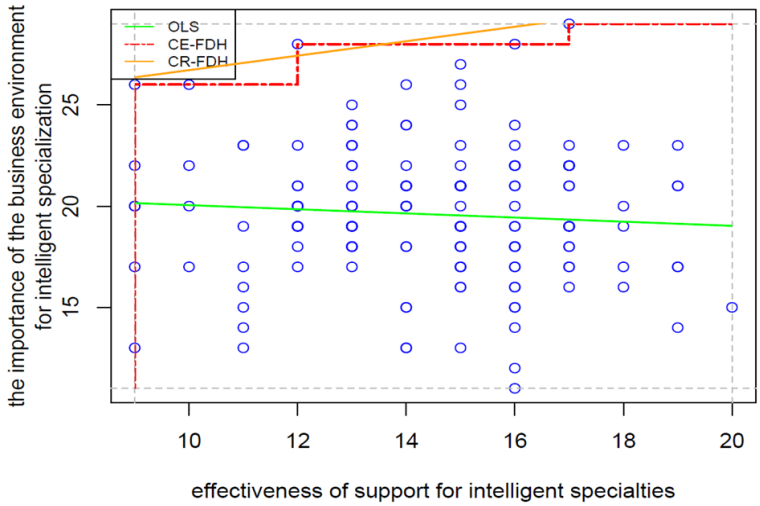


Figure 1. Importance of business environment institutions in the context of building a public support system and developing smart specialisations
Source: own elaboration

Developing the idea of smart specialisations, as well as supporting pro-innovation activities among businesses, should be a priority activity of public authorities at the regional level. Both decision-makers and administrative structures at the regional level should consider supporting and promoting cooperation networks within the framework of smart specialisations, as one of the basic challenges of the contemporary economy. As the study shows, strengthening the links between the world of science and the world of business, as well as building an innovation ecosystem and supporting initiatives of business environment institutions such as clusters or hydrogen valleys should be considered as one of the most important actions taken within the public support system for enterprises including the hydrogen technology sector

5. DISCUSSION

This study contributes to the growing field of research related to public management and innovation, and the development of hydrogen technologies. It largely focuses on the evaluation of regional innovation support showing how the concept of smart specialisation is perceived by hydrogen technology companies and what can be improved in this respect. This article analyses the decision-making mechanisms taken in the regions to support innovation through the prism of the evaluations of the companies surveyed. Using a typical research pattern and starting from identification, through diagnosis and evaluation, and concluding with research analyses, results and conclusions were obtained that are consistent with those presented in the literature.

The results obtained confirm the theses presented in the paper "Smart Specialisation: what gets lost in translation from concept to practice?" (Gianelle, Guzzo and Mieszkowski, 2020, p.1386) , indicating that regional decision-makers lack the capacity and resources necessary for efficient management within the innovation support system set by smart specialisation strategies. The results obtained highlight the need to increase the effectiveness of support, as well as the need to revise aid programmes to better meet the needs of hydrogen technology companies. Better management of smart specialisation strategies and more pertinent decisions responding to regional specificities can result from intensified cooperation between the public sector and the business sector.

Improving the quality of public policies and decisions concerning the regional innovation system and supporting the development of new fields, sectors and industries (i.e. renewing pathways and creating pathways) to stimulate regional potential is now becoming an essential requirement. The studies carried out point to the need to adapt public actions to the challenges and needs of the market, which are still undergoing new transformations. The specifics of the hydrogen technology market require disruptive technological innovation and investment to make the impact more effective. This is also

reflected in the claims made in the publication 'Environment and Planning C: Politics and Space' (Coenen *et al.*, 2017, p. 605) , among others, that public impact is only justified and needed if the complex interactions that take place between the different organisations and institutions involved in innovation do not work.

It should be pointed out that, in line with previous findings, the ability of energy companies to adapt to a turbulent environment will be important in the future. This environment will also be influenced by innovation development policies, including smart specialisations that develop the potential of regions. The competitive position on the market can be largely shaped by services or investments, which can be of comparable importance for companies as investments in technical infrastructure. As argued by (Weber and Cabras, 2017, p. 1222) , in order to improve the efficiency of public services, public organisations will face the challenge of optimising and innovating their policies and services

Conclusions from the analysis conducted on the basis of the collected empirical material allow us to conclude that, in the context of innovation capacity building, there is also a need to implement integrated management strategies in enterprises that will focus on the implementation of innovative solutions. This assertion is consistent with the opinions contained in the work "Smart specialisation strategy assessment in Baltic states" (Gemma and Bulderberga, 2017, p. 135-141) and "How outward looking is smart specialisation? Rationales, drivers and barriers' (Uyarra, Marzocchi and Sorvik, 2018, p. 2345) , presented in the aforementioned literature, who highlight the importance of developing smart specialisations in the context of various challenges. In the case of the deployment of hydrogen technologies by energy companies, these may oscillate around issues such as hydrogen energy, renewable energy sources and renewable energy technologies, renewable and mineral resources management, renewable energy engineering, renewable energy sources and waste management.

6. CONCLUSION

The analysis of support for the development of innovation in hydrogen technology companies carried out in this work allows us to define challenges in the perspective of future updates and improvements in the implementation of innovation policy in the regions. On the other hand, the conclusions resulting from the study help to make new or correct existing decisions on the directions of public support, which will consequently foster modern solutions for the dynamisation of innovation development in regional economies.

The analyses carried out lead to the conclusion that for the majority of the surveyed enterprises, the greatest benefit resulting from the implementation of the support system based on smart specialisation strategies, which constitute guidelines for innovation development policy, is the modernisation of the regional economy. Therefore, it is worth continuing activities supporting the development of innovativeness of enterprises, as the effects are visible not only from the perspective of individual beneficiaries of support, but also in the broader context of the economy in the region. However, in order to increase the effectiveness of innovation support, it is necessary to review and adapt existing programmes and impact mechanisms.

Smart governance can help better tailor support instruments to the actual needs of businesses, reducing the gap between public policy objectives and outcomes. Support programmes and mechanisms should better respond to the dynamically changing needs of enterprises and be easier to identify and use by potential recipients. Increased awareness among business managers and decision-makers regarding the use of available support tools can directly contribute to improved competitiveness, not only in local markets, but also in international arrangements. It is also important here to carry out a detailed analysis of the impact of support programmes on the energy sector to better tailor them to the unique challenges of the industry and to ensure that they are effective in driving innovation and sustainability.

Public support for hydrogen technologies should be continued and systematically expanded, given the potential to contribute to the energy transition and to strengthen the market position of companies. By focusing on the development of the hydrogen market, regional innovation can be stimulated, job creation can be supported and decarbonisation goals can be contributed to.

With regard to the assessment of the potential to develop the innovation and technological readiness of companies involved in the hydrogen economy value chain, several conclusions can be drawn. Stepping up efforts to produce hydrogen highlights its important role in the energy sector. The analyses

also show that it is equally important to focus on other links in the chain, such as storage, distribution and end-uses. Hydrogen storage, due to the specificity of this energy carrier, requires decisions on increasing funding and seeking breakthrough technological innovations in order to become more economically efficient. It should be borne in mind that developing hydrogen applications, both in industry and in sectors such as transport or heating, can contribute significantly to decarbonisation and increased flexibility of energy systems. Hence, it is important to create investment mechanisms and tools, as well as to support research in these directions. Logistical and infrastructural challenges accompany decisions related to increasing the innovation of hydrogen distribution systems. The distribution of hydrogen, on the other hand, is an important element that needs to be addressed not only in terms of infrastructure development, but also in terms of ensuring safety and operational efficiency.

Strengthening cooperation between hydrogen technology providers and their customers, through knowledge sharing and competence development, is key to accelerating technology adoption and realising the full potential of hydrogen. This approach can also foster innovation and enable a more comprehensive use of hydrogen as an energy carrier in different sectors.

On the basis of data on the importance of support for the activities of companies in the context of smart specialisations, it is possible to conduct a detailed analysis and develop conclusions aimed at optimising the management strategy in the area of the hydrogen economy. In formulating further recommendations for the future, it should be emphasised that there is a need to decide on the modification of the current structure of public support in the implementation of smart specialisation strategies. This support concentrates most of its efforts on the system of financing enterprises within operational programmes. At the same time, the system of financial support alone for the purchase of new technologies by companies is becoming insufficient in the context of the need to build an ecosystem of links between them, public administration and business environment institutions. The system of public support under the smart specialisation strategy should create a favourable environment for innovation and stimulate research and development. At the same time, the attitude towards innovation processes and the attitude of enterprises towards development activities should be considered as determinants that significantly influence the decision-making, but also the effectiveness of institutional solutions aimed at helping to build capacity in the regions.

It should be stressed that economic operators perceive the need for support from both the national and regional levels, which indicates the need for a harmonious combination of the activities of these two levels of administration in terms of the instruments offered. Average evaluations of current support programmes may indicate the existence of unfulfilled expectations of businesses in relation to available forms of assistance. Thus, in order to increase the effectiveness of the public impact, support programmes should be analysed more thoroughly and adapted. They should be more responsive to the needs of enterprises. From this perspective, it is important to intensify the dialogue between businesses and pro-innovation policy-makers to ensure that these initiatives prove to be more relevant and meet the expectations of the economic sphere.

In addition, strengthening education and promotional activities can help companies to make better use of available resources and support programmes. This can include both information on how to access these programmes and education on the benefits of using them.

It should also be pointed out that there is moderate satisfaction with current forms of public support and, in particular, considerable variability in the perception of their effectiveness, which may indicate heterogeneity in the needs and expectations of enterprises. Further analysis is advisable here, aiming to identify and understand the reasons why some enterprises consider some tools to be very effective, while others have a different view. For example, vouchers for specialised services are considered ineffective by companies in the hydrogen technology sector, while in other sectors vouchers are perceived quite positively. The quartile values presented in the paper indicate that there may be barriers to accessing or using support, which may also require special attention in order to increase the effectiveness of the instruments offered. In order to increase efficiency, organisations managing support programmes need to conduct a thorough review and adapt their tools to the specific needs of different groups of entrepreneurs. Improving communication and advisory services regarding the available support measures will certainly help businesses to better understand and use the resources on offer.

Smart governance also involves coordinating actions across different levels of administration to create a coherent system that supports the development of hydrogen technologies. Strengthening cooperation networks can be considered a key dimension of smart governance in innovation ecosystems.

Cooperation and networking are key to innovation and growth, so initiatives to promote the emergence of clusters or hydrogen valleys should not only be continued, but also developed taking into account the specific needs and expectations of entrepreneurs. Such activities stimulate the exchange of experience, cooperation and the creation of synergies between different market players. Management strategies should be guided by the expectations and needs of the business sphere. This should involve adapting instruments to specific business contexts and needs, offering flexible financial solutions and specialised advisory assistance. This individual dimension of influence can significantly increase the effectiveness of innovation stimulation in the regions.

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TOWARD INTELLIGENT PALLET POOL MANAGEMENT – PALLET DAMAGE IDENTIFICATION AND INPUT DATA STRUCTURE IN CAMERA- AND AI-BASED DECISION SUPPORT SYSTEMS

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ABSTRACT

Purpose: *The aim of this article is to conduct a comprehensive assessment of structural damage in reusable EPAL wooden pallets (800 × 1200 mm) and explore the potential of intelligent vision systems as tools supporting technical diagnostics and decision-making in pallet pool management.*

Need for the study: *Given the essential role of pallets in ensuring continuity and efficiency of logistics chains, there is a growing need for reliable and objective methods to assess their technical condition. Current practices based largely on visual inspections are time-consuming, error-prone, and lack standardization.*

Methodology: *The study involved observational analysis of 135 pallets made from both dry and wet structural components. The inspection environment was carefully prepared to ensure uniform lighting and ergonomic station layout, enabling precise identification of surface defects and safe handling. All types of damage were photographed and categorized, forming a consistent classification system.*

Findings: *Significant differences were observed in the types and frequencies of defects depending on material moisture. Dry-component pallets exhibited primarily cracks (47.19%), construction gaps (16.85%), and warping (13.48%), while wet-component pallets were mostly affected by discoloration (39.24%), nail corrosion (29.11%), and resin leakage (15.56%). These findings highlight the impact of production parameters on pallet durability prior to operational use.*

Practical Implications: *The developed damage classification system can serve both traditional technical diagnostics and training datasets for machine learning models. Integrating intelligent vision systems with Warehouse Management Systems (WMS) enables automated, fast, and consistent defect detection, maintenance planning, and withdrawal of damaged units. Neural network-based solutions reduce analysis time and eliminate human subjectivity. This approach supports the digital transformation of logistics in line with Industry 4.0 principles and complements expert-based methods with AI-powered efficiency.*

Keywords: EPAL wooden pallets, Structural damage, Logistics operations, Intelligent vision systems, Industrial AI, Machine learning, Damage classification, Automated inspection, decision-making

Jel codes: C44, C63, D22, D24, L15, M11, O33

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1. INTRODUCTION

The pallet, as a carrier of goods, has been known since the Second World War; despite its simple construction, it is an excellent device for facilitating the process of transporting, storing and high storage of goods in the warehouse. In the literature and theoretical studies, there is a wide range of explanations for the term "load pallet", but according to the Polish standard - PN-90/M-78200 - a load pallet is a device intended for stacking loads in or on it and adapted for mechanised movement as a pallet load unit. This term, however, does not emphasise the function of the pallet from the point of view of the logistics chain, yet it has a significant impact on more efficient transport and storage activities, for example by enabling the mechanisation of handling and transport work or reducing mechanical damage to goods/loads during transport and storage (Sowa, 2021). According to the SFS-EN ISO 445:2013 standard, pallets are defined as “rigid horizontal platforms of minimum height, suitable for use with pallet trucks and/or forklifts and other suitable handling equipment, for loading, storing, moving, forming, and stacking or displaying goods and loads” (SFS-EN ISO 445:2013 2013; Deviatkin et al., 2019).

They are therefore important components in global supply chains and are one of the most widely used carriers, accounting for around 80% of total global trade volume. (Kocí, 2019); Tornese et al., 2021).

They contribute to optimising warehouse management and operational efficiency, enabling integration across the supply chain, which includes retailers, distributors, manufacturers, and logistics service providers. This ensures the rapid and safe delivery of products to end customers (Sánchez et al., 2020).

The load pallet is most commonly a wooden structure used for transporting goods or cargo (Sabattus, 2022), but it also serves as a stable platform on which larger goods and smaller packages are placed, thus facilitating logistics operations. Pallets are designed by manufacturers to be easily handled by forklifts and other equipment used in logistics (Sowa, 2019). Today, the pallet market is moving towards increasing diversity in terms of dimensions, materials used, and types of applications. Nevertheless, the most popular type remains the flat, wooden, reusable, single-panel, four-way entry EUR-type pallet (800 x 1200 mm) without wings. The key raw materials used in wooden pallet production include timber (or chipboard), nails for fastening, electricity for processing equipment, and heat or fuel for phytosanitary treatments (SFS-EN 13698-1, 2004).

The pallet production process involves the use of both dry and wet wooden components, which significantly affects the quality of the final product.

With the growing operational scale and the increasing diversity of pallet types, managing so-called pallet pools – systems for shared use of pallets among various supply chain participants – has become an increasingly complex challenge for logistics managers. A key issue in this context is making well-informed decisions regarding pallet allocation, rotation, repair, replacement, and retirement. Such decisions often have to be made under conditions of uncertainty, limited feedback from end-points in the supply chain, and cost pressure.

Additionally, variations in quality standards, lack of transparent data on the life cycle of pallets, and ambiguity around responsibility for damage among system partners negatively impact the overall efficiency of pooling models. As a result, the importance of data-driven solutions and digital tools that support real-time decision-making is growing, as these can significantly enhance the performance of pooling systems and reduce losses associated with poor decisions.

The effectiveness of pooling systems and the quality of decisions made within them largely depend on the physical properties of the pallets themselves, as well as their reparability, recyclability, and resistance to operational damage. Wooden cargo pallets are widely used due to their relatively low cost, ease of repair and recyclability. However, various forms of damage can occur during production that affect their functionality and durability.

Modern logistics processes require effective methods for monitoring and assessing the technical condition of transport and storage equipment. In this context, the search for innovative solutions capable of optimising the diagnostic and damage analysis process of EPAL load pallets becomes increasingly important. Traditional visual inspection methods, based on assessments performed by human inspectors, can be time-consuming and prone to subjectivity and human error. Therefore, there is a growing need to implement technologies that could automate and streamline this process (Wu & Lu, 2019).

Intelligent vision systems, utilising image analysis algorithms and machine learning methods, could represent a breakthrough in the field of technical diagnostics of pallets. The application of such systems could enable automatic detection and classification of defects, eliminate subjective evaluations, and improve the efficiency of decision-making regarding further use (Silva & Paladini, 2025) or withdrawal of pallets from circulation. The implementation of intelligent vision technologies could contribute to increased operational reliability and the optimisation of logistics costs (Benbarrad et al., 2021; Wang et al., 2019).

2. LITERATURE REVIEW

In order to position the conducted research within the context of the current state of knowledge and to emphasize the importance of intelligent systems in pallet pool management, this section presents a structured literature review. The focus is placed on scientific and industry publications concerning the use of vision systems, artificial intelligence (AI), and machine learning (ML) methods in logistics diagnostics, particularly in the identification and classification of structural damage in reusable load carriers.

Given the interdisciplinary nature of the topic—combining aspects of production engineering, logistics, and AI-based decision support systems—the literature review is presented in a tabular format. This structure enables a clear comparison of the main application areas, key diagnostic factors, and the authors or sources from which the studies originate.

This literature overview serves as a crucial reference point for further discussion on the potential integration of vision systems into the processes of managing the technical condition of pallets. At the same time, it allows for the identification of dominant research directions, knowledge gaps, and the potential for further development of intelligent diagnostic tools in pallet pool management.

Tabele 1. "Synthesis of Research Directions on the Application of AI and Vision Systems in Pallet Pool Management

Management Area	Factors	References
Quality Management	- Defect identification and classification - Automated reporting - Quality trend identification - Reduction of inspection errors	(Imoh, 2024), (Ottakath et al., 2023), (Sabattus, 2022), (Sánchez et al., 2020) (Sowa, 2021), (Sowa, 2019)
Technical Diagnostics in Logistics	- Load unit condition monitoring - Early damage detection	(Ferreira & Reis, 2023), (Qamar & Zardari, 2024), (SFS-EN 13698-1, 2004), (SFS-EN ISO 445:2013, 2013)
Automated Visual Inspection	- AI-based image recognition - Inspection cost reduction - Elimination of human subjectivity - Acceleration of quality control cycle	(Bi et al., 2023), (Di Capua et al., 2022), (Imoh, 2024),(Ottakath et al., 2023), (Suma et al., 2024), (Svanberg, 2023)
Material Flow Management	- Material receipt control - In-line quality control - Batch traceability	(Ananvaithayakij, 2022), (Benbarrad et al., 2021), (Mithas et al., 2022), (Ogbeyemi & Zhang, 2024), (Ottakath et al., 2023), (Parikh et al., 2022), (Tikwayo & Mathaba, 2023), (Vaka, 2024)
Human Resource Management	- Human-robot collaboration - Operator support through	(Abosuliman & Almagrabi, 2021), (Albayrak et al., 2023), (Ogbeyemi et al., 2024), (Ottakath et al., 2023),

	defect visualization - Minimization of human error - Automatic reaction time control	
Workplace Ergonomics	- Reduction of micro-injuries and fatigue - System adaptation to anthropometry - Interfaces supporting visual perception - Facilitation of inspection tasks	(Ivanov et al., 2021), (Ottakath et al., 2023)
Defect Identification	- Automatic micro-defect detection - Damage pattern analysis - Adaptive learning algorithms	(Benbarrad et al., 2021), (Imoh, 2024), (Javaid et al., 2022), (Kim et al., 2024), (Ottakath et al., 2023), (Ren et al., 2022)
WMS System Integration	- AI-supported warehouse decision-making - Predictive system maintenance - Automated inventory status verification	(Ottakath et al., 2023), (Tikwayo & Mathaba, 2023), (Xiao et al., 2023)
Preventive Maintenance Management	- Predictive diagnostics - Automatic wear recognition - Monitoring visual changes in components - Integration with IoT data	(Ivanov et al. 2021), (Javaid et al., 2022), (Ottakath et al., 2023)
Operational Cost Optimization	- Automated control as a cost-reduction method - Lower losses through early detection - More efficient resource allocation - Downtime reduction	(Ivanov et al. 2021), (Ottakath et al., 2023)
Risk Management	- Failure prediction - Visual inspection of structural component quality	(Ivanov et al. 2021), (Ottakath et al., 2023), (Wu & Lu, 2019)
Sustainable Development	- Extension of component life cycles - Visual identification of components - Automated inspection of semi-finished products - Waste reduction	(Deviatkin et al., 20190), (Koci, 2019), (Pasupuleti et al., 2024), (Sowa, 2021), (Tornese et al., 2021)
Information Flow Management	- IT systems integration - Analytics and reporting	(Mithas et al., 2022), (Ottakath et al., 2023), (Silva & Paladini, 2025)

	- Information security management

Source: own elaboration

3. METHODOLOGY

The main objective of this study was to categorise the types of damage observed in the structural elements of wooden flat EPAL pallets. This article attempts to analyse the impact of these defects on the structural integrity and functional performance of cargo pallets, with particular emphasis on their role in transport and storage processes.

An additional objective was to evaluate the surface condition of pallets made from both dry and wet structural components, including identification of corrosion on fasteners (nails), desorption cracks, shape deviations (warping), resin leakage, or material discoloration.

A standard visual inspection method was employed, based on organoleptic assessment of the surface of the test objects (cargo pallets), without the use of specialized optical tools. The inspection was conducted on a sample of 135 EPAL pallets within production facilities.

Although a traditional inspection method was used, the resulting dataset and defect classification can serve as a basis for the future implementation of automated inspection systems using computer vision and artificial intelligence techniques. Such technologies could support real-time defect detection and classification, minimise human error, and enhance decision-making processes in intelligent pallet pool management.

In the first stage, the research sample was selected randomly – pallets were chosen from those produced using both dry and wet wooden components. This randomisation was important to ensure the representativeness of the results. The pallets were then placed on the production hall floor at regular intervals to allow for safe and unrestricted access during evaluation.



Figure 1. Test sites at the RSP production hall
Source: own elaboration.

The sample was divided into two groups: pallets made from wet components and those made from dry components. The group of wet-component pallets was analysed first. After this assessment, a similar procedure was conducted for the dry-component group. In both test groups, all structural elements of the cargo pallets were examined. The final stage involved comparative analysis of the findings from both groups, identifying damage types and assessing their potential impact on pallet performance.

4. RESULTS

As a result of the conducted study, aimed at assessing structural damage in cargo pallets made from wet and dry structural elements, detailed information was obtained regarding the types of defects observed in both test groups. The pallets made from wet structural elements were assessed first,

followed by an identical analysis of pallets manufactured using dry components. All structural components of the pallets were examined, allowing for the precise identification and classification of the types of damage present in both groups.

Following the damage assessment, a number of typical structural defects were identified and categorized as follows:

- fracture of structural elements (Figure 2.),
- corrosion of nails (Figure 3)
- construction joints (Figure 4),
- warping (Figure 5),
- resin leakage (Figure 6),
- discolouration, staining Figure (7.)

It is worth noting that the frequency of occurrence of these defects varied depending on the type of material used in pallet production, as is detailed further in the results section.

The analysis conducted at this stage of the study allowed for an accurate determination of the impact of structural material type (wet or dry) on the kind and degree of degradation of cargo pallets. Importantly, the collected data not only serve as a basis for evaluating traditional diagnostic methods, but above all, they may be used as input data for training and implementing intelligent vision systems. Although a manual visual assessment method was used, based on expert identification of defects, it should be emphasized that this analysis serves as a foundational stage for the development of automated technical diagnostic tools. The established classification of defects and their detailed descriptions form a knowledge base that can feed machine learning systems and become an integral part of the architecture of AI-based decision support systems. Thus, the study presented here does not constitute an alternative to modern image processing solutions, but rather serves as a preparatory phase, enabling their effective deployment and further development in the context of intelligent pallet pool management.



Figure 2. Fracture of structural elements of cargo pallets
Source: own elaboration.



Figure 3. Fracture of structural elements of cargo pallets
Source: own elaboration.



Figure 4. Construction joints
Source: own elaboration.



Figure 5. Warping
Source: own elaboration.



Figure 6. Resin leakage
Source: own elaboration.



Figure 7. Discolouration, staining
Source: own elaboration.

Table 2 presents the identified defects of EPAL pallets made from dry structural elements.

Table 2. Pareto analysis of identified defects in dry EPAL pallets

Defect	Number	Percentage share	Cumulative % value
Cracks in structural elements	42	47,19	47,19
Construction joints	15	16,85	64,04
Splurges	12	13,48	77,53
Nail corrosion	8	8,99	86,52
Resin leakage	8	8,99	95,51
discolouration	4	4,49	100
Protruding nails	0	0,00	100
Loose knots	0	0,00	100

Source: own elaboration.

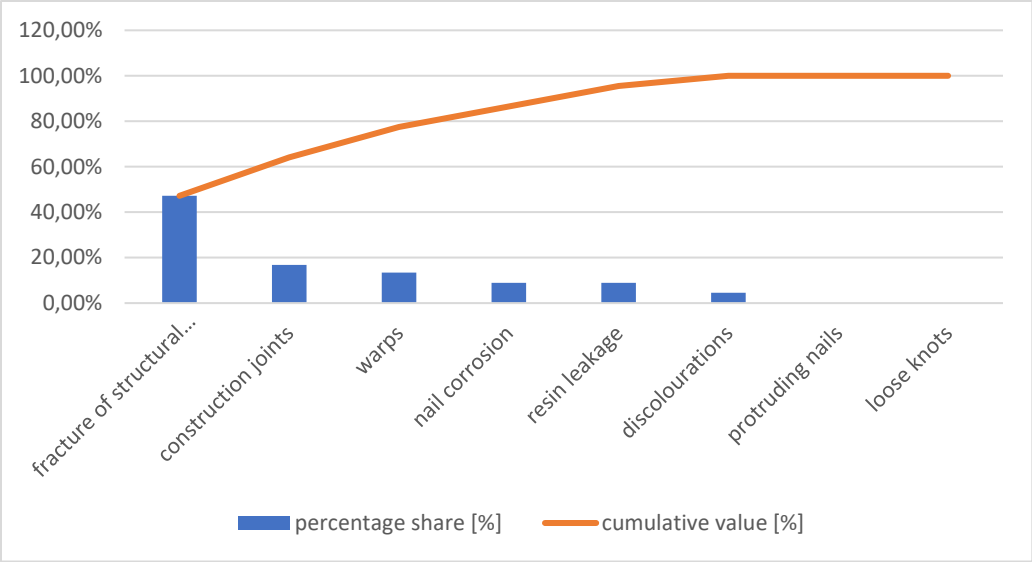


Figure 8. Pareto-Lorenz chart of identified defects in EPAL pallets made of dry components
Source: own elaboration.

A Pareto-Lorenz analysis of the identified defects in EPAL pallets made of dry structural components showed that the predominant defects were cracks in structural components, structural gaps and warping, which totalled 77.52%.

Table 3. Pareto analysis of identified defects in EPAL wet pallets

Defect	Number	Percentage share	Cumulative % value
Discolouration	62	39,24	39,24
Nail corrosion	46	29,11	68,35
Resin leakage	23	14,56	82,91
Cracks in structural elements	19	12,03	94,94
gaps	8	5,06	100
Protruding nails	0	0	100
warps	0	0	100
Loose knots	0	0	100

Source: own elaboration.

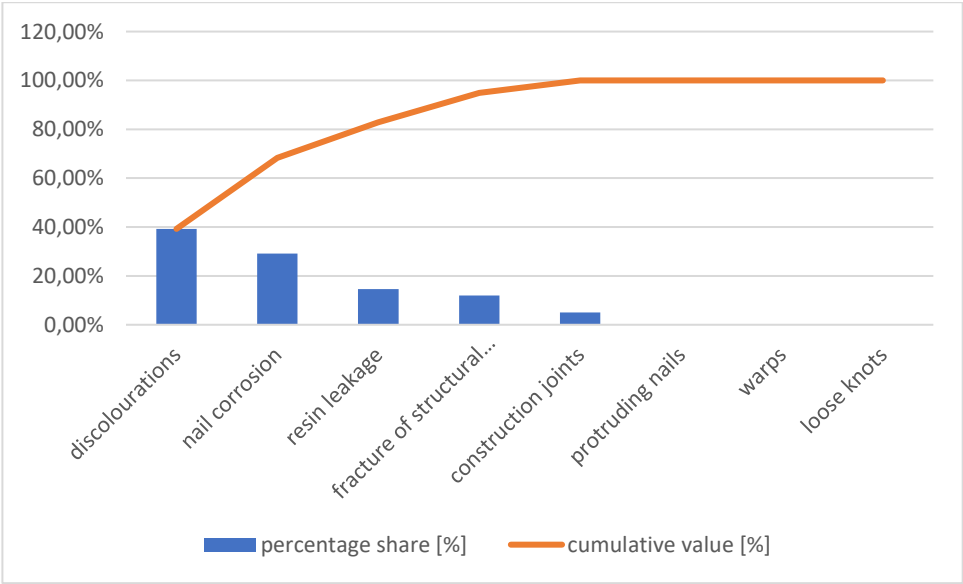


Figure 9. Pareto-Lorenz chart of identified defects in EPAL pallets from wet components
Source: own elaboration.

5. DISCUSSION

The Pareto-Lorenz analysis of the identified defects in EPAL pallets made from wet components revealed that the predominant defects were discolouration, nail corrosion, and resin leakage, which together accounted for 82.91% of all observed cases.

These results represent a valuable dataset that can be utilized in the design and enhancement of intelligent vision systems based on advanced image processing techniques and artificial intelligence (Ren et al., 2022). The preliminary damage classification, conducted using manual methods, serves as a foundation for training machine learning models and developing algorithms for automatic defect detection and assessment (Ren et al., 2022).

The use of high-resolution industrial cameras combined with image analysis algorithms would enable automated identification of defects such as cracks, construction gaps, nail corrosion, warping, resin leakage, and discolouration — in a fast, repeatable, and efficient manner.

Importantly, intelligent vision systems should not be treated as an alternative to studies like the one presented in this article, but rather as their natural extension. The data obtained through visual inspection and manual classification provides a knowledge base on which learning systems can be built and trained. This enables the comparison of the effectiveness of classical inspection methods with approaches based on artificial intelligence algorithms (Kim et al., 2024), while benefiting from the strengths of both.

Systems based on neural networks, trained on real images of pallets with varying degrees of damage, could automatically classify defects and support decision-making regarding further pallet use. Compared to classical inspection methods, these solutions offer higher repeatability, reduced analysis time, increased diagnostic precision, and minimized risk of human error (Xiao et al., 2023).

An additional advantage would be the possibility of integrating vision systems with databases and warehouse management systems (WMS), which would enable real-time monitoring of the technical condition of pallets and support proactive maintenance planning. This facilitates effective logistics resource management while reducing the risk of failures in the supply chain.

In the context of the structural damage analysis of EPAL cargo pallets, decisions regarding their further use should be based on objective, measurable, and repeatable diagnostic methods. The use of vision systems enhanced with AI algorithms represents an important step toward the automation of this process — not replacing existing methods, but rather building on them and evolving from their results.

The high precision of analysis made possible by machine learning allows for the detection of both minor irregularities, such as discolouration or point nail corrosion, and more severe defects affecting the load-bearing capacity of the pallet. Moreover, adaptive data processing algorithms learn from each case, continuously improving the system and adjusting it to changing environmental and operational conditions.

Therefore, future research should focus on:

- optimizing algorithms for detecting subtle defects,
- increasing the robustness of systems against varying environmental conditions,
- integrating with tools that support decision-making in logistics, manufacturing, and warehousing.

The implementation of such solutions represents a significant step toward full automation of technical diagnostics of cargo pallets, contributing to increased operational efficiency and reduced operational costs in modern supply chains.

6. CONCLUSION

An analysis and evaluation of structural damages in reusable flat wooden EPAL pallets (dimensions: 800×1200 mm). The study included pallets made from both wet and dry structural components. A crucial element of the research was the proper preparation of the inspection environment, particularly ensuring adequate lighting intensity in the production hall. Uniform, shadow-free lighting enabled accurate identification of defects such as cracks, structural gaps, warping, discoloration, nail corrosion, and resin leakage.

The workspace was arranged ergonomically, allowing full access to all pallet elements and minimizing the risk of accidental damage during handling. The study revealed a variety of damage types. In pallets made from dry components, the most common defects were cracks (47.19%), structural gaps

(16.85%), and warping (13.48%). In pallets made from wet components, the dominant defects were discoloration (39.24%), nail corrosion (29.11%), and resin leakage (15.56%). These defects significantly affect the load-bearing capacity and functionality of pallets in the supply chain.

The obtained results are crucial for both pallet manufacturers and end-users, as they enable the identification of dominant defect types and their causes, supporting the development of effective prevention and mitigation strategies. This, in turn, contributes to increased pallet durability and operational safety, improving logistics efficiency and reducing operational costs.

Furthermore, the analysis of the potential of intelligent vision systems shows that their implementation could significantly enhance the diagnostics and damage assessment processes of EPAL pallets. These systems could facilitate automated defect classification, eliminating the need for manual inspection and reducing the risk of human error (Prunella et al., 2023; Kuang et al., 2022).

Key benefits of implementing intelligent vision systems include:

- The ability to automatically detect and classify defects, reducing errors stemming from subjective inspector assessment (Prunella et al., 2023; Kuang et al., 2022).;
- Improved repeatability of inspection results and reduced evaluation time, contributing to logistics cost optimization;
- Integration with Warehouse Management Systems (WMS) for real-time monitoring of pallet condition and faster response to damage;
- Support for decision-making processes through analysis of defect data and their impact on pallet functionality.

Vision systems represent an extension and logical continuation of classical visual inspection methods. Their effectiveness is enhanced by the inclusion of reliable input data, such as that derived from detailed structural assessments.

Future research should focus on optimizing image processing algorithms to improve the detection of subtle defects and minimize classification errors. Moreover, studying the influence of environmental conditions on the performance of vision systems could expand their applicability across various logistics and industrial sectors. The implementation of such technologies represents a significant step toward the automation of decision-making processes in the technical assessment of load-bearing pallets, improving operational efficiency and reducing maintenance costs.

The conducted study enabled a systematic analysis and evaluation of EPAL pallet structural damage, considering the impact of wet and dry wooden components prior to their use. The results indicate that essential quality differences and defect occurrence can be identified as early as the production stage, which may significantly influence further utilization in logistics chains.

Visual inspection allowed for the identification of characteristic damages such as cracks, structural gaps, nail corrosion, warping, resin leakage, and discoloration. The study demonstrated that pallets made from wet components were more prone to surface damage such as discoloration and nail corrosion, whereas pallets made from dry components exhibited more frequent cracks and structural gaps. These differences are relevant for optimizing production processes and selecting raw materials with appropriate mechanical and technological properties.

The conclusions are relevant not only for pallet producers but also for logistics companies and warehouse operators who must consider the impact of raw material quality on the longevity of transport units. In this context, the implementation of intelligent vision systems may offer an innovative solution for objectively assessing pallet quality already at the production stage, potentially eliminating defective units before they enter the supply chain.

The use of image processing systems in quality control could not only enable automatic defect detection but also real-time classification, which would significantly improve production processes. Integration with quality management technologies would further support decisions related to optimizing wood drying parameters, component assembly methods, and final inspection procedures before market distribution.

To summarize, the quality of structural elements in EPAL pallets is critical to their durability and functionality, and intelligent diagnostic systems could become a standard tool for quality evaluation and production process optimization. Future research should focus on refining visual inspection methods, applying machine learning algorithms for damage analysis, and integrating modern vision technologies with quality control systems in wooden pallet production.

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SPRINT INTO THE FUTURE: INTELLIGENT MANAGEMENT THROUGH LLM-POWERED COMPUTER SIMULATIONS IN AGILE PROJECTS

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ABSTRACT

Purpose: *This study investigates how Large Language Models (LLMs) integrated with computer simulations can enhance intelligent management in Agile Project Management. It examines generative AI's ability to create simulation models from natural language, enabling faster and more accurate scenario analysis. The research integrates Agile Earned Value Management (AgileEVM) metrics to support decision-making, optimize resources, and improve adaptability in complex IT projects.*

Need for the study: *Traditional project management tools require specialized skills and struggle with evolving Agile requirements. As IT projects grow in complexity, solutions that merge technical precision with operational flexibility are essential. LLM-generated simulations provide advanced analytics without coding expertise, addressing gaps in speed, accessibility, and adaptability.*

Methodology: *A framework using GPT-4 generated Python-based simulations from textual project descriptions, incorporating AgileEVM metrics (CPI, SPI, velocity, defect rates). A case study tested three project scenarios with varying cohesion, leadership, and complexity. GPT-4 outputs were benchmarked against ARENA discrete-event simulation and Asana AI across 20 sprints.*

Findings: *GPT-4 simulations matched ARENA results with <2% CPI/SPI variation and <10% defect metric deviation. Team cohesion, leadership quality, and complexity strongly affected Agile performance.*

Practical Implications: *The approach allows managers to build high-fidelity simulation tools rapidly, reducing time and cost. Integrating AgileEVM metrics enables "what-if" analyses to anticipate risks and refine strategies, promoting data-driven, intelligent management in Agile environments.*

Keywords: Large Language Models; Agile Project Management; Computer Simulation; IT Project Planning; AI-Driven Decision Making

Jel codes: C63; C88;

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1. INTRODUCTION

IT projects play a crucial role in driving technological innovation and transforming various sectors of the economy, including healthcare, finance, education, and logistics. They serve as catalysts for change, offering novel solutions to traditional challenges and shaping modern business strategies (Lindsjørn et al., 2016; Pricopoaia et al., 2024). The final selection of an optimal project development approach should be based on theoretically sound criteria, account for specific user needs and project requirements, and consider key factors such as team size and expertise, project budget and deadlines, and task complexity (Schwaber & Sutherland, 2020). Therefore, researching software development processes and methodologies is crucial for understanding industry trends and identifying the best strategies for sustainable business growth. This raises the need to adapt existing tools developed for project management so that they can also be used in projects conducted according to agile methodologies and aligned with the principles of intelligent management.

Thus, one of the key challenges in project management is modeling development alternatives and determining the most effective approach, which serves as the primary objective of this study. The framework proposed in this article allows the integration of Large Language Models (LLMs) with computer simulation using the AgileEVM methodology. The use of this concept will provide the ability to strategically plan approaches to selecting quality projects and enable project managers to radically facilitate and accelerate such planning.

2. THEORETICAL ASPECTS OF PROJECT MANAGEMENT AND PERFORMANCE EVALUATION

Project management is an interdisciplinary field encompassing the planning, organization, execution, and control of activities to achieve predefined objectives within specified time, budget, and quality constraints. A defining characteristic of projects is their temporary nature, well-defined scope, and the necessity for efficient resource utilization (Project Management Institute, 2018). In contemporary contexts, these practices are increasingly being shaped by the principles of intelligent management, which integrate data-driven decision-making, advanced analytics, and adaptive strategies. Modern project management approaches (Dingsøyr et al., 2012; Schwaber & Sutherland, 2020) have evolved from traditional waterfall methodologies to Agile frameworks, emphasizing flexibility, iteration, and adaptability to dynamic market and technological conditions. Agile methodologies encompass several distinct frameworks, each tailored to different project needs, scope management approaches, and team interactions:

1. Scrum – One of the most widely adopted Agile methodologies, Scrum follows an iterative approach in which work is divided into short cycles called Sprints. It defines specific roles (Product Owner, Scrum Master, Development Team) and ceremonies, such as Daily Scrum, Sprint Review, and Sprint Retrospective, to ensure transparency and continuous improvement (Schwaber & Sutherland, 2020).
2. eXtreme Programming (XP) – A software development methodology that prioritizes code quality and frequent client interactions. XP employs practices such as pair programming, continuous integration, and unit testing to minimize errors through iterative development and close developer collaboration (Beck, 2005).
3. Crystal Family – A collection of lightweight Agile methodologies designed to accommodate teams of different sizes and characteristics. Crystal methodologies emphasize direct communication, adaptability, and process flexibility, enabling teams to tailor their workflows to project-specific requirements (Cockburn, 2004).
4. Adaptive Software Development (ASD) – A framework centered on dynamically adjusting project strategies in response to evolving business and technological conditions. ASD promotes iterative software delivery, continuous experimentation, and adaptive learning to respond to uncertainties effectively (Highsmith, 2007).
5. Dynamic Systems Development Method (DSDM) – A structured Agile framework primarily applied in large-scale business projects. DSDM maintains rigorous control over project scope and requirements while allowing flexibility in prioritizing deliverables. It requires continuous stakeholder involvement and iterative product development cycles (Stapleton, 1997).

6. Feature-Driven Development (FDD) – An Agile approach focusing on systematically delivering functional features aligned with business priorities. FDD emphasizes domain modeling, feature-based planning, and iterative deployment of completed system components (Palmer & Felsing, 2002).

One of the most critical aspects of project management is evaluating project performance, which refers to the ability to achieve predetermined objectives optimally in terms of time, cost, and quality. In Agile methodologies, specific performance metrics provide both quantitative and qualitative insights into team productivity and product quality. Velocity and delivery speed are among the key indicators—velocity refers to the number of work units (e.g., story points, completed tasks) delivered by a team in a single iteration (Sprint). This metric enables forecasting future work pace and iteration planning. Delivery speed, on the other hand, measures the time elapsed between task initiation and final implementation. High-performing teams aim to minimize delivery speed by eliminating inefficiencies and operational bottlenecks. Another important factor is team stability, as team composition variability affects efficiency and long-term project success. Team stability is measured by analyzing turnover rates and the number of new members joining within a given period. A stable team fosters synergy, improves communication, and enhances coordination, all of which contribute to increased performance strategies (Lindsjørn et al., 2016). Additionally, project success is not solely determined by speed but also by the quality of the deliverables. In IT projects, product quality is assessed using metrics such as defect rates, test coverage, failure rates, and compliance with user requirements. High product quality reduces rework costs and enhances stakeholder satisfaction (Boehm, B., & Turner, 2004). Finally, team efficiency evaluates a team's productivity in terms of delivering business value. It can be assessed by comparing planned versus completed work, resource utilization, and the level of collaboration and self-organization within the team. High-performing teams exhibit strong autonomy, effective communication, and the ability to quickly adapt to shifting project priorities (Dingsøyr et al., 2012). In conclusion, project management effectiveness depends on both the selected methodologies and a team's ability to manage resources efficiently, overcome challenges, and deliver high-quality outcomes. Metrics such as velocity, team stability, product quality, and team efficiency are essential indicators of project performance and enable organizations to optimize their workflows to maximize value.

3. ADVANCED ANALYSIS OF THE EARNED VALUE MANAGEMENT SYSTEM IN THE CONTEXT OF AGILE METHODOLOGIES

The Earned Value Management System (EVMS) constitutes a sophisticated project management mechanism that integrates key performance dimensions, including scope, schedule, and cost, to ensure precise planning, performance monitoring, and the implementation of control mechanisms. By leveraging data generated by EVMS, project management professionals can conduct advanced predictive analyses regarding costs, schedules, and technical project outcomes. The implementation of EVMS necessitates adherence to established industry standards (National Defense Industrial Association, 2018), which regulate the execution of various subprocesses, such as contract management, team organization, and risk monitoring.

A fundamental aspect of EVMS is the establishment of a realistic Performance Measurement Baseline (PMB), which serves as a reference point for the systematic evaluation of project status and facilitates informed managerial decision-making. From the perspective of project management sciences, the functionality of EVMS remains highly dependent on its socio-organizational environment, meaning that factors such as team competencies, decision-making processes, and stakeholder engagement may exert either a positive or negative influence on system effectiveness. In academic discourse, EVMS is classified as a socio-technical system, necessitating the simultaneous refinement of both its technological components and the social dynamics surrounding it (Cho et al., 2020).Within this framework, EVMS maturity is defined as the degree to which its subprocesses comply with established industry standards and their effectiveness in project execution. Studies have demonstrated that a higher level of EVMS maturity correlates with improved project performance, as a well-integrated EVMS enhances project control and predictive accuracy (Aramali et al. 2022; Government Accountability Office 2021). Enhancing the effectiveness of EVMS, and consequently increasing the probability of

project success, therefore requires the optimization of both technical processes and the inclusion of social determinants in the assessment of its functionality (Cho et al., 2020). In the context of Agile methodologies, the implementation of EVMS necessitates the adaptation of traditional performance metrics to accommodate the iterative nature of project execution. The key performance indicators (KPI) employed in Agile EVM are presented in table 1.

Table 1. KPI in Agile EVM

Metric	Description
Planned Value (PV)	Represents the planned value of work to be completed within a given timeframe.
Earned Value (EV)	Reflects the actual value of work completed, in accordance with the defined project scope.
Actual Cost (AC)	Aggregates the financial expenditures incurred up to a specific point in the project lifecycle.
Cost Variance (CV)	Denotes the difference between EV and AC, indicating either budget efficiency or cost overruns.
Cost Performance Index (CPI)	The ratio of EV to AC, providing a consolidated measure of cost efficiency.
Schedule Variance (SV)	The difference between EV and PV, determining the extent to which the schedule adheres to planned objectives.
Schedule Performance Index (SPI)	The ratio of EV to PV, facilitating the assessment of project progress relative to the planned schedule.

Source: own elaboration based on (Aramali et al. 2022; Government Accountability Office 2021).

In Agile project management frameworks, such as Scrum, execution follows an iterative approach (Sprints), wherein work scope is defined through user stories and evaluated based on story points. The effective deployment of Agile EVM necessitates the completion of several key steps. First, it is essential to determine the total number of story points in a release, as the sum of all points assigned to user stories within a given release defines the Budget at Completion (BAC). Next, teams must monitor work progress by updating the number of completed story points at the conclusion of each iteration, which allows for the dynamic calculation of EV. Simultaneously, tracking actual costs through continuous monitoring of project expenditures ensures an accurate assessment of the Actual Cost (AC). Finally, performance metrics such as CV, CPI, SV and SPI should be calculated regularly to enable real-time project evaluation and support timely, data-driven corrective decision-making. The adoption of Agile EVM is associated with a range of organizational benefits. One key advantage is the early detection of deviations, as systematic monitoring of EVM metrics enables the prompt identification of schedule and budget discrepancies, allowing for timely mitigation. Additionally, the use of indicators such as the CPI and SPI enhances forecasting accuracy, supporting more precise predictions regarding costs and completion timelines, which in turn aids strategic decision-making. Agile EVM also contributes to increased transparency in project governance by providing stakeholders with objective, quantifiable data on project status, thereby fostering trust and improving communication among teams.

Agile EVM serves as an advanced mechanism that integrates classical earned value management techniques with flexible Agile project management methodologies. It enables precise assessment of project progress, resource utilization efficiency, and alignment with planning objectives. The successful implementation of Agile EVM is contingent on both its technical deployment and the ability to adapt to the socio-organizational environment of a project, necessitating an interdisciplinary approach to project management.

4. IMPLEMENTATIONS OF SIMULATION MODELLING AND AI IN PROJECT MANAGEMENT

4.1. Use of computer simulation in project management

Simulation modeling involves creating computer models that represent real systems or processes. It enables the replication of real-world operations using mathematical models, allowing for the analysis of how external variables (input factors) and internal parameters influence system behavior. Today, simulation modeling is widely utilized in both science and management. In the field of management, it plays a key role in cost reduction, accelerating development cycles, improving product and service quality, and enhancing knowledge management (Banks et al., 2005; Wooley et al., 2023). Simulation modelling has been a productive topic of research in many fields, including project management applications, particularly concerning IT projects (Rodríguez et al., 2011). Pikh et al. (2025) use simulation modeling to automate the procedure for selecting the optimal solution for the IT project development process, providing reliable support and increasing the efficiency of project management. Hanne and Nickel (2005) considered the problem of planning inspections and other tasks within a software development project with respect to the objectives of quality, project duration, and costs. They built a discrete-event simulation model comprising the phases of coding, inspection, test, and rework and formalised the problem of project scheduling as a multiobjective simulation optimisation problem. Authors in Ratushny et al. (2019) developed a computer model for estimating scenarios for fire system development projects. The model is based on an algorithm that simulates these projects, as well as a rapid assessment of each scenario for the development of fire protection system environments. To support decision-making in project management application of simulation modelling and statistical control charts can be used (Acebes et al. 2014). Beyond risk analysis, mitigating uncertainty is crucial for achieving project objectives. To address this, Naeni and Salehipour (2011) represented percent completions as fuzzy numbers and applied fuzzy set theory to estimate project performance.

4.2. Gen-AI in Project Management: support and automation

Advanced applications of Generative Artificial Intelligence (Gen-AI) gained widespread recognition in 2022 as user-friendly tools emerged, enabling automation and optimization in fields such as project management and engineering with unprecedented efficiency and adaptability (Durth et al., 2023). Gen-AI is a field of artificial intelligence that focuses on creating new content, such as text, images or program code, by using advanced machine learning models. In the context of large language models (LLMs) and natural language processing (NLP), gen-AI plays a key role in automating and improving natural language processes (AlShannaq et al., 2024). Large language models are sophisticated natural language processing algorithms that have been trained on huge text datasets to predict the next words in a sentence, translate text, answer questions or generate consistent and meaningful answers. Generative artificial intelligence has great potential in project management, streamlining key processes, increasing efficiency and supporting decision-making. With properly trained LLMs, Gen-AI can significantly improve project planning, monitoring and execution. A significant advancement in the application of artificial intelligence to content generation has been made possible by the release of apps like ChatGPT, Claude, Perplexity, which provide end users with access to LLMs (Uppalapati & Nag, 2024; Choudhary, 2025). In recent years, the most widely used Gen-AI model has been GPT-3 (later GPT-3.5 and GPT-4), particularly through its application as ChatGPT, which has gained significant traction not only in management but also in education, business, programming, and various other domains, contributing to its rapid rise in popularity (Mossavar-Rahmani & Zohuri, 2024). With such rapid development, artificial intelligence models are becoming a helpful tool in project management. One of the most significant applications of AI in this field is the automation and enhancement of project planning (Sravanthi, 2023). Artificial intelligence models can analyze historical data, identify patterns, and use them to predict realistic schedules, resource allocation, and potential risks. This enables managers to make faster and more accurate decisions regarding execution strategies. Gen-AI can also generate detailed project plans, taking into account client requirements, available resources, and operational risks (Crawford et al., 2023). AI models are capable of simulating various scenarios and assessing their impact on project execution, allowing for better preparation for potential threats (Auth et al., 2019). Another key functionality of AI in project management is the automation of reporting and progress monitoring

(Hofmann et al., 2020). These models can generate reports based on data from multiple sources, summarizing project status, identifying delays, and recommending corrective actions.

4.3. AI and Simulation-Based Project Management: A Structured Framework

The rapid expansion of modeling languages has reignited interest in the long-standing challenge of automating code generation and program synthesis. Tools like OpenAI's Codex and GitHub Copilot are reshaping software development by offering advanced automated coding capabilities. By comprehending both programming syntax and human-readable instructions, these tools help developers write, debug, and optimize code more efficiently. Codex and Copilot convert natural language prompts into functional code, significantly reducing the time required for routine tasks and boosting developer productivity (Chen et al., 2021). Beyond assisting programmers, these tools also broaden access to coding by lowering the barrier for non-programmers to create simulation models. By allowing users to interact using natural language, they make coding more intuitive for individuals without formal programming expertise (Nguyen et al., 2023). As demonstrated in Jackson's study (Jackson et al., 2023), automated code generation based on supply chain management problem descriptions can be a valuable tool for developing simulation models. As project management becomes increasingly complex, organizations are turning to advanced technologies to enhance decision-making, optimize workflows, and predict potential risks. Computer simulations and generative AI offer innovative solutions by modeling project scenarios, automating repetitive tasks, and improving resource allocation. Proposed framework (fig. 1) outlines the integration of these technologies into project management processes to increase efficiency and reduce uncertainties.

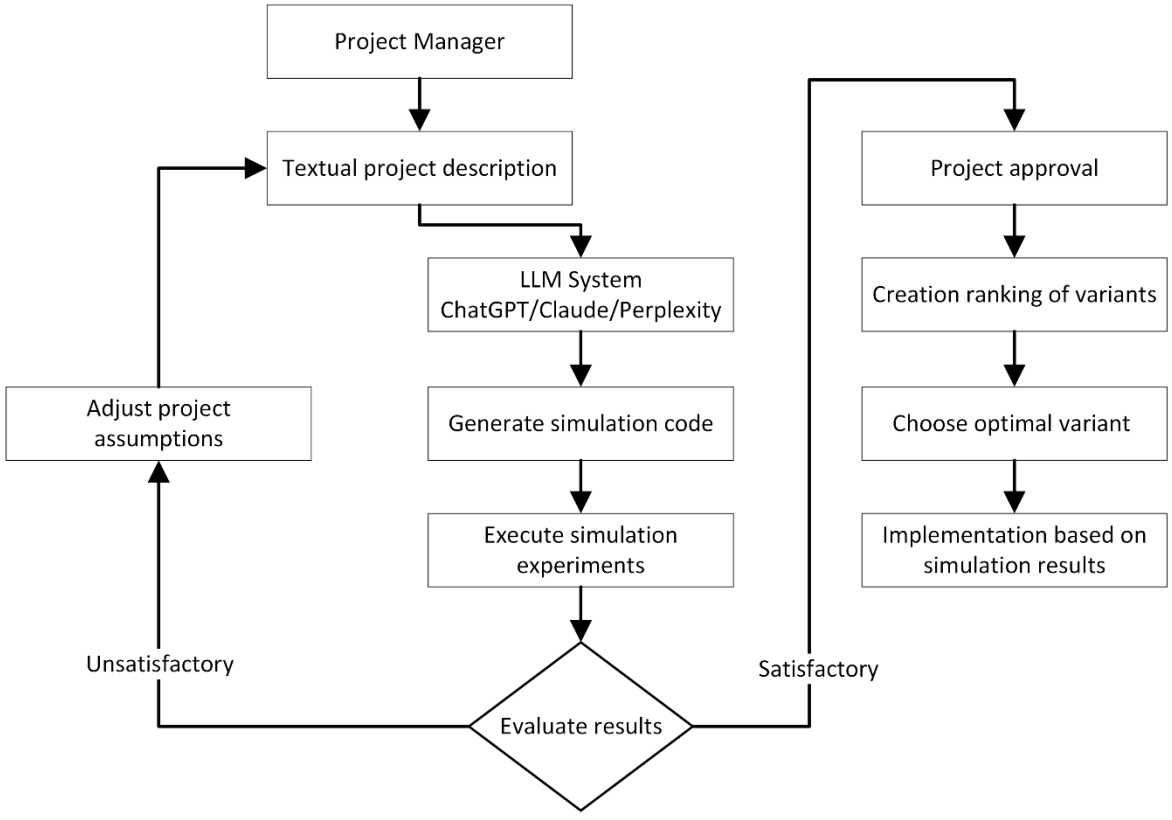


Figure 1. Framework for integrating computer simulation and Gen-AI in Project Management
Source: own elaboration.

The proposed framework focuses on integrating the capabilities of generative AI and simulation modeling. A project manager can create a simulation model (program code) by providing a textual description of the analyzed project, using tools such as ChatGPT, Claude, or Perplexity, which are based on LLMs. The generated simulation model code is then executed.

The results of these simulation experiments either lead to the approval of the project or require adjustments to the project assumptions or decisions, followed by a new series of simulation experiments. This approach allows for the preliminary selection of variants and the creation of a ranking. Among the variants that pass the initial selection, the optimal one is chosen for implementation, with the basis for evaluation being the results of simulation experiments for selected scenarios.

5. RESULTS

To show the practical application of the presented framework integrating computer simulation and Gen-AI in Project Management, we used the case-study presented in (Szyjewski & Muszyńska, 2013). It showed how to use simulation modeling with Earned Value in project management using the Agile approach. The case-study presented in our work was extended to 3 different scenarios (Table 2) to show the applicability of simulation in what-if analysis. To ensure comparability and clarity, the scenarios were defined using a consistent set of parameters covering project scale, team structure, leadership, complexity, and key Agile-based performance indicators such as velocity, CPI, and SPI. These parameters were selected based on their relevance in empirical studies on Agile performance, as well as their ability to capture both quantitative (e.g., cost, duration, delivery speed) and qualitative aspects (e.g., team cohesion, product quality) of project execution. This approach allowed us to simulate realistic variations in team dynamics, delivery outcomes, and management challenges across different project contexts.

Table 2. Simulation scenarios assumptions

Parameter	Project 1	Project 2	Project 3
Project Value [PLN]	500	2,000,000	1,200,000
Team Size	6	8	10
Team Composition	Domain experts with experience	Domain experts from different divisions	Mixed-experience, multi-role team
Team Cohesion	Cooperative, task-focused	Low, conflicts and blame-shifting	Moderate, improved over time
Complexity [Story Points]	10	20	15
Sprint Length [weeks]	2	2	2
Number of Sprints	20	20	20
Project Leader Soft Skills (0-1)	0.7	0.9	0.5
Error Rate [%]	5%	15%	8%
Bug Detection Efficiency [%]	90%	95%	88%
Delivery Delay [weeks]	2	6	3
Post-release Problems	Minor, non-critical bug fixes	High cost, low quality, low margin	Moderate quality issues
Average Velocity	~474	~437	~475
CPI (avg)	0.02	0.00	0.01
SPI (avg)	0.95	0.42	0.63

Source: own elaboration.

The approach we presented shows how simple simulation models can be created automatically from natural language verbal descriptions, and how project managers and AI-based systems can work together. Table 3 shows the prompt used in the ChatGPT4 application to generate simulation code.

Table 3. Sample prompt for simulation model in project management with Earned Value

Prompt for GPT application
Acting on the assumptions given in the table: "Table 2 added here" Provide Python code to simulate the described project management problem. Present the main results of the project evaluation based on the Earned Value methodology using charts, including CPI, SPI, velocity, number of defects, and average bug fix time

Source: own elaboration.

It is important to note that the generated code was created without any expertise in programming and simulation modeling. The AI application used set the random parameters on its own regarding each of the three scenarios studied. This gives project managers a chance to use advanced computer simulation tools that have been available for a long time but in a much faster time and without the expertise to build such models in specialized simulation software. The code generated in Python:

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
# General parameters
NUM_SPRINTS = 20
SPRINT_DURATION = 2  # weeks
# Input data for three projects
PROJECTS = {
   "Project 1": {
      "total_sp": 10000,
      "base_velocity": 480,
      "velocity_noise": 30,
      "ac_base": 24000,
      "ac_variation": 1000,
      "bugs_per_sprint": 10,
      "bug_fix_time_mean": 2,
      "bug_fix_time_std": 0.5
   },
   "Project 2": {
      "total_sp": 20000,
      "base_velocity": 420,
      "velocity_noise": 50,
      "ac_base": 130000,
      "ac_variation": 5000,
      "bugs_per_sprint": 25,
      "bug_fix_time_mean": 3.5,
      "bug_fix_time_std": 1.0
   },
   "Project 3": {
```

```
        "total_sp": 15000,
        "base_velocity": 460,
        "velocity_noise": 40,
        "ac_base": 52000,
        "ac_variation": 3000,
        "bugs_per_sprint": 15,
        "bug_fix_time_mean": 2.5,
        "bug_fix_time_std": 0.7
    }
}
# Function to generate sprint data
def generate_project_data(name, params):
    records = []
    ev_cum, pv_cum, ac_cum = 0, 0, 0
    pv = params["total_sp"] / NUM_SPRINTS
    for sprint in range(1, NUM_SPRINTS + 1):
        velocity = max(0, np.random.normal(params["base_velocity"], params["velocity_noise"]))
        ev = min(pv, velocity)
        ac = np.random.normal(params["ac_base"], params["ac_variation"])
        ev_cum += ev
        pv_cum += pv
        ac_cum += ac
        cpi = ev_cum / ac_cum if ac_cum != 0 else 0
        spi = ev_cum / pv_cum if pv_cum != 0 else 0
        bugs = np.random.poisson(params["bugs_per_sprint"])
        fix_time = np.random.normal(params["bug_fix_time_mean"], params["bug_fix_time_std"])
        records.append({
            "Project": name,
            "Sprint": sprint,
            "PV": pv,
            "EV": ev,
            "AC": ac,
            "CPI": cpi,
            "SPI": spi,
            "Velocity": velocity,
            "Defects": bugs,
            "Bug Fix Time": fix_time })
    return pd.DataFrame(records)
# Generate data for all projects
all_data = pd.concat([
    generate_project_data(name, params) for name, params in PROJECTS.items()
], ignore_index=True)
# Set seaborn style
sns.set(style="whitegrid")
# Function to create and save plots
def plot_and_save(metric, ylabel, title, filename, kind="line", marker=False):
    plt.figure(figsize=(10, 6))
    for project in all_data["Project"].unique():
        subset = all_data[all_data["Project"] == project]
        if kind == "line":
            plt.plot(subset["Sprint"], subset[metric], label=project,
                     marker='o' if marker else None)
        elif kind == "bar":
            plt.bar(subset["Sprint"] + 0.25 * (list(PROJECTS.keys()).index(project)-1),
                    subset[metric], width=0.25, label=project)
```

```
        plt.title(title)
        plt.xlabel("Sprint")
        plt.ylabel(ylabel)
        plt.legend()
        plt.tight_layout()
        plt.savefig(filename)
        plt.close()
    # Generate and save all plots
    plot_and_save("CPI", "CPI", "CPI Over Time", "cpi_plot.png", marker=True)
    plot_and_save("SPI", "SPI", "SPI Over Time", "spi_plot.png", marker=True)
    plot_and_save("Velocity", "Velocity", "Velocity Over Time", "velocity_plot.png")
    plot_and_save("Defects", "Number of Defects", "Defects Over Time", "defects_plot.png",
kind="bar")
    plot_and_save("Bug Fix Time", "Fix Time (days)", "Bug Fix Time Over Time", "bug_fix_plot.png",
kind="bar")
    # Boxplot for velocity
    plt.figure(figsize=(8, 6))
    sns.boxplot(data=all_data, x="Project", y="Velocity", hue="Project", palette="pastel",
legend=False)
    plt.title("Velocity Distribution by Project")
    plt.xlabel("Project")
    plt.ylabel("Velocity")
    plt.tight_layout()
    plt.savefig("velocity_boxplot.png")
    plt.close()
```

Finally, according to the given prompt, the results of the simulation are shown in the graphs on the output variables (figure 2). The simulation was carried out in Pycharm 2024.3.11 software.



Figure 2. Results from simulation implementation

Based on the presented results, it can be observed that the three simulated project scenarios exhibit significant differences in key performance indicators. These differences reflect the variation in team structures, project complexity, and leadership characteristics assumed in the model. The simulation results, demonstrate how EVM metrics – including CPI, SPI, velocity, number of defects, and average bug fix time – respond to structural and organizational variables. Project 1 showed the highest stability and efficiency: its CPI and SPI values were close to optimal, while the team maintained consistently high velocity and quality (low number of defects and short resolution times). Project 2 produced the weakest results, with low cost and schedule performance, high defect rates, and long bug fix times, indicating major organizational issues and poor team cohesion. Project 3 occupied an intermediate position: initially inefficient, it showed gradual improvements in velocity, defect reduction, and process stability over time. In summary, these results highlight the importance of human factors – such as team

cohesion, role clarity, and adaptive capacity – in determining the success of Agile projects. While Earned Value Management provides a quantitative framework for monitoring progress, the quality and reliability of project outcomes depend largely on soft factors shaping team dynamics. The conducted what-if analysis effectively illustrated how relatively small variations in team composition, leadership style, or task complexity can significantly affect key indicators of performance, including cost efficiency, delivery speed, and overall product quality.

5.1 Comparative simulation evaluations

The study validates a simulation model developed using proposed framework (generated Python code for simulation by GPT4) by benchmarking its outputs across three independent projects against two alternative models. The first comparison model was built in ARENA, a discrete-event simulation platform widely recognized for its accuracy in modeling project management processes (Fang & Marle, 2012). The second comparator employed Asana, a popular project management solution recently enhanced with AI features (e.g. AI teammates, smart workflows) that automate task execution and provide intelligent insights. The validation considered averages from 20 sprint iterations for key EVM metrics (CPI, SPI), velocity, defect count, and average bug-fix time. The summary results are presented in table 4.

Table 4. Comparison of average results between analyzed models

Project	Method	CPI	SPI	Velocity	Defects	Avg Bug-Fix Time (days)
1	GPT4	0.0190	0.91	480	12	2.0
	ARENA	0.0188	0.909	478	13	2.1
	Asana AI	0.0176	0.89	455	17	2.7
2	GPT4	0.0028	0.41	340	24	4.5
	ARENA	0.0027	0.408	338	25	4.6
	Asana AI	0.0025	0.395	320	30	5.3
3	GPT4	0.0092	0.63	495	15	3.2
	ARENA	0.0090	0.628	492	16	3.3
	Asana AI	0.0087	0.61	470	20	3.9

Source: own elaboration.

In the ARENA and GPT4 models, discrepancies across CPI/SPI are under 2 %, velocity under 1 %, and defect and fix-time differences are under 10 %, indicating strong alignment. The Asana AI model, by contrast, exhibits larger variances: CPI and SPI lower by 5–10 %, velocity reduced by 5–7 %, defect counts increased by 20–25 %, and bug-fix time increased by similar magnitude.

ARENA's strength lies in its granular modeling of structural and event-driven dynamics, and the simulation model generated by GPT4 in Python code successfully replicates these relationships. Asana AI, while efficient in operational project management, applies abstraction layers and rule-based decision models that oversimplify the simulation, resulting in lower fidelity and larger performance deviations. The alignment between the GPT4 and ARENA simulation models demonstrates that GPT4 can accurately restore both structural integrity and behavioral fidelity of a manual simulation framework.

6. CONCLUSION

Computer simulations and generative AI offer innovative solutions by modeling project scenarios, automating repetitive tasks, and improving resource allocation. The framework proposed in the paper integrates these technologies into project management processes with the objective of enhancing operational efficiency, strengthening intelligent management practices, and mitigating uncertainties. Traditionally, simulation has been used by project managers to optimize decision-making, but its

implementation required proficiency in specialized software. This paper demonstrates how Large Language Models can build simulation models for scenario analysis in project management using natural language descriptions. An adaptation of the Earned Value method to Scrum conditions was developed, integrating manufacturing process flows with Agile EVM variable calculations in a simulation model.

The results show that the proposed method simplifies the development of simulation models, making it a valuable tool for analyzing the progress of IT projects managed under Agile-based methodologies. Generative AI and simulation modeling emerge as complementary techniques that can deliver the actionable insights needed for intelligent management, while intuitive visualizations further support effective decision-making.

The concept provides a strong foundation for further research into the integration potential of generative AI in project management within complex organizational environments. Future work should explore extending this approach with modules for advanced risk analysis, cost estimation, and predictive scenario forecasting in multi-team projects. Empirical implementations could enable systematic evaluation of LLM-based tools on process efficiency and deliverable quality within Agile development frameworks.

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CHAPTER 3
Intelligent Management for Sustainable Development

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ARTIFICIAL INTELLIGENCE (AI) IN LOCAL GOVERNMENTS: HOW DO INTELLIGENT TECHNOLOGIES IMPROVE CITY MANAGEMENT AND RESIDENT COMMUNICATION?

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ABSTRACT

Purpose: *The aim of this article is to indicate the role of artificial intelligence in local governments, mainly how smart technologies improve city management and communication with residents. Analyzing different applications of AI, it is emphasized how intelligent systems contribute to efficiency, transparency and responsiveness in local management.*

Need for the study: *In the current reality, local governments need to manage resources more effectively, provide public services more efficiently and engage residents in decision-making processes. AI has become a key driver of innovation in smart city initiatives, but there is still a gap in understanding its real applications and impact and adapting it to the needs of residents.*

Methodology*: This article is based on a review of secondary sources, including scientific literature and reports. It also indicates examples of cities that have successfully implemented AI. The study synthesizes the findings from these cases to identify challenges, benefits and barriers to implementing AI technologies. It also presents preliminary results from interviews with local government representatives.*

Findings: *The article identifies key areas in which artificial intelligence has a significant impact on the activities of local governments. The results show that AI significantly improves city governance by optimizing resource allocation, improving public service delivery, and enabling proactive problem-solving. For example, AI-based predictive analytics or communication tools (e.g. chatbots). It also identifies challenges such as data privacy, ethical concerns, and technology readiness, which are key for local governments.*

Practical Implications: *The article provides local governments with practical insights into the benefits and challenges of implementing AI technologies to help them make decisions. It also highlights the importance of developing ethical frameworks and inclusive policies to ensure that AI solutions benefit all citizens equally.*

Keywords: Artificial Intelligence (AI), local government, resident, smart cities, management, communication

Jel odes: H76, O33, M39, L86

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1. INTRODUCTION

The recent advances in artificial intelligence, which has been around for a long time, have made it a leader in technological tools that affect various aspects of management and society. It refers to technologies that simulate human perception, behavior, and decision-making through a variety of applications. More than half of the world's population lives in cities, and this percentage is growing. City management is becoming increasingly complex due to increasing urbanization, climate change, and the expectations of residents regarding the quality of public services. Traditional management methods are often unable to meet these challenges, which is why local governments are looking for innovative solutions. AI offers tools for real-time data analysis, trend forecasting, and resource optimization, which can significantly improve the efficiency of city management. To ensure that the cities of tomorrow create opportunities for everyone, it is important to understand how artificial intelligence is developing, which has already significantly affected various sectors, including healthcare, education, industry, and finance. The use of artificial intelligence in city management and communication with residents is already a reality. Cities are already improving their administration, managing urban traffic, and introducing Big Data. However, reaping the benefits of AI requires local governments to be technologically, organizationally, and legally prepared. Traditional methods of city management often do not meet the requirements of today's citizens. Cities around the world are increasingly adopting AI-based technologies to improve the delivery of public services, optimize urban management, and facilitate more effective communication with residents. These changes are consistent with the broader concept of smart cities, where digital technologies are used to enhance sustainability, governance, and citizen engagement (Batty, 2018). The term "data democratization" is becoming increasingly popular as part of a broader effort to make knowledge and information accessible to everyone (Marr, 2017). It refers to giving everyone access to all data and information produced by an organization, regardless of prior knowledge and without lock-in, as well as avoiding the typical bottlenecks present in most data analyses. Inclusivity is important so that no one feels left out.

AI has become a key driver of innovation in smart city initiatives, but there is still a gap in understanding its real-world applications and impact, as well as its adaptation to the needs of residents. Research commissioned by the European Commission highlights the significant potential of AI to improve public sector services across the EU. However, the broader introduction of AI in local governments depends on many factors, including the availability of digital infrastructure and citizen acceptance. In the literature, on the one hand, there are more and more examples of the use of AI in areas such as transport, environmental protection, traffic management and energy, on the other hand, there is little research and the use of AI in communication with residents. Most of the talk is about bots or assistants, which are also not very widespread. The article will cite the results of research from various reports, as well as provide examples of cities using AI in management and communication with their stakeholders. Additionally, the results of preliminary research – interviews conducted among local government representatives – were cited. Despite its many advantages, the integration of AI with local government administration also involves significant challenges, which the authors will also refer to. By analysing desk research, reports and case studies from different cities, this paper provides insights into the practical applications of AI in city administration.

2. LITERATURE REVIEW

Artificial intelligence (AI) is a field of computer science that focuses on creating systems capable of performing tasks that require human intelligence, such as learning, reasoning, and decision-making (McKinsey, n 2021). Recently, the rapid development of AI has made it increasingly important due to advances in machine learning, natural language processing (NLP), and big data analysis (Russell & Norvig, 2021). According to a report by Gartner (2025), AI is one of the most important technological trends that has the potential to transform almost every area of life, including city management and public administration. In an era of rapid technological development, artificial intelligence (AI) is becoming a key tool in city management and communication with residents. Local governments around the world

are increasingly reaching for intelligent solutions to meet the challenges of increasing urbanization, limited resources, and residents' expectations regarding the quality of public services. Applications of AI in local management range from automated decision-making systems that streamline administrative tasks to predictive analytics that enable proactive problem-solving in areas such as traffic management, waste collection, and public safety. Predictive analytics based on artificial intelligence allows local governments to predict traffic patterns, crime hotspots, and threats, such as fires, enabling rapid response to challenges (Hersperger et al., 2018). The development of AI technology therefore enables the dynamic development and optimization of the functioning of urban areas. It undoubtedly leads to an improvement in the quality of life of residents, including the quality of public services and road traffic. Traffic management systems improve the fluidity of transport, which in turn reduces traffic jams and exhaust emissions. Many cities are introducing intelligent systems in wastewater management, which allows for monitoring of water consumption and identifying potential failures. Artificial intelligence is already monitoring air quality and planning spatial development. Thanks to this, it is also possible to respond appropriately to climate change. All this translates into more effective and sustainable city management.

The integration of artificial intelligence (AI) in city management and communication with residents is an important task in local governments, increasing efficiency, improving service delivery and supporting citizen engagement. The use of AI significantly strengthens the ability of local governments to understand and respond to the needs and preferences of residents. For example, AI enables personalized service delivery, helps optimize resources and increases the responsiveness of public institutions in communication with citizens (Kim et al., 2023). It should be emphasized that to increase and improve its intelligence. artificial intelligence needs the city. It can only develop by acquiring new data, and after all: "There's no data like more data" (Lee, 2018: 14). Cities have huge data generators, which results from the fact that they are an important place for society. Cities can also offer the best possible data for learning artificial intelligence from: real data, as opposed to carefully selected and cleaned data sets that are modeled on a computer. Modern AI allows both the ingesting of large data sets that would otherwise take a long time to analyze and the conducting of complex analyses in a much shorter time (Akthar, 2023). This ability improves decision-making processes and ensures that local government can direct needed resources to the appropriate departments or areas, which increases efficiency.

The necessity of incorporating artificial intelligence (AI) within local governmental entities is driven by the imperative to address the growing intricacy of urban challenges, including but not limited to traffic management, energy consumption optimization, and the enhancement of municipal services. Conventional management methodologies frequently demonstrate inadequacy when confronted with rapidly evolving circumstances and escalating societal expectations. As articulated by the authors of the McKinsey & Company report (2018), cities that allocate resources to smart technologies can attain operational efficiency enhancements of up to 20-30%. Concurrently, the European Commission's report on artificial intelligence (2020) underscores the imperative for ethical and transparent AI implementation, respectfully safeguarding citizens' rights. As articulated by Berryhill et al. (2019), the integration of AI has the potential to liberate nearly one-third of public officials' time, enabling them to prioritize tasks that directly benefit citizens. In larger organizations with more complex organizational structures and a dedicated data department, a Large Language Model (LLM) can be programmed from existing Generative AI models and trained or tuned using internal data. This LLM can then be shared with all employees to suggest new paths for the organization. LLMs have been applied in a variety of fields (e.g., education, healthcare, ecology), performing various functions such as speech recognition, information retrieval, text summarization, and dialogue systems. LLMs have demonstrated remarkable performance and potential in generating and processing natural language texts for diverse purposes and audiences (Ding et al., 2023). However, LLMs also pose risks, including concerns regarding data quality, model reliability, ethical issues, and social impact. These programs necessitate an initial investment from the organization and may also require substantial cultural changes. It is crucial to acknowledge that the implementation of AI, particularly in the context of data democratization, is an ongoing process that requires continuous attention and adjustment.

Local governments worldwide are progressively adopting artificial intelligence (AI) to enhance operational efficiency and improve service quality for their constituents. The integration of AI in local governance facilitates the automation of administrative processes, such as application processing and

document management, leading to significant cost and time savings. Additionally, AI plays a crucial role in the analysis of social and economic data, enabling more effective urban planning and resource allocation (Pandey, 2024; Kitchin, 2016). In this vein, cities are increasingly leveraging AI technologies to facilitate urban planning, public safety, environmental protection, and various administrative tasks. For instance, AI urban planning, which permeates the everyday urban space of life and work, ushers in a new era with the advent of the Artificial Intelligence of Things (AIoT) (Cugurullo et al., 2023). A significant application of AI lies in citizen engagement platforms, where AI-based tools facilitate real-time communication between local governments and the public, enabling effective responses to queries and provision of assistance (Hamirul et al., 2023). Communication with residents stands as a pivotal domain in which AI can play a substantial role. Specifically, intelligent chatbots and virtual assistants leveraging natural language processing (NLP) technologies empower local governments to swiftly deliver customized responses to residents' inquiries and challenges (Panda et al., 2025) .A notable instance is the city of Tallinn, which implemented an AI-driven chatbot to address residents' queries concerning public services, resulting in a substantial reduction in response time.

In local governments, AI is of great importance for technical and social infrastructure as a platform for cooperation between economic, social and public entities, as well as for the efficiency of decision-making and security. AI systems are increasingly recognized as essential tools for increasing the operational efficiency of local government units. Farida et al. (2023) emphasize the importance of understanding the interdependencies between technology, policy and community expectations in the effective implementation of AI systems within local governance. These systems not only facilitate data-driven decision-making but also support proactive community engagement, enabling local governments to better meet the needs of their constituents (Yiğitcanlar et al., 2022). AI can simultaneously improve data operations and respond to citizen inquiries and opinions, underscoring its role as a conduit between local government and residents.

Despite the numerous benefits, implementing AI in local governments is also associated with challenges, which the authors will refer to later in the article. One of the main problems is the concern about data privacy, especially in the context of using AI to monitor and analyze the behavior of residents (Zuboff, 2019). Additionally, there is a risk of digital exclusion, particularly among older or less affluent social groups who may encounter challenges in using modern technologies (Van Dijk, 2020). Consequently, it is imperative for local governments to adopt AI in a transparent and ethical manner, considering the needs of all social groups. The heterogeneity of entities within a given territory, particularly in urban contexts, necessitates the utilization of substantial data sets and the establishment of effective collaborative frameworks for development (Noworól, 2020: 27–35). Undoubtedly, artificial intelligence (AI) holds considerable promise in the realm of urban management, including communication with residents. However, it is imperative to acknowledge that the implementation of AI demands meticulous planning, taking into account both technological and ethical challenges, as well as intersectoral collaboration. The willingness of local governments and citizens to adopt AI technologies is also crucial. Challenges often include infrastructure deficits, a shortage of AI specialists in public sectors, and the lack of a solid regulatory framework (Moreno, 2023; Noordt & Misuraca, 2020). The judicious implementation of strategic investments and reforms is identified as a critical factor in leveraging the full potential of AI. When implemented effectively, AI has the potential to substantially enhance service delivery and governance outcomes in local governments (Motadi, 2024; Popescu et al., 2024).

3. METHODOLOGY

This article takes a qualitative research approach, using secondary data analysis and a case study, to examine the impact of artificial intelligence (AI) on urban governance and local government communication with citizens. The methodology aims to provide a comprehensive, evidence-based assessment by synthesizing existing literature, government reports, and real-world case studies of cities that have implemented AI-based solutions.

Secondary data analysis is a widely used research method in management studies because it allows for the examination of existing empirical data, reports, and industry publications (Johnston, 2017). The

use of secondary sources allows for a systematic review and synthesis of findings from multiple perspectives.

To ensure rigor and relevance, sources were selected based on criteria such as timeliness, credibility, and filtering of sources that specifically address AI implementation in cities, public service improvements, and citizen engagement. The authors acknowledge the limitations of secondary data, including potential errors in data collection, reporting, and consistency. To mitigate these limitations, the paper draws on multiple sources to ensure accuracy and validity. City examples (case studies) were chosen as a qualitative method that allows for a broader analysis of specific examples of AI implementation in local governments (Yin, 2018). By focusing on specific cities that have implemented AI-based solutions, this study can identify best practices, challenges, and lessons learned from different urban settings. Cities that are considered leaders in the use of AI were selected. To increase validity, multiple examples were identified to compare experiences from different urban contexts. Data for the case studies was collected from official city reports, academic publications, industry articles, and interviews with local government officials. Data available on city websites and social media were also used. Cities were selected based on criteria such as diverse geographic representation, diverse AI applications (e.g., transportation, public safety, civic engagement), and data availability.

The article also presents preliminary partial results of interviews conducted among selected representatives of local governments in Poland. After obtaining the consent of the respondent, each interview was recorded and deleted after transcription. Prepared questions were asked one by one. The researcher did not prompt the respondents or suggest answers. The interviews were appropriately coded. The article presents mainly the statements of four respondents: respondent 1 – a medium-sized city, respondent 2 – a large city, respondent 3 – a provincial city, and respondent 4 – a small rural-urban commune. Further research is currently underway, and their results will be presented in subsequent studies.

Through the analysis of secondary sources, government reports, and case studies from various cities, as well as the results of individual interviews, this article provides insights into the practical applications of AI in local governments. The findings will help policymakers understand the potential benefits and challenges of adopting AI in a city, and ultimately guide them toward more efficient and citizen-centric governance.

4. RESULTS

The results of the research included in the report on the study of local governments in Poland (Ministry of Digital Affairs, 2023) may be interesting. The main reason for undertaking the creation of such a report was the fact that the area related to the use of new digital technologies in local governments is currently not sufficiently explored and there is still a lack of data on this issue. The main conclusions from the study indicate that implementation work in the field of new digital technologies is currently being carried out in almost half of the surveyed local governments, which is aimed at improving the functioning of the institution. The level of implementation of new digital technologies is the highest in local government entities located in the Warmian-Masurian, Silesian and Opole voivodeships, while support in this area is expected by units from the Lublin, Pomeranian and Podlaskie voivodeships. As the results of the study show, more than half of the local governments are planning to implement new digital technologies. The most frequently indicated in the surveyed local governments was the use of solutions based on e-services. Almost all surveyed units use them. The needs of citizens are the main reason for their introduction. They are less often implemented with a view to improving the internal operations of the office. In the case of technologies such as the Internet of Things or artificial intelligence, the percentage of indications confirming their use is low, and their use is most often limited to achieving the organizational goals of units. As it results from the conducted individual interviews, when asked "Why did your local government decide to implement solutions based on artificial intelligence?" local government representatives answered, among others, that: "We wanted to improve the service of residents" (respondent 1), "greater efficiency of service of residents, e.g. chatbots, automatic answers to the most frequent inquiries (respondent 2), "AI helps us analyze large data sets, e.g. optimize waste collection routes" (respondent 3 - provincial city) or optimize transport, as well as - which is a particularly important goal of implementing AI in small communes - "automation of

applications, such as e.g. registration certificate" (respondent 4 - small rural-urban commune). It can therefore be noticed that AI is used in many areas of local government management. According to the respondents, it can automate repetitive administrative activities, e.g. in accounting, registers, handling resident inquiries, be useful in prediction, e.g. mobility planning or support the management of large data sets. Respondent 3 emphasized that artificial intelligence "is a tool that reliably and quickly transmits data from the city that would take years to collect using analogue technology." Respondent 2 added that "AI in local governments is a challenge, and although it is a useful tool, it still requires time to learn how to use it."

Huge amounts of data require processing and analysis. AI enables the identification and processing of valuable information from these data streams. Examples include: monitoring road traffic, energy consumption or real-time resource management. Integration of AI with IoT allows for better city planning and infrastructure optimization. Artificial intelligence is primarily used to analyze large amounts of data collected by local governments, e.g. data on street traffic, air pollution levels, energy consumption, etc. By analyzing this data, local governments can better plan their activities and make better decisions. For example, during the COVID-19 pandemic, Gdynia used such solutions to identify gatherings that violated the then-applicable epidemic restrictions. City monitoring cameras analyzed the recorded image using an AI algorithm to detect gatherings of more than a few people in the observed points of the city. The information was passed on to the City Guard, which decided to intervene (Ziarko, 2022). A similar system is used in Wrocław to identify illegal landfills. In this case, images recorded by drones are used, which are then analyzed by AI to identify waste, e.g. abandoned car tires, in green areas. In Łódź, artificial intelligence was used to automate, among other things, the generation of correspondence and the administration of the financial and accounting system. RPA (Robotic Process Automation) technology and Wizlink robots were used for this purpose. Administrative processes are carried out faster and more efficiently, and human time is better used.

Przeybilovicz et al. (2020) conducted an international comparative study on citizen participation in smart city initiatives. They emphasized the importance of using information and communication technologies (ICT) to mediate the engagement of local authorities and citizens. The results of the studies of cities in Brazil, the United Kingdom, and the Netherlands show that the roles and functions undertaken by citizens are dynamic, as they participate in a mode that evolves and changes over time. The authors identified patterns of citizen interaction: contestation, acceptance, and cooperation, which indicates, among other things, the important role that governance plays in shaping patterns of citizen participation. Their research showed that citizen participation is increasingly recognized as essential for developing sustainable urban strategies, showing how AI enables local governments to leverage community insights and preferences, ultimately leading to better urban planning and resource allocation.

Zhu et al. (2022) examined the impact of service quality in a smart city on citizen engagement, especially in crisis situations. Based on the stimulation and reorganization (SOR) model and uncertain governance theory, the authors analyzed selected Chinese cities to determine the impact of service quality on citizen engagement during a public emergency such as the COVID-19 outbreak. This study highlighted how AI-based communication platforms increased citizens' awareness and response to critical situations, strengthening their involvement in urban management and public safety. Another example of emergency management is Amsterdam. Amsterdam is one of the leaders in Europe in the use of artificial intelligence (AI) and digital technologies in city management, including green areas. The city integrates AI tools with social participation, striving for sustainable development and increasing resilience to climate change. An example of an application is the LIFE (Local Inclusive Future Energy) project, which uses digital twins to optimize local energy systems, including the integration of urban greenery with energy infrastructure. The city implemented AI systems for stormwater management and flood prediction, optimizing drainage and water retention. AI-based platforms facilitate communication between city officials and citizens, allowing residents to participate in public consultations, submit comments and proposals on planned investments, and access information on the state of the urban environment. Amsterdam is also using AI at the airport, where it uses AI-enabled scanners that are so precise that airport staff do not require travellers to remove safe liquids and laptops from their bags. Such actions improve passenger flow management, helping to move the queues for security checks faster. Additionally, the system signals real threats. Amsterdam effectively uses AI and digital technologies in management, integrating them with active citizen participation. Thanks to this, the city

not only improves the quality of the urban environment but also increases resilience to climate change and engages residents in decision-making processes.

The Harvard report identified six types of local government problems for which AI is considered highly suitable: resource allocation, big data, expert shortage, predictable scenarios, procedural and repetitive tasks, diverse data aggregation and summarization (Mehr, 2017). It indicated many benefits for local governments, including: reducing the burden on public employees, increasing efficiency, creating new employment opportunities, solving resource allocation problems, rationalizing costs, providing improved public services and improving citizen satisfaction (through personalization and 24/7 availability (Androutsopoulou et al., 2019). The involvement of residents in city activities builds the image and their loyalty, they can then feel safer and appreciated. An example is Helsinki, which uses AI in many areas, such as the management of green areas. They analyze the needs of residents and the impact of climate on urban vegetation. AI helps in making decisions on where to plant trees and how to improve the quality of life in the city. The city places great emphasis on social participation in urban planning processes. As part of the "Summer Streets" initiative, workshops were organized in January 2023 with the participation of residents and local entrepreneurs, during which participants co-created projects to transform streets into pedestrian-friendly spaces, taking into account urban greenery. Using UrbanistAI, participants could create and visualize their ideas. This initiative was part of the city's plan to close three central streets to car traffic during the summer months, aimed at gathering public and business opinions on the potential use of the streets. Thanks to this approach, the city increased the involvement of its community and allowed for a better understanding of the proposed changes. Cities, with the involvement of residents and artificial intelligence, can better optimize recreational space and fight concrete. Helsinki, as part of the OmaStadi participatory budget, also uses elements of gamification, allowing residents to submit and select projects for implementation, including those related to green areas. In order to facilitate the process of submitting ideas, the city has developed a card game that helps residents create and develop project proposals. Helsinki, therefore, effectively integrates artificial intelligence with social participation, including in the management of green areas, using tools such as UrbanistAI and initiatives such as OmaStadi. Thanks to this, the city creates urban spaces that respond to the needs of residents, while maintaining transparency and an ethical approach to the use of modern technologies.

AI technology can also be used to improve communication with residents and improve the quality of public services provided. An example is the use of chatbots or voicebots, e.g. the Krakow City Office 2022 (Krakow City Office, 2022) launched a Virtual Official application that uses artificial intelligence for customer service. This assistant answers residents' questions related to city services, provides information on current events and attractions, and helps solve current problems. A similar solution was introduced by Gdynia, which used an artificial intelligence solution in 2012 to improve the services provided by city offices. In order to facilitate contact with offices via online forms, the City Office implemented a solution that automates the filling in of selected fields, thanks to which many different services are supported using this system. The chatbot available to residents can refer to 170 matters that they want to deal with. In Poznań, on the other hand, a voicebot was launched to support office employees in their daily work. The solution is to shorten the time needed to reach the right consultant by asking residents the right questions. Voicebot will recognize a given case and carry out the process of booking a visit to the office. In this way, residents can book a visit to the Department of Civil Affairs and Communication Rights, the Civil Registry Office and the Department of Municipal Economy. The City Office in Poznań has also launched an e-consultant, whose task is to understand the intentions of the caller and redirect him to the appropriate employee of the city hall as quickly as possible (TVP3, 2024). AI is increasingly being used to communicate with residents via social media. For example, For example, Barcelona uses AI to communicate with its residents, including analyzing social media posts and surveys, to better understand the needs of its citizens. Thanks to mobile applications and online platforms, residents can submit suggestions for the city’s development, making the decision-making process more democratic and accessible to all. The Decidim platform plays a key role here, integrating different data sources and enabling residents to actively participate in shaping city policy. Residents submit ideas, and AI groups group similar projects and predict their popularity. Instead of relying solely on corporate AI solutions, Barcelona aims to create open, community systems that support deliberation and civic participation. Additionally, through pilot projects such as DECODE (Decentralised Citizen Owned Data Ecosystems), the city wants to give citizens transparency and control over their personal

data, deciding what information they want to share and for what purpose. This approach promotes data sovereignty and counteracts surveillance-based models. The city then only receives aggregated statistics, not personal data. This project has shown that citizen data sovereignty and AI can go hand in hand, although this requires some regulation and local involvement, hence the importance of proper communication with residents.

The main actions taken by local government units to improve the level of digital advancement are mainly investments in new equipment and software (Ministry of Digital Affairs, 2023). This is primarily due to legal requirements, growing expectations of citizens and the digitization of processes in other administrative entities. Local governments primarily try to provide basic equipment in administration buildings (computers, photocopiers, etc.) and new digital tools, and implement the latest IT systems to manage the finances and budget of the commune. The initiators of actions aimed at improving digitization in Polish local government units are usually IT department employees, to a lesser extent commune leaders (mayor). Communes and counties focus on the development and improvement of competences in the field of new digital technologies, sending employees primarily to external training. They most often concern cybersecurity, the operation of equipment, systems and programs, and the operation of e-services. Respondents asked in interviews emphasized that "The growing importance of AI in everyday administrative processes requires public sector employees to adapt to new challenges and acquire appropriate competences in this area" (Respondent 2) or "The education of officials is key - not only technical, but also soft skills: understanding the impact of AI on citizens" (Respondent 3). Respondent 4 added: "The lack of knowledge and practical skills can be a significant barrier in the process of digital transformation of public administration. Resistance to change can also be a problem, as well as, in some aspects, the lack of clear regulations". Hence, the use of AI means not only the benefits mentioned, but also certain challenges. Therefore, one must be aware of them.

One of the most common applications of artificial intelligence in city management is intelligent transport systems. AI-powered traffic monitoring solutions use computer vision, IoT sensors, and predictive algorithms to manage congestion and optimize traffic flow. Cities such as Singapore and Barcelona have successfully implemented AI-powered traffic lights that adjust signals in real-time based on road conditions, significantly reducing travel delays and emissions. Many cities, such as London and Tokyo, use AI to analyze data from traffic cameras to quickly detect accidents and congestion. These systems enable faster response from emergency services and inform drivers about alternative routes. By analyzing real-time data, the city can quickly respond to incidents and improve traffic safety. The city of Krakow The city uses AI in its traffic management systems, such as the Tram Traffic Supervision System (TTSS) and the Area Traffic Control System (UTCS). The TTSS provides priority to trams at intersections, while the UTCS regulates car and pedestrian traffic by adjusting traffic lights to traffic density. The city also uses AI in dynamic passenger information, installing multimedia screens at bus stops that display the real-time location of buses and trams. This makes it easier for passengers to plan their journeys and access information about traffic disruptions.

Interesting results on the topic of citizen engagement and the use of AI in local governments were presented by Vinichenko et al. (2021), who studied the willingness of residents of megapolises to participate in large-scale urban projects facilitated by AI. Their findings suggest that effective communication and established participation frameworks contribute to a favorable socio-psychological environment, significantly increasing residents' loyalty and commitment to local development initiatives. The factors that made participating in megaprojects attractive to residents of megapolises were the opportunity to gain experience in working on a large project, interest in communicating with different people, and the possibility of making a career and getting a good salary. This study emphasized the key role of AI in creating systems that enable more effective dialogue and interaction between local governments and their constituents, thereby improving the overall satisfaction with municipal governance.

The majority of people in Europe believe that digital technologies, including AI, have a positive impact on their jobs, economy, society, and quality of life. 62% of Europeans have a positive opinion of robots and AI, and 70% believe that it improves efficiency. 67.8% of Americans believe that AI can positively impact city life and offer insights into its most beneficial applications. However, there are significant knowledge gaps, as 33% cannot define a "smart city" and 61% have expressed concerns about the responsible use of AI by local governments (Panszczyk, 2025). 84% of Europeans also believe that AI requires careful governance to protect privacy and ensure transparency (European Union, 2024).

This is why the Artificial Intelligence Act (EUR-Lex, 2024) was introduced (for the first time ever) to establish harmonized rules on AI to support the trustworthiness of AI in Europe. It sets out a clear set of risk-based rules for AI developers and creators regarding specific uses of AI. The Act is part of a broader package of policy measures to support the development of trustworthy AI. These measures guarantee security, fundamental rights and human-centric AI and strengthen the uptake, investment and innovation in AI across the EU. The AI Act ensures that Europeans can trust what AI has to offer. While most AI systems are risk-free and can contribute to solving many societal problems, some AI systems pose risks that we need to address to avoid undesirable outcomes. The AI Act defines four levels of risk for AI systems, such as risk (European Union, 2024):

- unacceptable, i.e. all AI systems considered to be a clear threat to human security, livelihoods and rights are prohibited; these include fraud, manipulation, social scoring, biometric categorization, and emotion recognition;
- high, i.e. cases that may pose a serious threat to health, safety or fundamental rights; these include, among others, AI security elements in critical infrastructure or AI solutions used in education that affect access to it;
- transparency – refers to the risk associated with the need for transparency in the use of AI; the Act introduces specific disclosure obligations to ensure that people are informed when necessary to maintain trust;
- minimal or no risk – this includes applications such as AI-enabled video games or spam filters.

AI is an integral part of the modern environment, it cannot be avoided. However, it should be used in a way that, on the one hand, helps different parties and, on the other, protects. The examples and research findings provided demonstrate that AI can significantly contribute to smarter city governance if implemented strategically and ethically. AI applications in areas such as traffic control, waste management, predictive analytics, and digital citizen engagement bring tangible benefits, including cost savings, reduced environmental impact, and improved citizen satisfaction. In addition, AI-based platforms help local governments personalize citizen communications and improve service delivery, thereby strengthening the relationship between public institutions and the communities they serve.

5. DISCUSSION

Artificial intelligence (AI) is becoming an increasingly integral part of urban governance, facilitating communication between local governments and citizens while increasing public participation in city governance. Various case studies illustrate the effectiveness of AI in promoting citizen engagement and improving service delivery in local governance. The use of AI in local government communication with citizens can result in crisis response. In the event of disasters such as fires and floods, the combination of advanced technologies, including AI, geographic information systems and real-time data analysis, enables emergency services to predict, optimize and track resource allocation and coordinate response activities more effectively. This enables better crisis management and mitigation of negative impacts on both people and the environment. In addition, AI can support urban planners in more effective management of infrastructure and resource allocation; by simulating different urban scenarios, decision-makers can visualize the potential impacts of their decisions before implementing them (Veiga et al., 2021; Inkinen et al., 2019). With advanced visualization capabilities, citizens can be involved in decision-making about response or recovery projects, ensuring transparency and accountability throughout the process.

There are many examples showing the successful integration of AI into city management. For example, AI applications in waste classification services often enable simplified operations and support community engagement in sustainability initiatives (Zhang et al., 2023). Similarly, AI-powered health monitoring systems have been implemented to improve public health outcomes, especially in underserved communities, demonstrating the versatility of AI applications across different domains of city management (Wilmink et al., 2020).

Local authorities are increasingly adopting AI to improve communication with residents and service delivery. For example, AI-based applications can help local authorities collect and analyze community feedback, inform residents about public services, and increase participation in democratic processes. In the context of local government interactions, AI tools such as chatbots and virtual assistants are

increasingly used to handle routine queries and provide information about various services (Hossain et al., 2023; Corbett et al., 2023). Chatbots powered by natural language processing and machine learning facilitate richer and more expressive interactions between citizens and government, making information more accessible and transactions smoother. Such innovations can significantly reduce response times, allow for timely responses to queries, and improve the quality of services provided to residents. The role of AI in data acquisition allows local governments to develop targeted initiatives that address the specific needs of the community. This adaptive communication model increases public engagement and satisfaction, leading to informed decision-making that reflects community priorities. The adoption of such technologies also prompts local governments to reconsider traditional modes of interaction and establish mechanisms that ensure citizens remain informed and engaged.

The examples of cities that use AI in their operations show that AI can be a powerful tool in the hands of local authorities. However, as studies indicate, the success of AI implementation depends not only on technology but also on the appropriate legal framework, social involvement and cross-sectoral cooperation. Despite the numerous advantages of AI in local governance, challenges still exist, including concerns about data privacy, algorithmic bias and the need for transparent decision-making processes. It is indisputable that AI provides local governments with significant benefits in terms of improving services and communicating with residents, but ethical issues and public trust remain crucial for its successful adoption. Citizens are increasingly concerned about the privacy, bias and accountability of AI systems implemented in public services (Pulijala, 2024; Schmager et al., 2024). The local government officials interviewed emphasized that "Clear and transparent ethical frameworks and national regulations are needed to support responsible implementation of AI" (Respondent 1) and that "Residents are not always clear whether they can trust that data collected by state digital applications are safe and protected and do not feel they have control over how they are used" (Respondent 4). Respondent 3 additionally emphasized that "Increased public trust is needed – AI implementation must be transparent and communicated in a simple way" and "AI cannot replace dialogue with residents – it should support, not replace humans in the decision-making process" (Respondent 2).

Artificial intelligence systems require large amounts of data for effective training and operation, and therefore the issue of privacy of individual data whose information is processed raises concerns. This is because public services collect sensitive and personal data, such as financial data and individual biographies. Governments must have strict privacy regulations to protect the confidentiality of sensitive public information and personal data from being used to train AI (Nalubega & Uwizeyimana, 2024). If citizens perceive insufficient transparency or a lack of safeguards against misuse, their support for AI initiatives may significantly decrease (Drobotowicz et al., 2021: 99-115). The democratization of data, enabling more people and organizations to access and use large amounts of information, provides numerous benefits in terms of efficiency and decision-making. However, this expanded access also poses critical challenges related to data privacy and security. Therefore, effective measures should always be implemented to protect the privacy of user data; examples include data anonymization, the use of encryption techniques, or setting data access policies according to user permissions (so that not everyone can access all types of information, but according to their level of responsibility or specific function).

The results of research commissioned by the European Commission (European Commission, 2024) highlight the significant potential of artificial intelligence (AI) to improve public sector services across the EU. The report indicates that AI can improve interactions between citizens and local governments, and increase analytical capabilities and efficiency in key areas such as healthcare, mobility, e-government and education. These sectors are often already ready to implement AI. The report also notes various challenges that hinder the adaptation and implementation of AI in local governments and more broadly in the public sector. These include complex public procurement processes, difficulties in data management, lack of regulatory clarity and concerns about bias in AI decision-making (European Commission, 2024). It therefore makes several recommendations to accelerate the adoption of AI, including increasing funding and resources for AI in public services, ensuring transparency and accountability in AI systems and adapting to stakeholder expectations. Local governments as well as the European Commission need to create a clear regulatory framework for AI, prioritizing long-term implementation and support for trustworthy human-centric AI solutions. Local governments also face challenges related to the public procurement process, which is often combined with burdensome administrative requirements, lack of clarity from the public sector regarding their needs/requirements,

emphasis on price/cost savings over quality of service and non-financial benefits, unclear regulatory requirements and the complexity of writing technical specifications. Local governments need to adopt transparent practices and create an accountable governance framework, as citizens expect managers to ensure honesty and integrity in AI tasks (Yiğitcanlar et al., 2022; Schmager et al., 2023). This will unleash the power of AI to address global challenges.

Other AI challenges facing local governments include: a lack of transparency in AI decision-making processes, difficulty in overseeing and evaluating AI solutions before they are implemented, potential biases/discrimination in systems, difficulty in establishing accountability for the AI system, lack of limited regulatory spaces, and high demands on explainability of AI solutions. Organizational constraints/challenges due to lack of human resources or political support are also important. It is also important to recognize that AI relies on historical data to predict and generate outcomes, so local governments must be aware of potential equity shortcomings in the original data. This requires ongoing review and auditing of AI models to identify and mitigate any biases. It is also important to promote diversity and inclusion in teams that develop and oversee AI systems to ensure that different perspectives are considered in the development process.

It is therefore important to reiterate that the implementation of AI in governance by local governments may raise ethical concerns, particularly in terms of ensuring confidentiality, equity, and inclusiveness. There is an urgent need to develop frameworks that address potential biases in AI systems to promote equitable access to AI-based services, especially for marginalized groups (Tawiah and Monestime, 2024). AI supports digital democracy tools that enhance public opinion analysis and citizen participation in governance, ensuring that residents' voices are heard and considered in decision-making processes. Ensuring that residents' voices are reflected and respected in AI systems is essential to building public trust. Furthermore, as cities transition to smart technologies, robust privacy and data protection measures must be implemented to further increase community trust and engagement. AI is driving the development of smart cities that are efficient, sustainable, and highly responsive to the needs of their residents. As AI technologies advance, cities will continue to evolve, making smart urban environments the foundation of tomorrow's sustainable future. However, managers need to be aware of them.

6. CONCLUSION

Artificial Intelligence is increasingly being used by local governments to improve city management and communication with citizens. AI technologies offer various benefits, including improved efficiency, better service delivery and increased citizen engagement. The integration of AI into local government operations and communication with citizens represents a significant change in city management strategies, with significant implications for governance, public service delivery and citizen engagement. AI is gradually transforming the management of cities and local authorities by streamlining communication, optimizing city services and improving citizen engagement. Historically, city management has been based on traditional bureaucratic methods, often characterized by inefficiency and unresponsiveness to citizen needs. However, the emergence of smart technologies and AI offers new avenues for city management that prioritize real-time data analysis and community engagement. AI facilitates the development of smart cities. AI in city management not only improves operational efficiency and improves communication with citizens, but also continues to evolve amidst challenges that require both administrative foresight and public engagement.

Adopting AI technology responsibly and proactively in the provision of public services is an opportunity for many local governments to overcome traditional barriers to public services. Digital communication channels between citizens and local government are often characterized by lower costs than traditional ones (face-to-face or phone calls), but some information can also be missed, because, for example, a resident, can only enter some search keywords to find the information he needs, may not find the information he is interested in. The use of AI technology can create governance systems that are citizen-centric, efficient, transparent and accountable. However, local governments must undertake deliberate planning, prioritize privacy and inclusiveness, implement strong data protection policies, conduct regular AI security audits and engage relevant stakeholders in the decision-making process. It is necessary to be aware of the various challenges that the use of AI in governance and communication

between local government and residents brings. It is important to understand where AI is needed/best suited. It is not worth using it everywhere. It is important to remember that at the end there is a human, and AI is not intended to be a replacement for logical thinking, but only a tool that will support this thinking. This was also emphasized by the respondents during the interviews that "AI is creating a new sphere of human existence. Everyone will use artificial intelligence to achieve their goals. However, it will not replace humans 100 percent" (Respondent 2) and "AI will never replace humans in making decisions that require empathy, but it will relieve them of routine" (Respondent 1).

The integration of AI into local government operations represents a significant shift towards more responsive, efficient and data-driven governance. The implications of these advances go beyond mere operational efficiency, as they contribute to supporting a more engaged society and promoting a sustainable future for cities. AI technologies significantly improve city governance by automating processes, optimizing resources and improving service delivery. They also bridge the communication gap between residents and local governments using advanced digital tools, supporting better engagement and participation. These advances contribute to more efficient, transparent and responsive local governance, ultimately improving the quality of life for city residents. As local governments navigate this digital transformation, a combination of innovation and ethical considerations will play a key role in shaping the future of community engagement. The balance between the benefits and challenges of using generative AI in local government is delicate. On the one hand, the ability to analyze and use large amounts of data can drive innovation, improve operational efficiency, and open up new market opportunities, while on the other hand, insufficient attention to privacy and ethics can lead to negative consequences, such as loss of trust from residents or even various financial penalties.

By integrating insights from existing literature with real-world urban applications, the authors aim to provide a comprehensive understanding of AI-based urban governance. They acknowledge its limitations. Future research should therefore be complemented with quantitative analyses, expert interviews, and citizen surveys to investigate the long-term impact of AI on urban governance and civic engagement.

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OPPORTUNITIES FOR THE USE OF ARTIFICIAL INTELLIGENCE IN RAIL TRANSPORT

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ABSTRACT

Purpose: *The aim of this article is to present potential areas of application of AI in railways. This includes applications in areas such as rail transport management, railway infrastructure, passenger and freight transport, rolling stock or employee training.*

Need for the study: *The importance of Artificial Intelligence (AI) technology is increasingly growing in both social and economic life. This technology is finding increasing application in large part by replacing human labour and improving the performance of tasks by machines. The application of AI in rail transport management contributes to improving its efficiency, safety and quality of transport.*

Methodology: *The following review article is based on literature and expert experience.*

Findings: *The conclusions indicate potential areas of application of AI in rail transport management, which may consequently contribute to an increase in the competitiveness of rail transport.*

Practical Implications: *The article may be helpful to learn about potential areas of AI application in rail transport.*

Keywords: Artificial Intelligence, rail transport, rail transport management, rail passenger and freight transport, rail infrastructure, rail simulators

Jel codes: L92; O31; O33

1. INTRODUCTION

Artificial intelligence (AI) is a field of knowledge that includes fuzzy logic, evolutionary computing, neural networks, artificial life and robotics. It is also the branch of computer science that deals with intelligence - the creation of models of behaviour and computer programs that simulate these behaviours (Bharadiya, 2023; Wiśniewski, 2019). The importance of artificial intelligence technology has been growing rapidly in recent years. This applies to both social and economic functioning.

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Artificial intelligence (AI) is making a significant difference to operational efficiency in organisations and businesses. By automating processes, AI eliminates the need to manually perform routine and time-consuming tasks, allowing employees to focus on the more strategic and creative aspects of their work. Automated data processing systems, robotics and intelligent analytical algorithms speed up project delivery and improve the quality of services and products (Gibała, 2024; Parveen, Chadha, Kumar, Singh, 2022; Iyer, 2021).

Artificial intelligence (AI) is bringing dynamic changes to the transport sector, opening up new opportunities and transforming existing methods of operation and transport management. In the transport, forwarding and logistics industry, AI is already optimising processes, speeding up decision-making and streamlining operations (Skowroński, 2023). The benefits that the use of AI expresses in terms of improved safety, efficiency and quality of service, both in passenger and freight transport, are evident.

One of the priority directions for transport development worldwide, including in the European Union, is to strive for an intelligent, environmentally friendly and passenger-accessible transport system. An important role in this system is assigned to rail transport, as emphasised by the EU transport policy guidelines. At the same time, the radical and very dynamic changes in the environment resulting from the implementation of information and communication technologies require modifications to be made to the existing business models and passenger strategies of rail operators.

AI on the railways in Poland is still used to a small extent, but the prospects are promising. The implementation of global solutions, combined with changes to current legislation in the country, will in the long run result in a quantum leap in the importance of artificial intelligence in this branch of transport (Wiśniewski, 2019).

This article will present areas in rail transport where AI technology is already being used. Potential opportunities for further application of AI in railways will also be discussed. With the increasing demand for safer, more efficient and greener solutions, AI is becoming an important tool for the transformation of this transport sector.

The main areas in rail transport where AI technology is already being used and there are potential opportunities to increase its participation include:

- rail transport management
- railway infrastructure,
- railway traffic organisation and management,
- passenger transport,
- freight transport,
- rolling stock,
- training and further training of railway workers.

2. LITERATURE REVIEW

In recent years, with advances in the development of Artificial Intelligence, there has been increasing interest in its application to economic processes, including the transport sector. This also applies to rail transport. Numerous studies have been presented in the literature in recent years on the general application of AI to the organisation and operation of rail transport. (Auleytner, 2024; Fiszer, 2024; Gibała, 2024; Bharadiya, 2023; Skowroński, 2023; Parveen, Chadha, Kumar, Singh, 2022; Iyer, 2021).

Modern AI-based solutions can be applied to different areas of the rail transport sector's operations. One of the key application areas for AI in rail is the maintenance of railway infrastructure and rolling stock. Analysing data from sensors deployed on the line and rolling stock allows for early detection of malfunctions as well as prediction of potential failures, significantly reducing repair and downtime costs (Zhao, Qin, Liu, Xie, 2020).

Another important area of AI applications in rail transport is the area of railway infrastructure and rolling stock security. This is as much about the safety and correctness of the elements as it is about the physical security of these elements, i.e. protecting them from vandalism or theft (Majewski, 2024). This also applies to protecting the safety of travellers at railway stations or on trains or transported freight (Żłobicki, 2024; Wiśniewski, 2019). AI can also play an important role in improving physical security

and protecting against cyber threats in rail traffic control systems, enabling early detection of hacking attacks and system errors (Gao, Li, Zhang, 2022).

Another field for the application of AI is the optimisation of timetables and traffic management, which can bring tangible benefits in terms of increasing line capacity and minimising delays (Chen, Song, Li, 2022).

Another area of AI use on the railways with significant application potential is the development of automated train guidance (Zhang, Li, Wang, 2021; Van Leijen, 2017).

AI can also be used to collect and analyse passenger transport data. This allows for more precise demand forecasting and personalisation of services. (Sun, Axhausen, Lee, Huang, 2020).

Another important area of possible application of artificial intelligence is training and further training, and simulations of the performance of infrastructure and rolling stock components. (Szuster, 2017). This includes training new railway employees or improving the work of existing ones. Examples include train drivers, where artificial intelligence can create scenarios for situations based on historical data or in-house (Niedzielski, Dyl, Niedzielska-Podlewska, 2023; Drewnowski, 2021; Combik, Michalik, 2020; Kunimatsu, Terasawa, Takeuchi, Tatsui, 2018; Drewnowski, Małachowski, 2018; Kozuba, Niedzielski, Maziarz, Drewnowski, Czapka, 2016; Kozuba, 2013). AI-enabled computer simulations also make it possible to dynamically adapt schedules to changing conditions such as breakdowns, weather conditions or changes in passenger and freight volumes. The possibilities of using AI can also apply to the simulation of the operation of various elements of railway infrastructure (Lisiecki, Szłapczyński, Chołodowicz, 2024), rolling stock (Naseri, Mohammadzadeh, Rizos, 2025; Bosso, Magelli, Zampieri, 2022) or even investment decision-making (Čamaj, Nedeliaková, Šperka, Ližbetinová, 2021).

Research to date indicates that AI is making a significant contribution to the transformation of the rail sector, offering new possibilities in terms of infrastructure and rolling stock diagnostics, safety, automation and traffic management, security or use in simulation and training.

3. METHODS

A literature review was carried out to explore the use of AI in rail transport. The aim of this review was to identify areas in railway operations where AI is already being used successfully, as well as potential areas where AI can still be applied. Available national and international literature on the use of AI in transport in general, as well as in specific transport modes, and in particular in rail transport, was analysed. An analysis of internet sources was also carried out with regard to expert statements on the application of AI in transport, including rail transport. On this basis, the following part of the article analyses the results obtained and reflects on the potential use of AI in rail transport, especially in those areas where it is not yet used or is still used to a limited extent.

4. RESULTS AND DISCUSSION

4.1. Rail infrastructure management

The management and maintenance of rail infrastructure is an important area where AI technology can be successfully applied to a large extent. In particular, it offers opportunities to improve safety, efficiency and to reduce and optimise the operating costs of railway infrastructure. Primary infrastructure areas where AI technology solutions can be applied include:

- rail road,
- overhead line,
- infrastructure safety.

One of the primary areas where AI can be applied is in the maintenance of the railway surface and substructure. This includes the acquisition of data and its analysis giving the possibility of making advance decisions on the repair and overhaul of infrastructure elements. This concerns both the day-to-day maintenance of these elements to ensure that they are in the appropriate condition required by the category of railway line concerned. It is also about planning well in advance the renovation or upgrading of this infrastructure. Sensors installed on tracks, switches or other traffic control devices can collect

information on the status of these elements on an ongoing basis (in real time) and transmit it to the relevant databases. The AI then analyses this data and identifies (predicts) potential faults before they occur and recommends appropriate actions for the ongoing maintenance of these elements. This can allow preventive maintenance of these components to be carried out in a more efficient and preventive manner. It also reduces the risk of unexpected failures which, after all, can hinder or even seriously endanger rail traffic (e.g. rail accidents). For engineering structures such as bridges viaducts or tunnels, for example, by analysing sensor data AI can detect micro-damage and predict potential failures. In this way, preventive maintenance can be carried out, minimising the risk of costly repairs and failures later. Similarly, on the basis of current wear and tear analysis, AI can suggest in advance actions to be taken to prepare for the repair or modernisation of a given piece of infrastructure or railway track bed. This is important insofar as these issues must be implemented well in advance due to the need to create the appropriate documentation, as well as to ensure adequate financial resources and time due to the tendering procedures for selecting contractors for these works.

Another potential application area for AI on electrified lines is maintenance and overhead power supply. AI-enabled systems can analyse data from cameras and sensors in real time to detect problems in overhead lines. Automatic fault detection allows faults to be rectified more quickly, thereby reducing disruption to rail traffic. This is particularly important as the operation of a line by electric traction practically paralyses traffic on the line in the event of a breakdown, which, especially in the case of passenger services, can expose travellers to serious consequences (e.g. loss of connections with air transport. Also, thanks to AI, overhead power consumption can be optimised, adjusting power consumption according to the current traffic on the line. This reduces traction energy consumption, resulting in measurable cost savings.Intelligent systems can also control the use of renewable energy sources, such as photovoltaic panels located in railway stations.

The use of artificial intelligence may also relate to ensuring an adequate level of safety of the railway infrastructure. This could include the automatic inspection of railway infrastructure to make it safer to operate. AI-equipped drones can monitor tracks, bridges and tunnels, analysing the condition of the infrastructure and detecting, for example, damage, landslides, obstacles along the route, unauthorised (illegal) trespassers on railway land or acts of vandalism, and automatically send alerts to the relevant services. This enables inspections to be faster and more precise. By optimising patrol routes, AI can enable more effective prevention efforts, minimising the risk of crime without the need to increase the number of patrols. This, in turn, can improve safety and reduce delays on the railway. The implementation of modern artificial intelligence technology can contribute to safer railway infrastructure (Majewski, 2024).

Systems with AI can also contribute to improving safety at single level crossings. The situation in this respect varies and depends on the category of railway line. For high-speed lines, double level crossings (viaducts) are even required. For trunk lines, the elimination (in the case of modernisation) of single level crossings is also recommended. However, single level crossings are still common on trunk lines. These are now equipped with automatic (self-acting) crossing signals supplemented additionally with barriers (half-way barriers) closing the crossing on the right-hand side of the road. The warning is activated when a train approaches the crossing using activation systems located on both sides at a suitable distance from the crossing. The approaching train, depending on the direction of travel, acts on the switching device. The device registers and transmits the signal of the approaching train to the control device, which activates the light and sound signals on the signals located on both sides of the wheeled road and the closure of the barriers also takes place. The end of the effect of the passing train on the system installed in the tracks behind the crossing causes the warning to be released and the barriers to open. AI can analyse data from cameras at level crossings, optimising the timing of lowering and raising barriers and warning of potential hazards, such as vehicles stopped on the tracks. This is particularly important at level crossings on lower category lines, where there may be crossings without barriers, or even where only a road sign (the so-called St Andrew's Cross) informs the driver of the crossing. The installation of cameras there and the use of AI can significantly improve road safety. At the same time, it should be remembered that road users are the main cause of accidents at single level crossings.

4.2. Organisation and management of railway traffic

Artificial intelligence (AI) in the organisation and management of rail traffic can significantly improve the efficiency, safety and punctuality of services.

One of the most important applications of AI in the organisation and management of rail traffic is the optimisation of train movements. This tool can be particularly useful for those managing and directing train traffic (dispatchers and traffic officers). AI algorithms can analyse train traffic data in real time, allowing dynamic schedule management and minimising delays. Forecast models help predict potential disruptions, such as breakdowns or the impact of weather conditions, allowing for dynamic responses to situations and better route planning and dynamic timetable adjustments. AI can, for example, stop traffic, call emergency services and communicate information to passengers. AI can also analyse ongoing train delays and propose alternative solutions. In the event of breakdowns or accidents, AI can direct trains to alternative routes or optimise transfers, reducing passenger waiting times.

AI systems can also successfully support the work of dispatchers overseeing rail traffic in a selected area. AI helps in decision-making by suggesting the best solutions based on data analysis. It can also manage the sequence of crossings and the cooperation between different railway operators or automatically control traffic control devices and signals or level crossings. In addition, AI can analyse historical data, so it can detect recurring traffic problems and suggest optimisation measures.

4.3. Passenger transport management

Artificial intelligence (AI) has the potential to make a significant contribution to improving the passenger experience in rail transport, enhancing safety and the quality of journeys. Particularly in passenger transport, the potential application of AI seems particularly broad.

In recent years, the greatest progress in passenger rail transport in Europe can be observed in the creation of a transparent communication system with the customer through the following measures (Drewnowski, Małachowski, 2018):

- carrier websites have been expanded and upgraded,
- mobile applications with real-time train traffic information and the possibility to purchase a ticket are created, the functionality of which is extended with additional services,
- modern dynamic passenger information systems are being implemented at railway stations and stops.

Important areas of application for AI in passenger service include travel safety and its continuous monitoring both on trains and in stations. AI can analyse data from cameras and sensors, helping to manage traffic at stations and on trains. AI can monitor passenger flow at stations and platforms, predicting congestion and suggesting optimal travel paths. It can also support dynamic signage and passenger information systems. By analysing images from surveillance cameras, AI can detect dangerous situations or suspicious behaviour in advance. Facial recognition systems can also help improve passenger safety. This is particularly relevant in the current situation with the ever-present risk of possible terrorist activities occurring in various modes of transport. So far, the greatest restrictions have been introduced in air transport. However, it should be remembered that rail transport can also be exposed to this danger. Therefore, the use of AI in this area can significantly increase the safety of rail travel. Systems using AI can also monitor passenger behaviour, e.g. identifying those in need of assistance and automatically alerting emergency services.

AI can also be helpful in the ongoing analysis and optimisation of timetables. AI can analyse data on passenger traffic and occurring later in real time to dynamically adjust timetables to these situations. This helps to minimise delays, quickly suggesting alternatives to minimise disruption to rail traffic. Chatbots and virtual assistants can also assist passengers in real time, providing information on delays or schedule changes. This is all the more important as, in passenger traffic, any delay or waiting for delayed trains (so-called connecting trains) is always frowned upon by passengers. Any unplanned extension of the journey time is perceived by the passenger as a personal loss of time, which translates into a negative evaluation of the carrier. This rarely takes into account whether the passenger is actually at fault or whether it is a random situation. Systems using AI can also analyse passenger behaviour, such as identifying those in need of assistance and automatically notifying emergency services.

AI systems can also be useful in the ticketing and seat-booking process and in optimising travel routes. The introduction of AI into passenger services allows for better personalisation of services. This is particularly important in today's booming transport market, where the individualisation of passenger service is becoming one of the carrier's significant competitive advantages.Intelligent systems using AI can analyse travellers' preferences and suggest optimal connections, adjust ticket prices according to demand and streamline the seat reservation process. The system can dynamically allocate seats in

carriages according to the number of passengers. Advanced systems can analyse the distribution of passengers in the carriages and suggest optimal seats to avoid congestion (Drewnowski, Małachowski, 2018).

With AI, passengers can receive personalised recommendations on routes, optimal transfers or dynamic ticket prices. Intelligent chatbots can assist passengers with ticket purchases, connection searches and bookings. AI can also assist with dynamic ticket pricing, which may be of particular interest to transport operators keen to make the most of the seats on offer on trains. AI analyses demand and adjusts ticket prices in real time, optimising train occupancy. It can also participate in personalising offers to the individual passenger. The system analyses travel history and passenger preferences, being able to suggest the best routes and promotions. It provides suggestions for the best seats on the train, convenient transfers or attractions along the route.

AI can also be used in automated customer service centres. AI can handle customer requests, answering questions about tickets, delays or additional services. It can also send passengers information about timetable changes, delays or alternative routes. AI can facilitate international communication, such as in mobile apps for tourists (real-time translation). AI can also recognise emotions in customer service. Voice or image analysis can help respond quickly to upset passengers and improve service quality. AI-enabled voice assistants and mobile apps can facilitate navigation at train stations and on trains, helping, for example, blind people or tourists.

Also while driving, AI systems can enhance the travel experience. AI can suggest movies, music or audiobooks based on passenger preferences (intelligent entertainment systems). AI can control temperature, air conditioning, lighting and other parameters in the carriages, adapting them to the needs of the passengers. Chatbots can also be used for train catering. Passengers can order food and drinks from the mobile app without visiting the dining car.

Finally, AI can support the integration of railways with other modes of transport. AI can synchronise trains at transfer stations or, for example, with public transport or taxis (optimising transfers). AI can also be used in dynamic passenger information systems. AI can provide updated travel information in real time.

4.4. Freight transport management

Artificial intelligence has great potential in the optimisation of rail freight traffic. Among its most important areas of application are route optimisation and timetable adjustment. AI can analyse large data sets, taking into account weather conditions, track traffic and transport demand. This allows it to dynamically adjust and optimise routes and timetables, minimising delays and operational costs.

AI can predict the demand for wagons and optimise their allocation. Particularly beneficial use of AI can concern the organisation of empty wagon transports. This applies in particular to dispersed transports (single wagons or small groups of wagons) where, after unloading, wagons are allocated to subsequent loads, with the best solution being such an allocation that the transport of the empty wagon is as short as possible (Zalewski, Siedlecki, Drewnowski, 2004). The use of AI can significantly support the decisions of wagon dispatchers in the allocation under subsequent loads based on the received transport demand.

AI can also be of great help in organising freight marshalling. By marshalling trains we mean trains that are put together at the starting station from wagons that have a single destination station or a common final technical (marshalling or shunting) station, i.e. they cover the journey from the starting station to the final station without exchanging wagon groups at intermediate stations. There are several types of marshalling. Depending on where the wagons are loaded and how the marshalling train is put together, there are marshalling routes (Zalewski, Siedlecki, Drewnowski, 2004):

- consignment - made up of wagons loaded by one or more consignors at one or more loading points and handed over to the railways at one delivery point;
- graded - put together by the railway from compact groups of wagons, loaded by one or more shippers at one station and handed over to the railway at several transfer points, or at several stations;
- technical - put together by the railways from wagons appearing at random, loaded at the marshalling yard and arriving in loaded condition by trains subject to marshalling..

AI can support the formation of marshalling trains at the starting stations by predicting in advance the potential wagons that can form a marshalling train. Especially is ot relevant for technical

marshalling. AI can predict well in advance whether there will be enough wagons in the trains arriving at a technical station to put together a marshalling train, which allows for earlier organisational preparation for this task. It should be noted in this connection that marshalling transport brings considerable economic benefits to the rail freight operator, manifested in a reduction in the amount of shunting work and a more intensive use of the transport fleet over time. Both types of benefits are primarily the result of a reduction in the number of switching stations for freight wagons on the journey from consignor to consignee. AI can also control automated loading and unloading systems at terminals and cargo points, for example by analysing data in real time. This reduces downtime at terminals, increasing the efficiency of freight transport.

AI can analyse cargo flow and optimise intermodal transport. AI in intermodal terminals can significantly support their work by optimizing the planning of transhipment operations, including the analysis of data on the movement of means of transport of individual modes of transport. This can enable the optimization of loading and unloading schedules of cargo units, which can minimize or even eliminate downtime and queues. AI can also quickly recommend alternative solutions, e.g. in the event of a catenary failure and the resulting disruptions to traffic. AI can also support the management of warehousing and storage of cargo units in the terminal, e.g. how to best position containers to facilitate their quick loading and shorten the transhipment time. AI can also support the control of autonomous vehicles transporting containers in the terminal, by optimizing their movement routes, which can also reduce the risk of potential collisions. It can also support supervision of the technical equipment of the terminal, e.g. by ensuring that loading devices are serviced on time. It can also optimize energy consumption at the terminal by adjusting its consumption to the current volume of work. An important task in which AI can be used is the management of security in the terminal area. Vision systems supported by AI can automatically detect unauthorized persons in the terminal area or other threats (e.g. the beginning of a possible fire), unauthorized persons in the terminal area or incorrect operations.

AI can also help control the collation and marshalling of freight trains at freight shunting and marshalling yards. The use of AI can primarily concern the optimization of the shunting and marshalling of freight trains. During shunting, AI can support the directing of groups of wagons to a selected track on a directional group. AI also allows for the optimization of the management (planning) of the movement of shunting locomotives and station workers, as well as reducing the wear of infrastructure elements (e.g. track brakes). This allows for the minimization of the number of necessary shunts (saving fuel costs), shortening the shunting and marshalling time of trains, optimizing the order of train substitution or adjusting the station work plans on an ongoing basis in the event of delays or changes in arriving trains. Systems based on AI algorithms can also forecast what numbers of wagons and what types of cargo will appear at the station in the coming days. This allows for more effective planning of the work of people and resources and optimal use of track groups and the working time of the hump at the station.

With AI, it is also possible to develop technology for autonomous goods trains, especially those running long distances, preferably in low-urbanised areas. This can minimise human error and optimise energy consumption. Currently, autonomous trains can only operate on isolated lines. An example of this is the Rio Tinto autonomous goods train in Australia running on a 100 km-plus freight rail line located in a desolate area. This allows for lower costs, more energy-efficient train journeys and the elimination of complicated logistics related to train operation by employees such as drivers (Van Leijen, 2017). In the case of autonomous trains, the problem is still unforeseen events that may occur in the area near the railway line (e.g. people crossing the tracks in prohibited places). Therefore, for now, such solutions only apply to non-urbanized areas, as in the case of Rio Tinto.

4.5. Rolling stock management

Artificial intelligence can significantly improve the safety and efficiency of rolling stock operations, while reducing operational costs. Among the most important applications of AI in rolling stock is the maintenance of rolling stock (locomotives and wagons). AI systems can continuously monitor the condition of rolling stock through the use of continuous sensors. Advanced algorithms analyse data from sensors on wagons and locomotives, detecting the first signs of wear and tear on equipment predicting failures based on the data. This allows maintenance to be scheduled at the right time. Early detection of faults and prevention of failures (e.g. wear on

wheels, brakes, engines). This also allows preventive maintenance to be carried out reducing the risk of delays and downtime.

AI can also be used to optimise fuel and energy consumption. AI algorithms can analyse the speed, gradient and load of the train and carry out an analysis of how the train is driven and make recommendations for economical vehicle operation (e.g. eco-driving, optimisation of fuel or electricity consumption). Also, AI-enabled vision systems can support the driver's reactions to hazards (e.g. detecting obstacles on the track in advance). AI can also analyse the driver's behaviour in real time, warning of fatigue or dangerous manoeuvres.

The next step in the development of railways is the implementation of autonomous trains (ATO - Automatic Train Operation). Thanks to AI technologies, it is possible to control trains without the involvement of drivers, which increases safety and precision in traffic. AI-based systems can analyse the environment, detect obstacles and dynamically adjust speed, reducing the risk of collisions and improving energy efficiency. There are currently more than 800 km of autonomous metro lines operating worldwide (most in France). Driverless vehicles also run on airport rail lines or monorail lines (Wiśniewski, 2019).

4.6. Training and further training of railway staff management (railway simulators)

Rapidly accelerating technical and technological progress and the related introduction of modern technologies into economic and social life determine the activities for raising the qualifications of employees in enterprises. On the one hand, this is a forced action resulting from the need to familiarise and introduce employees to the operation of modern machinery, equipment or applications. On the other hand, modern technologies provide an opportunity to test and improve the skills of employees in scenarios that could not be carried out within the framework of analogue systems (Drewnowski, 2021).

The most advanced in the use of simulators in training systems is air transport, which for decades has used a range of simulators in its pilot training processes, both military and civilian (Kozuba, 2013). In 1909, the Antoinette aircraft manufacturing company developed a training device that mimicked the cockpit of an aeroplane for flight instruction – the Antoinette Trainer. The Antoinette Trainer was one of the first truly synthetic flight simulation motion platforms. This platform consisted of two half-sections of a barrel mounted and moved manually to represent the pitch and roll of an aeroplane (Hayes, 2005). The outbreak of the First World War and the effective use of aviation on the battlefield, accelerated the development of solutions for training military pilots. One solution was the Ruggles Orientator, developed in 1917. Ruggles Orientator. The structure, placed on a wheeled platform and rotating vertically and horizontally, mimicked a pilot's cockpit. In 1927, an American, Edward Link, developed the Link Trainer, also known as the Blue Box. Based on electromechanical solutions, this simulator simulated turbulence and disturbances occurring during flight. During the Second World War, 500 000 pilots were trained on these simulators. After the war, it was widely used in military pilot training in the United States (Niedzielski, Dyl, Niedzielska-Podlewska, 2023). Another widely used aircraft simulator was The Link D2 Trainer, developed in about 1937, fitted with movable ailerons, rudder and elevators. The cockpit was instrumented with compass, altimeter, rate of climb indicator, airspeed indicator, turn and bank indicator, radio compass (Hayes, 2005).

Rail transport relied in the construction of railway simulators on the successful experience of air transport. It is worth noting at this point that Poland can be counted among the forerunners in the use of simulators in the training of train drivers, as it had already organised a Central Training Centre (Centralny Ośrodek Szkolenia Maszynistów) in Warsaw for train drivers using a steam locomotive simulator before the Second World War. The simulator used, developed by the PKP[3]. Psychotechnical Testing Office (Biuro Badań Psychotechnicznych PKP), was successfully used for psychotechnical training of train drivers. In line with the popular trend of using psychology in the world of work, analysing work, its productivity and safety, the bureau introduced psychotechnical testing of railwaymen and candidates for railway safety jobs in a bid to eliminate the number of railway accidents (Pisarski, 1974). Thanks to the use of these modern methods, the number of railway accidents has been reduced by 56% in a few years (Budkiewicz, Kączkowska, 1978).

[3] PKP - Polish State Railway

Simulators are today an essential part of the process of training and improving the skills of train drivers. Their role will grow with the increasing digitalisation of the railways and the entry of a new generation of workers into the market. They are used to the virtual world and modern train driver training should be adapted to this. Experience shows that training on simulators is more engaging and at the same time more effective. The trainees not only acquire knowledge faster, but also consolidate it better, which translates into their readiness to work in a dynamic railway environment (Szuster, 2017).

Simulators are a useful addition to the training process, especially during the first stage of the driving licence course, and once obtained, allow driving techniques to be improved during periodic courses (Combik, Michalik, 2020). The use of simulators is also supported by lower operating costs compared to training with real vehicles in real traffic (Kozuba, Niedzielski, Maziarz, Drewnowski, Czapka, 2016).

The current use of AI in railway simulators can significantly increase the realism, training efficiency and skill analysis of drivers and railway staff. AI in rail simulators can allow for increased training realism, but also for infrastructure testing, optimised driving and better interaction with the environment.

With AI, advanced simulations of driving conditions can be generated. AI can control train traffic and modify traffic signals depending on the situation (Kunimatsu, Terasawa, Takeuchi, Tatsui, 2018). It can also generate realistic weather conditions (rain, snow, fog) affecting driving conditions and visibility and dynamically make changes to weather conditions. AI can also dynamically create random (crisis) events that may occur during driving, such as brake failures, obstacles on the track, fire in the depot, electrical traction failure, passenger evacuation or sudden human intrusion. AI can generate simulations of damage to traction, switches or traffic control systems. It can also map the condition of the railway superstructure, which affects driving comfort. AI can also simulate other train sets on the route in a realistic way, e.g. delays, signal changes.

In the training of drivers and other personnel, AI can generate individual training scenarios, with AI analysing the user's skills and adjusting the simulation's difficulty level to suit them, as well as assessing errors and learning progress. AI can monitor driving style, such as braking too sharply or driving uneconomically, and then suggest corrections. It is worth noting that today, in addition to the most common simulators for train drivers, simulators dedicated to employees in other positions directly related to the operation and safety of railway traffic are increasingly being implemented using virtual reality technology. Such a simulator makes it possible to see how a trainee will perform his or her duties in stressful and abnormal situations, while the use of AI makes it possible to simulate the work of, for example, a crossing supervisor, signalman or traffic warden.

AI can also create simulations for optimising fuel and electricity consumption in traction vehicles. As an eco-driving training, AI can simulate conditions for optimal train driving to save fuel or electricity. In addition, it can also analyse driving economy, i.e. indicate when to slow down to avoid sudden braking, and optimise the use of the recuperative braking system.

With AI, it is also possible to simulate realistic situations of interaction between a railway employee and passengers and staff. In simulating passenger behaviour, AI can generate different types of passengers (e.g. those in a hurry to get on the train, those requiring assistance, those who are rowdy). Simulations of on-board incident handling activities can also be created. AI can create emergency scenarios, e.g. a passenger falling asleep, aggressive behaviour, lost luggage. AI can also map traffic and crowding on platforms at peak times to practice controlling passenger movement at stations.

Simulators can also successfully combine AI with the use of Virtual Reality (VR) or Augmented Reality (AR) for realistic training. AI can analyze the driver's reactions in a full VR environment, or it can overlay rolling stock condition information onto a real image for operating training using AR for technicians and drivers.

AI can also be used in the development of simulators for designing rail routes. AI can be used to test new track layouts, where AI can simulate traffic on a newly designed route, assessing its efficiency. It can also analyze potential critical points, i.e. predict places where potential collisions, slowdowns or congestion of rail traffic may occur.

5. CONCLUSION

As it results from the considerations presented in the article, the use of artificial intelligence in rail transport opens up new possibilities for the operation of the railroads and can significantly

contribute to revolutionizing this branch of transport. The use of AI can apply to practically every area of activity of this transport sector. Of course, AI is currently only entering the functioning of social and economic life, however, it is already visible that its importance will deepen with each year and this trend is already unstoppable. This also applies to railways.

The article presents both the already used AI applications on the railroads but focuses primarily on the potential possibilities of its further application in the functioning of rail transport. As technology develops and modern AI systems are integrated, we can expect an increase in the safety, efficiency of operation and quality of services provided on the railway, also taking into account important ecological issues. The consequence of the widespread implementation of AI systems may be the implementation of the long-standing assumptions of the European Union's transport policy for the growth of this mode of transport in passenger and freight transport.

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DECISION-MAKING IN URBAN TRANSPORT POLICY AND INTELLIGENT MANAGEMENT: THE CASE OF PAID PARKING ZONES AND TECHNOLOGICAL IMPLEMENTATION IN POLISH CITIES·

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ABSTRACT

Purpose: *This study examines how paid parking zones influence urban decision-making and how ANPR and AI-driven analytics enhance enforcement efficiency, predict demand, optimise pricing, and support adaptive parking policy-making.*

Need for the Study: *Urban congestion and parking inefficiencies remain critical issues in modern cities, affecting mobility, air quality, and economic activity. Amid rapid technological advance, municipalities increasingly rely on automated solutions such as ANPR to regulate parking. However, there is limited research on how these technologies influence decision-making in urban transport policies.*

Methodology: *This study employs a literature review, municipal data collection, and comparative analysis across major Polish cities. It evaluates the effectiveness of paid parking zones, pricing policies, and technological tools, particularly ANPR-based enforcement systems, in managing congestion and ensuring compliance.*

Findings: *The research identifies significant variations in parking policies among Polish cities, with higher fees and extended enforcement hours correlating with improved parking space turnover. The implementation of ANPR has resulted in a substantial increase in compliance rates, streamlining enforcement and reducing reliance on manual inspections. Warsaw, as an early adopter, demonstrated a tenfold increase in scanned vehicles between 2020 and 2024.*

Practical Implications: *Findings highlight the importance of integrating technology-driven enforcement tools into urban transport policies. Policymakers should consider expanding ANPR systems to enhance compliance, reduce operational costs, and inform data-driven decisions on urban mobility strategies. The study underscores the necessity for a balanced approach that aligns parking policies with broader sustainability goals and public transport development.*

Keywords: artificial intelligence, Automatic Number Plate Recognition (ANPR), paid parking zones, predictive analytics, sustainable mobility, urban transport policy decision-making.

Jel codes: C88, H76, L91, O33, R41, R48

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1. INTRODUCTION

Despite growing awareness of its harmful effects, individual road transport continues to dominate urban mobility. Authorities and residents frequently opt for cars as their primary mode of transport, leading to significant environmental and social challenges. Extensive studies indicate that road transport causes severe environmental damage due to emissions and infrastructure development. Road transport infrastructure consumes valuable land that could be used for housing or social infrastructure and contributes to urban heat islands and poor water management. Vehicle emissions, including greenhouse gases and harmful pollutants, further degrade air quality and public health (Litman, 2006; Maibach et al., 2008).

The widespread use of cars has led to severe congestion, particularly in European cities with densely built-up centres and narrow roads that are unsuitable for heavy traffic. Polish cities such as Wrocław, Poznań, and Warsaw rank among the most congested in Europe, with drivers spending significant amounts of time in traffic. In response, Polish municipalities have introduced paid parking zones (PPZs) to manage congestion and external costs associated with road transport. Additionally, many cities feature paid guarded car parks, municipal surface car parks, and green zones.

The growing adoption of Automatic Number Plate Recognition (ANPR) technology has transformed the enforcement of paid parking policies, allowing for more effective monitoring of parking compliance.

AI algorithms process ANPR data in real time to detect parking-behaviour patterns, identify emerging congestion hotspots and generate actionable insights for dynamic enforcement deployment. By automating verification, ANPR reduces reliance on manual inspections, boosting both operational efficiency and enforcement accuracy. This data-driven approach aligns with the intelligent management paradigm, in which organisations employ digital technologies and analytical models to continuously monitor key performance indicators, swiftly correct deviations and refine processes and strategies . In the context of paid-parking zones, intelligent management means integrating demand, cost and enforcement-efficiency data into a single coherent system that underpins tactical measures such as dynamic pricing and strategic policymaking by municipal authorities.

This study examines how large Polish cities utilise PPZs and available parking infrastructure to mitigate these challenges, focusing on their scope, pricing policies, technological implementation, and effectiveness in relation to local economic and demographic factors. Furthermore, it evaluates the role of ANPR in ensuring compliance and its broader implications for data-driven decision-making in urban transport policies. These AI-powered insights not only streamline enforcement operations but also feed into predictive models for urban mobility planning and sustainable transport interventions.

2. LITERATURE REVIEW

Despite decades of substantial investment in road infrastructure, modern cities across the globe continue to grapple with the persistent and debilitating issue of chronic traffic congestion. This pervasive problem not only significantly undermines the efficiency of urban transport networks but also demonstrably degrades air quality within urban environments and diminishes the overall quality of life experienced by city residents (Maibach et al., 2008; INRIX, 2022). In response to these pressing challenges, researchers, urban planners, and transportation practitioners have increasingly turned their attention towards the transformative potential of Artificial Intelligence (AI) as a crucial element in achieving intelligent management of complex urban mobility systems, particularly in optimising both traffic flow and parking management strategies.

AI-enabled systems, especially those intricately built around the capabilities of Automatic Number Plate Recognition (ANPR) technology and the broader framework of Intelligent Transport Systems (ITS), hold the significant promise of delivering more agile, adaptive, and fundamentally data-driven approaches to urban traffic control and resource allocation. These advanced, technology-driven methodologies offer a compelling alternative to traditional, often static, statistical methods that have historically been employed in attempts to understand and mitigate urban congestion (Deakin & Al Waer, 2011; Wydro, 2005). The integration of AI into these systems allows for real-time analysis of traffic patterns, prediction of future congestion hotspots, and dynamic adjustment of traffic signals and parking availability, all contributing to a more holistic and effective form of intelligent management of urban transportation networks. Furthermore, the data generated and analysed by these intelligent management

systems provides invaluable insights for long-term urban planning and policy decisions aimed at fostering more sustainable and liveable cities.

ANPR generates vast “Big Data” repositories on vehicle movements—capturing metrics such as dwell time, location and trajectories—which AI algorithms can interrogate to uncover complex correlations and latent patterns invisible to manual analysis (Werner, Mierzwiak & Pochmara, 2008; Bibri & Krogstie, 2017). Machine-learning models trained on these datasets underpin several key applications:

- Dynamic Parking Pricing: Real-time adjustment of parking tariffs based on occupancy and demand to distribute vehicles evenly and alleviate hotspots (Ministerstwo Infrastruktury, 2005; Ayuntamiento de Barcelona, 2025).
- Predictive Traffic Modelling: Forecasting future congestion levels using historical and current sensor data, enabling proactive signal timing changes and route recommendations (Deakin & Al Waer, 2011; Land Transport Authority Singapore, 2025).
- Anomaly and Incident Detection: Continuous monitoring of multi-sensor feeds (ANPR, cameras, loop detectors) to flag unusual patterns—such as prolonged stoppages or sudden build-ups—that may indicate accidents or obstructions (Barwiński & Kotas, 2015).
- Personalised Driver Information: Delivering tailored guidance on parking availability, journey times and alternative routes through mobile and in-vehicle interfaces, thereby supporting informed travel decisions (Tumielewicz, n.d.; Barwiński & Kotas, 2015).
- Sustainable Mobility Support: Evaluating the impact of pricing and regulatory measures on private-vehicle use to refine policies that incentivise low-emission modes and public transport uptake (Koźlak, 2008; Bibri & Krogstie, 2017).
- Empirical examples from Polish cities, notably Szczecin’s ITS deployment, illustrate the practical benefits of integrating AI with ANPR and telematics subsystems—achieving smoother flows, reduced emissions and enhanced traveller information (Kijewska, 2018; SITK Szczecin, 2025). Yet, significant challenges remain: ensuring robust data security through encryption and access controls (Anthopoulos & Fitsilis, 2015), securing citizen buy-in via effective outreach (Anthopoulos & Fitsilis, 2015), and addressing high implementation costs and system interoperability (Koźlak, 2008; Barwiński et al., 2015).

. In sum, the existing literature underscores the transformative potential of Artificial Intelligence within urban transport systems, facilitating a paradigm shift in decision-making processes from reactive responses to proactive and predictive strategies. This evolution supports the development of more sustainable and liveable urban environments. To further realize these benefits, future research endeavours should rigorously evaluate the long-term impacts of AI integration on travel behaviour patterns and concurrently refine the ethical, legal, and technical frameworks governing the roll-out of AI-driven Intelligent Transportation Systems, ensuring responsible and effective intelligent management of urban mobility.

3.METHODOLOGY

3.1 Data Collection for Intelligent Paid Parking Zone Assessment

To develop a comprehensive understanding of Paid Parking Zones (PPZs) across Poland's major urban centres, data were systematically collected from diverse municipal institutions and publicly accessible sources. These data streams are crucial for an intelligent management perspective on urban mobility. Key data sources include:

- Municipal Websites**:** Official city administration websites were accessed to gather information regarding the existence, geographical scope, and pricing strategies of PPZs in cities such as Białystok, Lublin, Bydgoszcz, Szczecin, Gdańsk, Poznań, Wrocław, Łódź, Kraków, and Warsaw. This provides foundational data for understanding the current state of PPZ management.
- Legislative Documents**:** A thorough review of the Public Roads Act and the Electromobility and Alternative Fuels Act was conducted to establish the legal framework governing the establishment and operation of PPZs (Public Roads Act, 2023; Electromobility and Alternative

Fuels Act, 2023). Understanding this legal context is essential for analysing the constraints and opportunities for intelligent management implementation.

- Economic Data: Average wage data for each studied city were compiled to facilitate an analysis of the relative financial burden of parking fees on local residents. This socio-economic perspective is vital for ensuring equitable and effective intelligent pricing strategies within PPZs.

ANPR Data Analysis for Intelligent Enforcement and Policy Insights**:** The research integrates data from cities utilizing Automatic Number Plate Recognition (ANPR) systems. This analysis evaluates the impact of ANPR on critical aspects of intelligent parking management, including parking compliance levels, revenue generation efficiency, and enhanced decision-making capabilities within transport policy.

3.2 Intelligent Decision-Making Framework for Urban Transport Policy

This research further investigates how data derived from PPZs and ANPR-based enforcement mechanisms contribute to informed urban decision-making, a cornerstone of intelligent management in urban mobility. By analysing historical enforcement data, municipalities can intelligently refine parking policies, dynamically adjust pricing mechanisms based on demand and occupancy, and strategically plan infrastructure investments. The study specifically explores:

- The Influence of ANPR Data on Intelligent Policy Adjustments: Assessing the extent to which data generated by ANPR systems informs and drives evidence-based modifications to parking regulations and operational procedures, reflecting an adaptive intelligent management approach.
- The Correlation between Enforcement Intensity and Compliance Rates: Implications for Intelligent Resource Allocation: Examining the relationship between the level of enforcement effort and the resulting compliance rates, providing insights for the intelligent allocation of enforcement resources.
- The Impact of Automated Enforcement on Municipal Revenue and Operational Costs: Efficiency Gains through Intelligent Systems: Evaluating the financial implications of deploying automated enforcement technologies on both revenue streams and operational expenditures, highlighting the economic benefits of intelligent management solutions.
- Application of AI-Driven Machine-Learning Models for Proactive and Predictive Intelligent Management: Investigating the use of advanced analytical techniques, such as AI and machine learning, to analyse historical ANPR datasets. This includes forecasting future parking demand patterns and simulating the potential outcomes of various policy scenarios, enabling proactive and predictive intelligent management strategies.

By integrating these elements, the study provides a comprehensive analysis of how technological advancements in paid parking enforcement are shaping decision-making processes within urban transport policies, moving towards more data-driven and intelligent management of urban mobility.

4. RESULTS

4.1 Issues and Negative Impacts of Individual Road Transport: The Imperative for Intelligent Management Solutions

Urban car traffic in city centres remains a seemingly unavoidable issue. Despite growing awareness of the negative consequences of car usage, both authorities and residents continue to choose cars as
a primary mode of transport. Research indicates that road transport is highly detrimental to the environment, primarily due to the external costs it generates (Jakle & Sculle, 2004; Mazur, 2010; EEA, 2022; Maibach et al., 2008). Intelligent management strategies offer a pathway to mitigate these negative externalities through optimized traffic flow and the promotion of sustainable transportation alternatives.

One of the major concerns is land use, as road infrastructure occupies valuable space that could otherwise be used for residential development, social infrastructure such as schools, nurseries, or hospitals, or green areas. Additionally, reduced land availability in central areas contributes to increasing housing prices, making property ownership unaffordable for average-income earners in many

countries. Furthermore, road surfaces contribute to environmental issues such as the urban heat island effect and disrupt local water management by reducing rainwater retention capacity (Litman, 2017).

While contemporary urban planning initiatives strive to alleviate these impacts through innovative design approaches, the scale of the challenge necessitates the integration of intelligent management systems to optimise land use and transportation networks.

A major issue associated with individual transport is vehicle emissions, which include both greenhouse gases and pollutants harmful to human health and the natural environment. Key pollutants emitted by road transport include sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), particulate matter (PM), carbon dioxide (CO_2), and methane (CH_4) (Drożdż, Rosa & Pomianowski, 2022; EEA, 2019; Kordas, 2009). Until the implementation of the Electromobility and Alternative Fuels Act (2023), which enabled municipalities to introduce Clean Transport Zones, paid parking zones were the only fiscal tool available to curb car traffic in city centres (Pietruch, 2017). Intelligent traffic management and parking systems, coupled with supportive legislation, are crucial for effectively curbing emissions and promoting cleaner urban environments.

Similar to other European cities, Polish urban areas face serious traffic congestion issues. "European cities rank among the slowest in the world due to the fact that most of their development occurred before the widespread adoption of cars. Dense central areas, narrow streets, and complex road networks make these cities ill-suited for car-based mobility. Last year's top-ranking cities for congestion, London and Paris, again claimed the first and second spots in Europe, with drivers losing 156 and 138 hours in traffic, respectively. Among the 25 most congested cities in Europe, three Polish cities—Wrocław, Poznań, and Warsaw—also feature prominently. In 2022, drivers in these cities lost an estimated 80, 74, and 64 hours in congestion, respectively" (INRIX Global Traffic Scorecard, 2022).

Given the rising congestion levels, this study investigates the role of intelligent management specifically through the lens of paid parking zones (PPZs)in alleviating congestion and reducing external transport costs In selected large Polish cities. The research focuses on data from the year preceding the introduction of Clean Transport Zones planned for Warsaw and Kraków, providing a baseline for assessing the future impact of integrated intelligent mobility policies. To achieve this, an extensive review of municipal policies, online sources, and data from city institutions was conducted, assessing the extent and pricing structures of PPZs. Additionally, this study evaluates how pricing policies align with the economic and demographic realities of different cities, a crucial aspect of equitable and effective intelligent parking management.

Moreover, the implementation of Automatic Number Plate Recognition (ANPR) technology has profoundly transformed the monitoring and enforcement of paid parking zones, a key component of intelligent parking management systems. significantly influenced how paid parking zones are monitored and enforced. By replacing manual enforcement with automated ANPR-based surveillance, cities such as Warsaw, Wrocław, and Gdańsk have witnessed a notable increase in compliance rates. The integration of Artificial Intelligence (AI) further enhances this intelligent system by enabling automated anomaly detection in parking behaviour, identifying unusual patterns such as repeated overstays or fraudulent transactions, thereby refining enforcement precision (Rychlicki, Kwiatkowski & Kasprzyk, 2015; Urbaniak, 2023). This research examines how data derived from ANPR systems supports critical decision-making processes within the framework of intelligent urban mobility management, including This research examines how data derived from ANPR systems supports critical decision-making processes, including:

- The effectiveness of pricing policies in regulating demand and increasing parking space turnover.
- The impact of intelligent enforcement technologies on municipal revenue and cost efficiency.
- How ANPR data facilitates the intelligent adjustment of transport strategies and urban planning initiatives to align with long-term sustainability goals.

The findings of this study contribute to the growing body of knowledge on how data-driven decision-making a core principle of intelligent management, can enhance urban transport policies and improve mobility in densely populated areas.

4.2 Parking Policy in Selected Polish Cities: The Case of Paid Parking Zones within an Intelligent Management Context

The foundation for the operation of paid parking zones (PPZs) in Poland is established in the Public Roads Act (2023). This legislation states that users of public roads are required to pay fees for parking motor vehicles in designated paid parking zones and central paid parking zones. Furthermore, the law specifies that PPZs should be established in areas with a significant parking space deficit, provided that such zones serve traffic management needs, enhance parking turnover, or support local transport policies.. Notably, a primary objective of PPZs is to limit the accessibility of private vehicles and incentivise the adoption of public transport, aligning with the goals of intelligent urban mobility management. A central paid parking zone (CPPZ) can be created in the functional city centre, which serves as the core of a city or district in municipalities with populations exceeding 100,000 residents. The municipal council, upon request from the mayor (or city president), who must first conduct an appropriate parking turnover analysis and obtain opinions from road and traffic management authorities, has the power to establish a PPZ or CPPZ. According to the Public Roads Act, the maximum fee for the first hour of parking in a standard PPZ cannot exceed 0.15% of the minimum national wage, while in a central PPZ, the maximum rate is capped at 0.45% of the minimum wage. At the time of writing, the minimum wage in Poland was PLN 3,600 (Council of Ministers Regulation, 2022), and it is expected to increase to PLN 4,242 in 2024 (Council of Ministers Regulation Proposal, 2024). Table 1 presents these values in USD and EUR.

Additionally, the decision to introduce subscription fees for parking permits falls under the jurisdiction of the municipal authority responsible for PPZ administration. The road traffic management authority, in coordination with the road administrator, is also tasked with designating parking spaces within PPZs and CPPZs for electric vehicles during charging periods at public charging stations, reflecting a move towards integrating sustainable transport into intelligent parking management

The implementation of Automatic Number Plate Recognition (ANPR) technology has led to a substantial improvement in the enforcement of PPZ compliance in cities like Warsaw, Wrocław, and Gdańsk. a key aspect of ensuring the effectiveness of intelligent parking management. This study further examines how ANPR-based monitoring influences parking compliance rates, the efficacy of pricing policies, and the overall planning of urban transport within Polish cities, highlighting the pivotal role of technology in achieving intelligent urban mobility.

Table 1. Maximum rates for the first hour

Zone	Year	PLN	USD (1 USD = 4,29 PLN)	EUR (1 EUR = 4,63 PLN)
PPZ	2023	5,40	1,26	1,17
	2024	6,36	1,48	1,37
Centre PPZ	2023	16,20	3,78	3,50
	2024	19,09	4,36	4,19

Source: own elaboration based on data from Narodowy Bank Polski (n.d.).

The authors decided to examine the paid parking zone policies in the largest Polish cities. According to information provided by the ten most populous cities in Poland, paid parking zones or central paid parking zones exist, as presented in Table 2. These data reveals a strategic element of intelligent urban mobility management, whereby certain cities explicitly aim to disincentivise private vehicle usage within historic or central districts through the implementation of CPPZs, which permit the application of higher parking tariffs. If drivers still choose to use a car despite these measures, higher fees are theoretically expected to increase vehicle turnover, as studies suggest that a typical car remains parked for 23 hours per day (Litman, 2006, 2017). Intelligent parking management leverages pricing mechanisms to optimize parking space utilization.

From a resident's perspective, a key issue is whether parking fees effectively deter people from using their cars. Therefore, it is crucial to consider not only the absolute parking cost but also its relative value compared to average wages in a given city. Consequently, the study examines how parking fees relate to average salaries across different cities, as presented in Table 3. Additionally, a comparison was made between the average parking fee for the first hour, the city's population size, and the ratio of parking costs to the average wage, as illustrated in Figure 1. This integrated view provides valuable insights for

the intelligent design of parking policies that are both effective in managing traffic and equitable for residents.

Table 2. Paid parking zones in the largest Polish cities

City	Population in thousands	PPZ	Centre PPZ or other
Białystok	297	yes (2 zones)	none
Lublin	340	yes (4 zones)	none
Bydgoszcz	350	yes (3 zones)	none
Szczecin	407	yes (2 zones)	yes
Gdańsk	467	yes	yes
Poznań	536	yes	yes (2 zones)
Wrocław	641	yes	yes (2 zones)
Łódź	685	yes (4 zones)	none
Kraków	771	none	yes (3 zones)
Warszawa	1778	2 zones	none

Source: own elaboration based on data from: Gdański Zarząd Dróg i Zieleni (n.d.); Urząd Miejski w Białymstoku (n.d.); Urząd Miasta Łodzi (n.d.); Urząd Miejski Wrocławia (n.d.); Zarząd Dróg i Transportu Miejskiego w Szczecinie (n.d.); Zarząd Dróg Miejskich i Komunikacji Publicznej w Bydgoszczy (n.d.); Zarząd Dróg Miejskich w Lublinie (n.d.); Zarząd Dróg Miejskich Poznań (n.d.); Zarząd Dróg Miejskich w Warszawie (n.d.); Zarząd Dróg Miasta Krakowa (n.d.). (accessed: 3.10.2023).

Table 3. Percentage share of the price of 1 hour of parking in the average salary in the selected city in %

City	Avarage wage (PLN)	Lowest price in PPZ (PLN)	Share in avarage wage (%)	Highest price in PPZ or Centre PPZ (PLN)	Share in avarage wage (%)
Białystok	6 013	1,60	0,027	2,80	0,047
Lublin	6 457	2,00	0,031	3,90	0,060
Bydgoszcz	7 116	2,60	0,037	3,80	0,053
Szczecin	7 640	2,80	0,037	3,60	0,047
Gdańsk	9 003	3,90	0,043	5,50	0,061
Poznań	7 914	3,50	0,044	7,00	0,088
Wrocław	8027	3,00	0,037	7,00	0,087
Łódź	6841	2,00	0,029	4,00	0,058
Kraków	9134	4,00	0,044	6,00	0,066
Warszawa	8833	4,50	0,051	4,50	0,051

Source: own elaboration based on data from: City of Gdańsk (2023),Gdański Zarząd Dróg i Zieleni (n.d.); Urząd Miejski w Białymstoku (n.d.); Urząd Miasta Łodzi (n.d.); Urząd Miejski Wrocławia (n.d.); Zarząd Dróg i Transportu Miejskiego w Szczecinie (n.d.); Zarząd Dróg Miejskich i Komunikacji Publicznej w Bydgoszczy (n.d.); Zarząd Dróg Miejskich w Lublinie (n.d.); Zarząd Dróg Miejskich Poznań (n.d.); Zarząd Dróg Miejskich w Warszawie (n.d.); Zarząd Dróg Miasta Krakowa (n.d.).

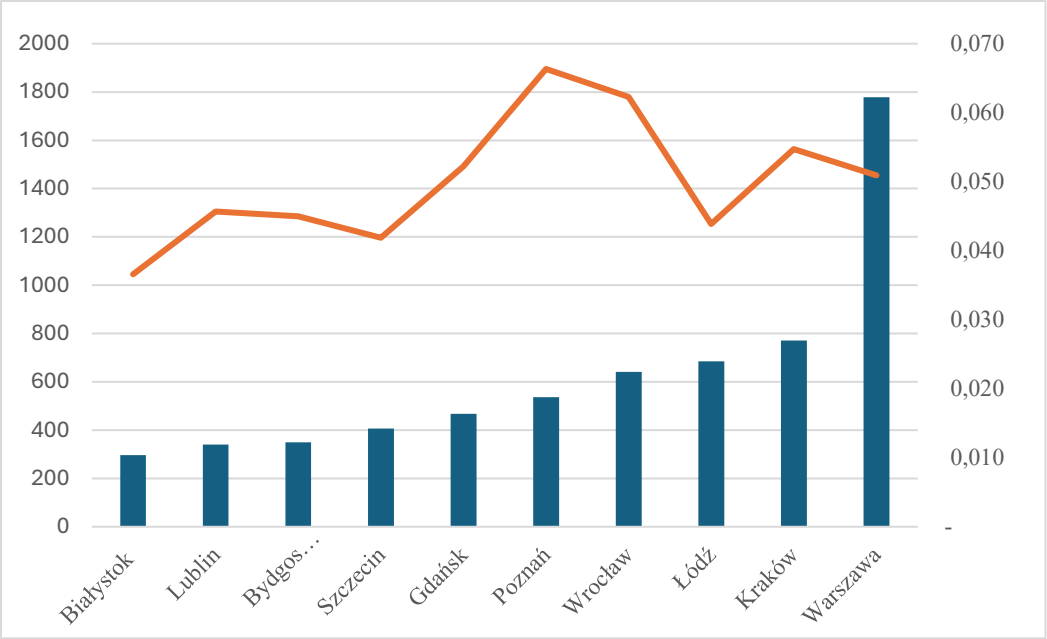


Figure 1. Percentage share of the price of 1 hour of parking in the average salary in the selected city in %

Source: own elaboration.

The above figure shows that, in absolute terms, the cheapest parking spaces are in Białystok (PLN 1.60), while the most expensive are found in selected zones of Poznań and Wrocław (PLN 7.00). However, when considering the relative value of parking fees in relation to the average salary in each city, the results are as follows: Białystok remains the most affordable city, where the average cost for the first hour in the cheapest and most expensive zones amounts to 0.037% of the average wage in the city. Szczecin ranks second with an average of 0.042%, followed by Łódź at 0.044%. In contrast, the most expensive cities in relative terms are Poznań (0.066%), Wrocław (0.062%), and Kraków (0.055%).

Apart from parking fees, another potential barrier for drivers is the operating hours of paid parking zones, i.e., the days and hours during which fees apply. Data provided by municipal authorities and parking zone operators indicate that fee enforcement hours vary across the cities analysed. A summary of these variations is presented in Table 4, highlighting the diverse approaches to temporal management of parking demand. Intelligent management systems can optimise these operating hours based on traffic patterns and demand fluctuations. It is important to note that some cities have designated areas where no official parking zones exist, referred to as unmonitored paid parking areas. The pricing structures and operating hours within these areas are often strategically designed to further discourage prolonged vehicle stays, representing a form of decentralised intelligent traffic management. For instance, Szczecin has two paid parking zones and several unmonitored paid parking areas, where fees apply seven days a week from 08:00 to 22:00, amounting to 98 hours per week, with a first-hour fee of PLN 10.00.

Additionally, all analysed cities have special parking conditions for people with disabilities and their caregivers. Moreover, most cities provide incentives for using low-emission or zero-emission vehicles, defined as vehicles with CO_2 emissions below 100 g/km, as specified in type-approval certificates under the NEDC urban cycle (for vehicles registered before 1 September 2018) or WLTP average cycle (for vehicles registered after 1 September 2018) (Lublin City Council, 2021). These incentives represent an intelligent integration of environmental sustainability goals within urban parking management frameworks.

Table 4. The duration of the paid parking zone

City	Hours per week
Białystok	40
Lublin	50
Bydgoszcz	45
Szczecin	45
Gdańsk	30-77
Poznań	50-70
Wrocław	45-77
Łódź	50
Kraków	60
Warszawa	60

Source: own elaboration based on data from: Gdański Zarząd Dróg i Zieleni (n.d.); Urząd Miejski w Białymstoku (n.d.); Urząd Miasta Łodzi (n.d.); Urząd Miejski Wrocławia (n.d.); Zarząd Dróg i Transportu Miejskiego w Szczecinie (n.d.); Zarząd Dróg Miejskich i Komunikacji Publicznej w Bydgoszczy (n.d.); Zarząd Dróg Miejskich w Lublinie (n.d.); Zarząd Dróg Miejskich Poznań (n.d.); Zarząd Dróg Miejskich w Warszawie (n.d.); Zarząd Dróg Miasta Krakowa (n.d.).

The increasing adoption of this innovative parking enforcement system, based on Automatic License Plate Recognition (ANPR) technology, is revolutionising traditional methods of fee enforcement, introducing significant improvements and representing a key component of intelligent parking management (Rychlicki, Kwiatkowski, & Kasprzyk, 2015).This e-control technology integrates cameras, lasers, and GPS, autonomously scanning vehicle license plates and cross-referencing them against a real-time database of vehicles with verified parking payments (Kalus, 2025). This automation significantly enhances the efficiency and scalability of enforcement operations, a hallmark of intelligent urban management.

Since January 2020, this system has been in operation in Warsaw, marking a pioneering national initiative in the application of intelligent transportation systems. Initially, the enforcement fleet consisted of two vehicles, expanding to nine in subsequent years. Within the first 12 months, these vehicles checked over 1.3 million parked cars, demonstrating the capacity of intelligent enforcement to achieve broad monitoring. After the first month of operations, it was observed that one e-control vehicle could inspect ten times more cars compared to two human inspectors, highlighting the substantial gains in operational efficiency inherent in this intelligent technology. In 2020, 1,342,313 vehicles were inspected, rising to 14,773,499 in 2024, a tenfold increase, underscoring the expanding scope and intensity of intelligent parking monitoring. In 2020, 411,816 fines were issued, accounting for 11.41% of all scanned vehicles. These penalties contributed at least PLN 70 million to the municipal budget, assuming a reduced fine of PLN 170 (rather than PLN 250) when paid within the first seven days. This discount policy, an element of intelligent revenue management, encourages timely payments, avoiding lengthy debt collection procedures. Consequently, these revenues constitute a significant financial resource for Warsaw's city budget, directly attributable to the efficiency gains of intelligent enforcement. Additionally, e-control vehicles covered 68,000 km in 2020, increasing to 252,270 km in 2024, representing a growth of 184,270 km (271%), in operational reach for this intelligent monitoring system. The number of fines issued using e-control in Warsaw in the years 2020-2024 is presented in Table 5, illustrating the increasing effectiveness of this intelligent enforcement strategy

The number of recognized license plates increased from 3,608,176 in 2020 to 14,773,499 in 2024, representing a 309% increase. This means that the number of recognized plates has more than tripled over five years, demonstrating the growing capacity of the intelligent ANPR system. The number of

additional fees in the form of fines for unpaid parking in the paid parking zone, issued based on e-control carried out by designated vehicles, amounted to 165,726 in 2020. In 2024, this number increased to 384,789. The increase in fines over five years totaled 219,063, which constitutes a 132.18% growth, reflecting the enhanced enforcement capabilities of this intelligent parking management tool.

Table 5. The amount of fines issued with the use of e-control in Warsaw from 2020 to 2024

Year	License plates recognized	Percent increase	Fines-Car Patrols	Percent increase	Fines-Foot Patrols (**Years Before System E-Control Implementation for Foot Patrols*)	Percent incr	E-control Total Fines
2020	3 608 176	-	165 726	-	160 269*	-	-
2021	5 678 793	57,39%	189 125	14,12%	77 093*	-51,90%	-
2022	10 991 873	93,55%	331 964	75,53%	27 935	-63,76%	11 019 808
2023	12 776 445	16,23%	392 873	18,35%	21 421	-23,32%	12 797 866
2024	14 773 499	15,63%	384 789	-2,06%	27 027	26,17%	14 800 526

Source: own elaboration based on data from Transport-Publiczny.pl (2023).

In 2024, revenues from fines for illegal parking in the capital amounted to PLN 61.733 million. This is over PLN 15 million more than in 2023 when the revenues totaled PLN 46.6 million. This substantial growth underscores the increasing effectiveness of intelligent enforcement technologies in revenue generation. The five-year analysis of Warsaw's operations demonstrates a significant increase in the number of fines issued through the intelligent e-control system, particularly with the use of specially designated vehicles. This trend strongly suggests that the system substantially enhances enforcement efficiency by enabling a far greater volume of vehicle inspections within a compressed timeframe a key advantage of automated urban management. The inherent automation of the system minimizes human errors and significantly accelerates the ticketing process, contributing to the overall efficiency of intelligent parking management.

The introduction of intelligent e-control in Warsaw has significantly improved the enforcement of parking fees. The system, utilizing vehicles equipped with cameras to scan license plates, allows for rapid verification of whether a vehicle has a valid parking payment. As a result, controllers can check a significantly higher number of vehicles in a short time compared to traditional foot patrols. Data from the system is processed in real-time, enabling immediate detection of violations.

Implementing this system optimises the employment of parking inspectors, allowing human resources to be redirected to other areas, such as debt collection. Increased awareness among drivers regarding the effectiveness of e-control contributes to greater compliance with regulations. The new parking fee control system represents a significant step toward modernizing urban traffic management, enhancing order, and efficiency within paid parking zones. E-control systems significantly improve enforcement efficiency, enabling a higher number of vehicle checks within a shorter timeframe. Cities that have implemented e-control have observed an increase in detected cases of unpaid parking.

The effectiveness of e-control in Warsaw is confirmed by statistical data. According to information provided by the Municipal Roads Authority of Poland's capital, this system has significantly increased the number of issued fines, which has directly translated into higher parking fee revenues and, consequently, an increase in the city's budget (Kalus, 2025). Furthermore, the e-control system enables real-time monitoring of parking zone occupancy, which is invaluable for planning changes in traffic organization and expanding parking infrastructure. As highlighted in the report "Transport and Urban Mobility. Report on the State of Polish Cities," compiled by the Urban Policy Observatory of the Institute for Urban and Regional Development, data from parking control systems are crucial for efficient urban mobility management (Gadziński & Goras, 2019).

It is also worth noting that while effective, the e-control system raises some concerns regarding data protection. Therefore, city authorities must ensure that data processing complies with the General Data

Protection Regulation (GDPR). Information on how the system operates in Warsaw can be found on the website of the Municipal Roads Authority: "Exporting E-Control Solutions - Municipal Roads Authority in Warsaw" (Municipal Roads Authority, 2024). In terms of data protection, reference should also be made to the guidelines of the Personal Data Protection Office (UODO) regarding the processing of data from Automatic Number Plate Recognition (ANPR) systems (UODO, 2024).

Additionally, when analysing technological aspects, reference should be made to the publication "E-Control of Paid Parking Zones as a Solution for Modern Cities - MCX," which presents the advantages and applications of e-control systems in paid parking zones and highlights increased enforcement efficiency and improved fee collection (Urbaniak, 2023).

In conclusion, the implementation of e-control systems in paid parking zones offers numerous benefits for both the city and drivers. Increased enforcement efficiency, optimised staffing, and improved driver compliance are just a few of these benefits. Figure 2 schematically presents the impact of data collection from e-control systems in paid parking zones on decision-making processes.

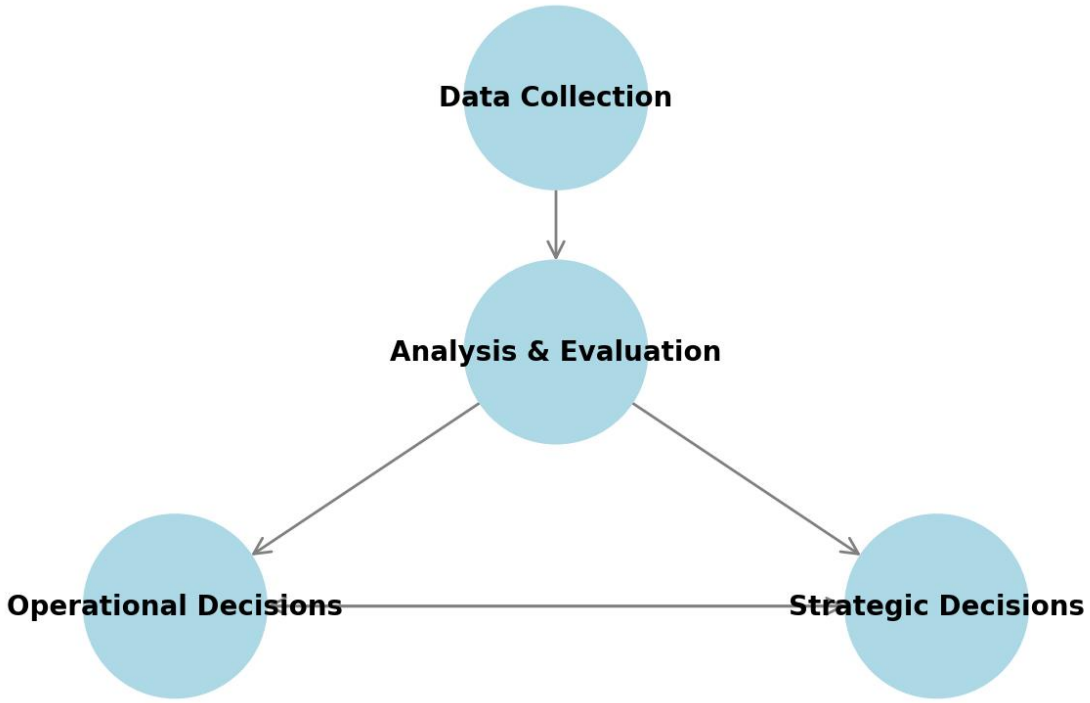


Figure 2. Decision-Making Process for the Paid Parking System and Transport Policy
Source: own elaboration.

The above model, illustrating the process of collecting data obtained through the functioning intelligent e-control systems in large urban agglomerations, demonstrates how vast amounts of data are gathered using license plate scanning cameras This wealth of data serves as critical foundation for informed decision-making across various levels of urban governance, embodying the principles of data-driven urban management. Granular information regarding the number of parked vehicles, the frequency and location of fee violations, and the real-time occupancy rates of individual parking zones is crucial for analysing the effectiveness of existing paid parking zone policies, and operational strategies a cornerstone of intelligent parking management. The collected data is analysed, enabling the assessment of the efficiency of current solutions. Based on these analyses, urban officials and city authorities can make more effective decisions regarding, for example, the expansion or modification of paid parking zone boundaries, data-informed adjustments to fee rates, to optimise demand, the strategic implementation of new intelligent technologies, and the data-driven optimisation of patrol frequency for enhanced enforcement efficiency. According to analyses included in the report "Transport and Urban Mobility. Report on the State of Polish Cities," developed by the Urban Policy Observatory of the Institute for Urban and Regional Development, data from parking control systems is essential for

efficient urban mobility management (Gadziński & Goras, 2019). The report's authors emphatically underscore that access to current, reliable, and granular data is a fundamental prerequisite necessary for making rational and effective decisions in the complex field of transport policy a core tenet of intelligent transportation planning. Additionally, in the publication "Paaid Parking Zones in Small Cities. Analysis of Solutions Based on the Example of Środa Wielkopolska," the authors examine the specifics of paid parking zones in smaller cities, highlighting the need to tailor systems to local conditions and demands an adaptation that can be informed by the principles of context-aware intelligent management (Kiciński & Zmuda-Trzebiatowski, 2018).

Based on data from the system, which automatically generates notifications of additional fees as an operational decision, parking zone controllers, having real-time access to data, can make quick intervention decisions in cases of violations. Data collected from paid parking zones can also be used to make strategic decisions regarding the city's transport policy. Information on parking zone occupancy can influence decisions on investments in transport infrastructure, such as the construction of new surface or multi-story parking facilities. Planned changes in the paid parking zone, such as the establishment of the Downtown Paid Parking Zone, result from data analysis and decision-making processes driven by the insights derived from intelligent parking management systems.

It is worth noting that e-control systems, utilizing Automatic Number Plate Recognition (ANPR) technology, offer substantial benefits for intelligent urban management, they also raise legitimate concerns related to data protection and individual privacy According to the guidelines of the Personal Data Protection Office (UODO), the processing of data from ANPR systems must comply with GDPR principles, including data minimization and purpose limitation requirements an ethical consideration paramount in the deployment of intelligent surveillance technologies (UODO, 2024).

Additionally, when analysing technological aspects, reference should be made to the publication "E-Control of Paid Parking Zones as a Solution for Modern Cities - MCX," which presents the advantages and applications of e-control systems in paid parking zones, explicitly highlighting the significant gains in enforcement efficiency and the notable improvement in fee collection rates achieved through intelligent automation (Urbaniak, 2023). It is also worth mentioning analyses concerning Intelligent Transport Systems (ITS), which consistently emphasize the transformative role of technology in optimising urban traffic management and enhancing overall urban mobility through intelligent system integration (Molecki, 2017).

5. DISCUSSION

This article has analysed several aspects of parking policy in Poland's largest cities. A comprehensive analysis would require considering a greater number of variables, such as regulations regarding the purchase of monthly or other subscription-based parking permits, which significantly reduce vehicle turnover in parking spaces. Nonetheless, we have identified several key differences in parking policies. For instance, in Białystok, the first hour of parking is 2.81 times cheaper than in Warsaw. However, when considering average wages in these cities, the price proportion is only 1.89 times lower in Białystok compared to Warsaw. Based on external research indicating that Poznań and Wrocław are the most congested Polish cities, this awareness is evident among local authorities, as these cities implement the highest publicly funded health insurance contributions in Poland, both in absolute terms and in relation to local average earnings.

In addition to pricing, the duration of parking enforcement throughout the week is also significant. This variation is considerable, sometimes nearly double. For example, Białystok’s parking enforcement operates for 40 hours per week, compared to 45 hours in Szczecin, 60 hours in Warsaw, 70 hours in Poznań, and up to 77 hours in selected zones in Wrocław and Gdańsk. The study suggests that higher parking fees and extended enforcement hours could theoretically increase vehicle turnover and reduce traffic congestion. However, the real-world effectiveness of these intelligent management strategies is intrinsically linked to prevailing local economic conditions and the degree of willingness among residents to comply with the implemented regulations.–From a strategic management perspective, a city’s ability to rapidly adapt its parking policies and ANPR/AI technologies can be understood through the lens of dynamic capabilities (Teece et al., 1997). Cities with strong dynamic capabilities are able to

swiftly integrate new technologies, transform operational processes, and reconfigure resources, resulting in improved outcomes in mobility management.

Intelligent management constitutes more than merely ANPR or AI technologies; it embodies an integrated socio-technical system of people, processes and technology. Such a system continuously monitors key performance indicators in real time, automatically corrects deviations and dynamically optimises pricing policies and enforcement patrol deployments.

Encouragingly, the majority of analysed cities offer specific incentives for low-emission vehicles and have established regulations accommodating disabled persons, demonstrating a growing awareness of the critical need to balance stringent parking policies with principles of accessibility and environmental sustainability key considerations in responsible urban management.

The findings of this study highlight the need for further in-depth research into the complexities on urban transport policies. Future scholarly investigations should endeavour to incorporate additional relevant variables, such as the availability and efficiency of public transport networks the prevalence and impact of micromobility options (e.g., e-scooters, shared bicycles), and a granular analysis of the impact of subscription-based parking permits on overall vehicle turnover within designated parking zones. Future should strategically explore the application of advanced Artificial Intelligence (AI) techniques— such as sophisticated convolutional neural networks for enhanced image recognition in enforcement, reinforcement learning algorithms for dynamic and adaptive pricing strategies, and powerful predictive analytics for robust scenario planning—to further optimise the effectiveness and adaptability of paid parking policies within the framework of intelligent transportation systems. The introduction of Clean Transport Zones (CTZ) in major cities such as Warsaw and Kraków in 2024 presents a unique and timely opportunity to observe how these new urban mobility solutions will interact with existing network of paid parking zones (PPZ). The cascading impact of CTZ implementation on urban congestion levels and broader urban mobility patterns will undoubtedly constitute a key area for future empirical study. The collective findings of our analysis emphasize the fundamental importance of adopting integrated and holistic approach to urban planning one that strategically treats parking policy not as an isolated instrument but as a crucial component of broader, coordinated efforts aimed at effectively managing urban congestion, measurably improving air quality, and ultimately enhancing the overall quality of life for urban residents a central goal of sustainable and intelligent urban development. These conclusions collectively underline that while PPZ can indeed serve as an effective tool for managing urban traffic density, their ultimate success hinges upon thoughtful and context-aware implementation that carefully considers prevailing local economic conditions, existing urban infrastructure constraints and opportunities and the overarching framework of broader transport policies within an integrated intelligent mobility strategy.

Paid parking systems (SPP) in Poland provide data that is actively utilized for informed decision-making at various levels of governance The use of modern technologies and data integration can contribute to better traffic management and the development of a sustainable transport policy on a national scale. As technology continues its rapid advancement, these intelligent parking systems will inevitably play an increasingly important role in the effective management of urban space. The utilization of artificial intelligence and advanced big data analysis techniques holds the potential to unlock a deeper understanding of complex mobility trends and enable more accurate the forecasting of future driver behaviours, paving the way for predictive and adaptive urban management.

At the local level, within the intricate dynamics of urban spaces, paid parking systems provide critical data that is directly used for decision-making regarding:

- Optimisation of parking zone boundaries and dynamic fee adjustments, based on real-time demand and occupancy data
- Strategic Implementation of new and innovative control and payment technologies, enhancing user convenience and operational efficiency,
- Evidence-based planning of future parking infrastructure, including the development of new parking facilities in response to identified needs, Data-driven shaping of local transport policies, promoting sustainable mobility alternatives and reducing reliance on private vehicles .

This rich data is also used to evaluate the effectiveness of actions taken by local authorities, enabling a continuous cycle of policy refinement and improvement In Warsaw, for instance, the operational data from the intelligent e-control system is actively used to analyse parking zone occupancy patterns and

detect specific areas where violations frequently occur, allowing for targeted enforcement and policy adjustments.

In some regions, particularly within densely populated urban agglomerations, the strategic coordination of parking policies across administrative boundaries is of paramount importance for seamless regional mobility. Intelligent paid parking systems can provide the crucial necessary for planning integrated regional transport and parking systems. Enhanced cooperation among cities within a region can lead to the beneficial standardization of parking policies, improving the user experience and overall efficiency.

At the national level, the aggregated data from paid parking systems across the country offers valuable insights for analysing broader mobility and parking trends. This comprehensive information can contribute significantly to shaping nationwide transport policies and strategically planning infrastructure investments. Furthermore, such data can be effectively used to assess the impact of various legal regulations on driver behaviour, informing future legislative adjustments for improved urban mobility and sustainability.

Successful intelligent management depends on uncompromising data quality and strong governance structures (including GDPR compliance), without which automated decisions risk being skewed or legally vulnerable. Equally critical is sustained, cross-departmental collaboration uniting IT specialists, road-management authorities, transport planners and finance teams to ensure that technological insights translate into coordinated policy adjustments. Finally, transparency around objectives and KPI design is essential so that all stakeholders understand and trust the system's decision-making logic.

6. CONCLUSION

This study has demonstrated that paid parking zones (PPZs), when combined with advanced enforcement technologies, can play a pivotal role in managing urban congestion and supporting data-driven transport policy in Poland's largest cities. Our comparative analysis revealed significant variability in PPZ scope, pricing and operating hours—factors that collectively influence parking turnover and driver behaviour. Cities with higher first-hour fees and extended enforcement windows (e.g. Poznań, Wrocław) achieved greater space turnover, whereas more affordable zones (e.g. Białystok, Łódź) saw lower relative impact on modal shift, underscoring the need for context-sensitive intelligent management strategies.

The introduction of e-control vehicles equipped with ANPR markedly transformed enforcement capacity in Warsaw, representing a significant advancement in intelligent parking management Between 2020 and 2024, scanned vehicles increased tenfold (from 1.3 m to 14.8 m) and fines grew by over 132 %, generating more than PLN 60 m in annual revenue by 2024. This underscores the financial and operational benefits of intelligent enforcement systems.

The results demonstrate that the adoption of intelligent management an integrated system of ANPR, AI and decision-making processes facilitates a transition from reactive fee enforcement to a proactive, predictive parking policy. To capitalise on these benefits, municipalities should establish an interdisciplinary Intelligent Management team that brings together IT specialists, road-management authorities and finance experts, and should invest in expanding ANPR infrastructure alongside advanced analytics and predictive-modelling tools. Future research ought to include longitudinal studies examining the impact of intelligent management on CO_2 emissions and modal-split dynamics. Ultimately, intelligent management will form the very core of tomorrow's smart cities, enabling adaptive, self-learning mobility systems that simultaneously optimise economic, social and environmental objectives.

Automation through ANPR has demonstrably reduced reliance on manual inspections, optimised the strategic deployment of enforcement personnel, and minimised the potential for human error, confirming ANPR's operational efficiency gains associated with intelligent technology corroborating the operational efficiency gains (Kalus, 2025; Pizorska, 2025).

Importantly, the strategic embedding of artificial intelligence (AI) within these systems elevates their strategic value for intelligent urban mobility governance. AI-driven analytics enable real-time anomaly detection— identifying patterns such as repeated overstays or fraudulent transactions—and provide sophisticated forecast future parking demand. This predictive capability, a cornerstone of

intelligent management, directly informs dynamic pricing adjustments and optimised enforcement strategies.). Furthermore, AI-powered revenue-forecasting tools support more accurate municipal budgeting and resource allocation, underpinning a crucial shift towards proactive, rather than reactive, urban mobility governance (Urbaniak, 2023; Gadziński & Goras, 2019

From a policy perspective, our findings underscore the necessity of a holistic, technology-supported approach to PPZ design, emphasizing the principles of intelligent urban planning. Municipalities should strategically:

- Calibrate fee structures against local wage levels to achieve a balance between affordability for residents and effective deterrence of unnecessary private vehicle use, informed by intelligent economic analysis;
- Align enforcement hours with observed demand patterns, strategically extending coverage in high-use zones, to optimise traffic flow, guided by intelligent data analytics;
- Scale ANPR deployments and integrate AI-based machine-learning models to continuously refine pricing algorithms and optimise patrol frequency leveraging the power of intelligent automation;
- Ensure rigorous GDPR-compliance in all data handling processes to maintain public trust and ethical standards in the deployment of intelligent surveillance technologies (UODO, 2024).

While this research provides robust evidence for the benefits of ANPR and AI in PPZ management, within the context of intelligent transportation systems, it is bounded by certain limitations. Data availability varied across the studied cities, and future research should aim to incorporate the impacts of micromobility usage, subscription-based permit systems, and the integration with public transportation networks for a more comprehensive understanding of intelligent urban mobility.. Moreover, as Clean Transport Zones (CTZ) roll out in Warsaw and Kraków, longitudinal studies will be crucial to assess their interaction with existing PPZs and their broader impact on urban sustainability outcomes within an integrated intelligent mobility framework

Ultimately, the strategic embedding of AI within paid parking systems holds the transformative promise not only enhancing operational efficiencies but also driving a fundamental shift towards genuinely data-driven governance in urban mobility, paving the way for intelligent and sustainable cities (Bibri & Krogstie, 2017).

However, the integration of AI with ANPR systems fundamentally transforms the decision-making process in urban traffic management from a reactive approach, often based on generalised statistics, to a proactive one grounded in in-depth, real-time data analysis —the essence of intelligent management. This enables municipal authorities to make more effective, informed, and strategic decisions regarding Urban Transport Policies, leading to improved traffic flow, enhanced safety, the promotion of sustainable mobility options, and ultimately – an improved quality of life within the urban environment. Nevertheless, fully translating this potential into concrete results necessitates further interdisciplinary research, a detailed analysis of ethical and technological implications (Drogowa-Pomoc.pl, n.d.) and the development of strategic implementation plans that account for the specific needs and characteristics of individual urban centres (Tumielewicz, R., n.d.), within a holistic vision of intelligent urban development.

The ongoing advancement of AI presents novel and exciting prospects for cities in the critical domain of urban infrastructure management. In the foreseeable future, an augmented and increasingly sophisticated role for artificial intelligence in transportation and public services is anticipated. The strategic introduction of AI into traffic management systems constitutes a pivotal step towards the realization of truly intelligent and sustainable urban centres, powerfully demonstrating the potential of contemporary technologies to enhance quality of life for urban dwellers and effectively address complex urbanistic challenges (AI o AI, 2024).

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THE CONCEPT FOR IMPLEMENTING METHOD OF MULTIDIMENSIONAL COMPARATIVE ANALYSIS FOR ASSESSING ELECTROMOBILITY IN SMART CITIES IN POLAND

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ABSTRACT

Purpose: *The aim of this study is to develop a concept for implementing the multidimensional comparative analysis method in the assessment of electromobility in smart cities in Poland. Electromobility, as one of the key elements of sustainable urban development and intelligent management, has gained increasing importance in recent years. However, its implementation in the Polish context requires a comprehensive multi-faceted analysis.*

Need for the study: *The choice of research topic was determined by its relevance. Previous analyses and published studies have focused primarily on issues related to sustainable development, urban mobility, or electromobility. However, theoretical gaps have been identified in the literature concerning a holistic approach—particularly in terms of comparing electromobility within smart cities.*

Methodology: *The research methodology is based on applying the multidimensional comparative analysis method to compare smart cities that have implemented electromobility development strategies. The analysis includes collecting both quantitative and qualitative data, such as the number of charging stations, the number of registered electric vehicles, and surveys of residents and local authorities. Statistical techniques and multidimensional methods will be used to create a comprehensive assessment model, which will serve as a foundation for future actions in the development of electromobility in Polish smart cities.*

Findings: *The research hypothesis assumes that the use of multidimensional comparative analysis method enables a reliable, objective, and multidimensional assessment of the current state and development prospects of electromobility in Polish cities, taking into account various criteria such as charging infrastructure, availability of electric vehicles, urban policies, and social attitudes.*

Practical Implications: *The conducted analysis may provide cities and their local authorities with a ready-made solution for assessing electromobility in smart cities, in the form of a key set of indicators accompanied by the desired direction of their development. Moreover, the study includes a ranking-based assessment of the potential for electromobility development in smart cities in Poland, along with an analysis of the factors contributing to the respective positions within the ranking.*

Keywords: Sustainable development; Electromobility; Smart cities; Multidimensional comparative analysis method; Management

Jel codes: Q01; R41; O18; C38; C43; M10; O32

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1. INTRODUCTION

Electromobility is increasingly recognized as a key element of smart city management strategies. Intelligent transportation management is an approach that utilizes modern technologies, data, and innovative management systems to improve the efficiency, safety, and sustainability of urban transportation. Actions and investments in this field not only contribute to reducing carbon dioxide emissions but also pave the way for the creation of innovative solutions related to mobility, energy efficiency, public services, infrastructure, urban systems, and promoting behavioral changes among residents towards more sustainable practices.

The ongoing initiatives and investments in this area have the potential not only to reduce emissions but also to support other aspects of smart city development, such as innovative solutions in mobility, energy efficiency, public services, residential and commercial infrastructure, as well as broader urban systems. The research methodology is based on the application of the multidimensional comparative analysis method to assess smart cities in Poland in terms of their electromobility development. The aim of this paper is to analyze which smart city indicators are essential for evaluating the development of electromobility and to assess the progress of smart Polish cities over the past years using the multidimensional comparative analysis method.

The application of the multidimensional comparative analysis method allows for a reliable, objective, and multidimensional assessment of the current state and development prospects of electromobility in Polish smart cities.

The following research thesis accompany the implementation of the objectives:

H1: the use multidimensional comparative analysis method enables a reliable, objective, and multidimensional assessment of the current state and development prospects of electromobility in Polish cities, taking into account various criteria.

H2: the development of electromobility is an important element of the implementation of the smart city concept in cities.

The collected research material will enable the development of a comprehensive concept presenting a holistic approach to the development of electromobility in smart cities. This concept will include a list of key sustainable development indicators, along with a ranking of cities accompanied by assessments and future recommendations for improvements.

2. LITERATURE REVIEW

2.1. Electromobility as part of the smart city strategy

Electromobility encompasses the integration of innovative transportation technologies powered by electricity, aimed at reducing carbon dioxide emissions, promoting sustainable development in cities, and striving for a smart future. Although its definition is not entirely consistent, two main approaches can be distinguished: narrow and broad. According to the definition by Grauers et al. (Grauers et al., 2013, p. 10-21), electromobility refers to a road transport system based on vehicles powered by electricity. These vehicles can generate energy on their own or draw it from external sources, typically from the power grid. Mataczyński (Mataczyński, 2018, p. 77) describes electromobility as transportation using electric wheeled vehicles that store energy in battery packs. Janczewski (Janczewski, 2017) defines electromobility as the concept of replacing traditional fossil fuel-powered vehicles with environmentally friendly, zero-emission electric cars, while Schuler (Schuler, 2019) refers to it as the development of vehicles powered by electricity, using batteries or fuel cells for propulsion.

Additionally, Bartłomiejczyk and Kołacz (Bartłomiejczyk and Kołacz, 2020, p. 22), Połom (Połom, 2021, p. 7), and Fernández (Fernández, 2021, p. 21) emphasize that the growing presence of electric vehicles is a sign of the development of electromobility and smart cities. However, smart cities encompass much more than just electric vehicles or individual transport. They include issues such as the use of alternative fuels, hybrid technologies, hydrogen and CNG vehicles, public transport systems, and heavy-duty vehicles. Electromobility is increasingly recognized as a key element of smart city strategies. Actions and investments in this area not only contribute to the reduction of carbon dioxide emissions but also pave the way for the creation of innovative solutions related to mobility, energy

efficiency, public services, infrastructure, urban systems, and promoting the shift toward more sustainable practices among residents.

The development of electromobility can be defined as the process of introducing, adapting, and widespread adoption of electric vehicle technologies and the associated infrastructure, aiming to meet transportation needs while minimizing the negative impact on the environment. In a broader context, the development of electromobility includes the following elements: the increase in the number of electric vehicles, charging infrastructure, sustainable energy development, changes in the transportation system, social and economic transformations, technological advancements, environmental protection, and emission reduction.

In a broader sense, electromobility (Politt, 2020) is a comprehensive process that encompasses the implementation of electricity-based technologies in transport, as well as the development of the appropriate supporting infrastructure and systems. In this context, electromobility refers not only to electric vehicles but also to the entire structure supporting their use, including charging stations, smart energy grids, energy storage systems, and interactions with traffic and transport intelligent management systems. The context of the article considers elements related to the holistic approach to electromobility (broad approach in the literature) and its connection to smart cities.

Electromobility is one of the key elements of smart city development strategies. Current initiatives and investments in this area have the potential not only to reduce emissions but also to support other aspects of smart city development, such as innovative solutions in mobility, energy efficiency, public services, housing and commercial infrastructure, as well as broader urban systems. Moreover, they influence citizen engagement and the shaping of new social attitudes and behaviors (https://smart-cities-marketplace.ec.europa.eu/action-clusters-and-initiatives/action-clusters/sustainable-urban-mobility/electric-vehicles-smart).

2.2. Intelligent management in smart cities

Smart city intelligent management means the implementation of modern technologies and solutions aimed at improving the quality of life of residents, effective resource management and sustainable development. To help select and assess which cities around the world have the characteristics and potential to be considered smart cities, the IESE Cities on the Move Index (https://www.iese.edu/media/research/pdfs/ST-0649-E) was created. This index evaluates cities according to nine key categories: human capital, social cohesion, economy, governance, environment, mobility and transport, urban planning, international profile and technology. All indicators are interconnected and are aligned with the strategic goal of supporting economic and social development and smart governance, leading to the creation of a global city that promotes entrepreneurship, innovation and social justice. In addition to technological and economic development, citizens and their involvement are key to transforming cities into smart cities.

Many Polish cities are taking steps towards becoming smart cities by utilizing information, tools of intelligent management and communication technologies (ICT) in managing infrastructure, transport, energy, and environmental protection. Among the cities in Poland that can be considered smart cities are: Warsaw, Wrocław, Kraków, Gdynia, Gdańsk, Białystok, Rzeszów, Kielce, Poznań, and Szczecin (https://almine.pl/smart_city_przyklady_polska/?utm_source=chatgpt.com). Smart cities face two main challenges in the field of electromobility: ensuring efficient mobility, often over large areas, and achieving sustainable urban mobility. Therefore, the transport and environmental indicators from the IESE Cities in Motion Index were considered in the analysis.

Table 1 contains a list of the indicators used for this category, along with descriptions of each and the sources from which they were derived.

Table 1. Indicators for assessing electromobility in smart cities

Indicator	Description	Source
Bicycle, moped or scooter rental service	Whether or not the city has a bicycle, moped or scooter rental service.	NUMO
Bike sharing	Number of shared bicycles in the city.	Bike-Sharing World Map
Metro stations	Number of metro stations in the city.	Metrobits

Traffic Inefficiency Index	This index estimates traffic inefficiencies. High values represent high driving inefficiencies, such as long travel times.	Numbeo
Traffic and congestion index	Index of traffic and congestion in the city.	Numbeo
Exponential traffic index	This index is estimated by considering time spent in traffic. It is assumed that travel time dissatisfaction increases exponentially beyond 25 minutes.	Numbeo
Metro lines	Number of metro lines in the city Metrobits	Metrobits
Length of metro system	Length of the metro system in the city.	Metrobits
Percentage of households with bicycles	Percentage of households with bicycles.	Euromonitor
High-speed train	Binary variable that shows whether the city has a high-speed train or not.	OpenRailwayMap
Vehicles in the city	Number of commercial vehicles in the city.	Euromonitor
Flights	Number of inbound flights (air routes) in a city.	OpenFlight
CO_2 emissions	Carbon dioxide emissions from fossil fuel use and cement production. Measured in kilotons	World Bank
Methane emissions	Methane emissions caused by human activities such as agriculture and industrial methane production. Measured in kilotons of CO_2 equivalent	World Bank
Environmental Performance	Index Environmental Performance Index (from 1 [poor] to 100 [good]).	Yale University
Emission Index	Index of carbon dioxide emissions	Numbeo
Pollution Index	Index of pollution	Numbeo
PM10	A measure of particles in the air with a diameter of less than 10 μm. Annual mean. IQAir	Global Residence Index
PM2.5	A measure of particles in the air with a diameter of less than 2.5 μm. Annual mean. IQAir	IQAir
Percentage of population with access to water supply	Percentage of the population with reasonable access to an appropriate quantity of water resulting from an improvement in the supply.	World Bank
Renewable water resources	Renewable water resources per capita.	FAO
Solid waste	Average amount of municipal solid waste generated annually per person (kg/year)	Waste Management for Everyone
Climate vulnerability	Risk to the city due to climate change	National Geographic

Source: own elaboration.

Other important indicators include PM2.5 and PM10, fine particulate matter suspended in the air, containing substances such as dust, soot, heavy metals, cement, and pollen. PM2.5 particles have a diameter of 2.5 microns or smaller, while PM10 particles have a diameter of up to 10 microns. The composition of these particles includes inorganic elements such as silicates and aluminates, as well as organic and carbon compounds. These indicators are included in the environmental pollution assessment and in indices that classify cities based on air quality, assigned with a negative sign.

The Environmental Performance Index (EPI), developed by Yale University, is based on the assessment of two main areas: environmental health and ecosystem vitality. Environmental health includes the impact of air pollution on human health, water quality, and environment-related diseases. Ecosystem vitality considers aspects such as air quality, biodiversity, the state of forests, fisheries, agriculture, and climate change.

Water is a key renewable resource vital for combating the effects of climate change. The indicator for total renewable water resources per capita takes into account both internal and external surface water resources, reflecting water availability for a given country and its ability to ensure sustainable development. Therefore, this indicator is included in the index with a positive sign.

The climate change vulnerability indicator assesses cities' sensitivity to climate change by the year 2070, assuming the continuation of current CO_2 emission levels. It includes predicted changes in temperatures across different seasons, which may have serious consequences for public health and economic stability. This indicator is included in the index with a negative sign.

Waste management issues are also significant. The amount of municipal waste produced annually per person (kg/year) poses a potential threat to public health and the environment. Improper waste management increases the risk for those working in waste collection and processing, which is why this indicator is included with a negative sign.

The availability of bike, electric scooter, and e-scooter rental services reflects the level of micromobility in the city. If such a system is operational, the indicator takes a value of 1; otherwise, it is 0.

Indicators such as commute time, traffic intensity, and transportation inefficiency relate to transportation issues that affect residents' quality of life and comfort. They also reflect road safety and the efficiency of public transport. A well-organized and efficient public transport system helps reduce accidents and traffic congestion. Due to the negative impact of these factors on urban development, these indicators are included in the CIMI with a negative sign.

Developed bicycle systems, assessed based on the urban bicycle system indicator, support daily mobility within the city and are positively considered in the CIMI.

Additionally, the number of metro stations, the length of the network, and the number of lines reflect the city's investments in public transportation. These indicators, like the number of flight routes and the availability of high-speed trains, indicate the level of development of transportation infrastructure, which positively affects the sustainable development of cities.

Finally, the number of vehicles and the percentage of households owning bicycles are indicators that have an inverse impact on the index. The bicycle ownership indicator has a positive impact, whereas the number of vehicles is considered with a negative sign.

3. METHODOLOGY

Methods of multidimensional comparative analysis allow for comprehensive studies on complex phenomena, enabling broad and objective understanding of them. In Poland, Hellwig was the first to attempt to describe complex phenomena using a synthetic feature (Hellwig, 1968, p. 307-327). A key aspect when creating a ranking based on the level of a complex phenomenon is the selection of an appropriate ordering method. The goal of linear ordering is to arrange a set of objects by determining their order according to a specific criterion. These methods are used in situations where a specific criterion can be adopted, allowing for the ranking of objects. The tool used in linear ordering is an aggregation function, which combines the partial information contained in individual variables and is calculated for each object. At the beginning of the analysis, the nature of each included variable must be determined. It is important to establish whether high values of a given variable have a positive significance for the phenomenon being analyzed (in which case they are called stimulants), or if lower values are more beneficial (in which case the variable is called a destimulant).

Methods and main formulas for normalization have been presented by authors such as Borys (Borys, 1978, p. 227-239),Grabiński (Grabiński, 1984, p. 45-48), and Abrahamowicz (Abrahamowicz, 1985, p. 54-58). In particular, Abrahamowicz emphasizes the need to link the choice of normalization formula with the selection of the appropriate aggregation method. According to studies described in the literature, two methods have the best formal properties: classical standardization and unitarization. In the unitarization method, the distance between a given value and the observed "worst" value is divided by the range. Importantly, this method also satisfies the non-negativity requirement, which is recommended by some researchers. The normalization process is carried out according to the appropriate formulas.

For stimulants:

$$x'ij = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}}$$

For destimulants::

$$x'ij = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}}$$

Where:

- i - object number
- j – characteristic number
- $\max\{x_{ij}\}$ and $\min\{x_{ij}\}$ are sought in the set of objects for the given characteristic.

In this work, an aggregate measure is used, which involves calculating the arithmetic mean of the transformed diagnostic variables. These variables were made comparable through the process of unitarization, and then the average value was expressed on a scale ranging from 0 to 100. The formula for the aggregate measure is as follows:

$$W_i = \frac{100}{m}\sum_{j=1}^{m} \alpha_i \cdot x'_{ij}$$

Where:

- m- the number of features (criteria) considered
- α_i – the weight of the i-th feature (criterion)

The table 2 presents a structured set of indicators for assessing electromobility in smart cities. Each indicator is classified based on whether it acts as a stimulant or a destimulant, along with the corresponding weight obtained. This classification provides a comprehensive framework for assessing the relative importance of each indicator in the context of the development of electromobility in smart cities.

Table 2. Indicators for assessing electromobility in smart cities

Indicator	Stimulant	Destimulant	Weight
Bicycle, moped or scooter rental service	x		4
Bike sharing	x		4
Metro stations	x		4
Traffic Inefficiency Index		x	5
Traffic and congestion index		x	5
Exponential traffic index		x	5
Metro lines	x		3
Length of metro system	x		3
Percentage of households with bicycles	x		3
High-speed train	x		4
Vehicles in the city		x	5
Flights		x	3
Methane emissions		x	2
Environmental Performance	x		4
CO_2 emissions		x	4
Pollution Index		x	5
PM10	x		5
PM2.5	x		5
Percentage of population with access to water supply	x		3

Renewable water resources	x		2
Solid waste		x	2
Climate vulnerability	x	x	3

Source: own elaboration.

Renewable water resources constitute a crucial element of sustainable urban development. The availability of drinking water and energy generated by water (e.g., hydropower) can facilitate the development of technologies that support electromobility, such as photovoltaic panels, wind farms, and hydropower plants. In cities utilizing renewable energy sources, it is possible to power electric vehicles with clean energy, contributing to CO_2 emission reduction and promoting sustainable transportation.

The use of renewable water resources in urban energy systems contributes to sustainable development and, consequently, may support electromobility as an integral part of urban transportation systems.

In cities effectively managing waste, for example, through recycling, material reuse, and waste minimization, waste can be utilized for energy production, which fosters the development of zero-emission technologies. Improved waste management also influences the use of secondary raw materials that can be employed in the production of electric vehicles, including batteries. Efficient resource management within cities supports the advancement of sustainable technologies, including electromobility, as a component of comprehensive urban policy.

The development of public transportation, including the number of metro lines, is one of the key elements of smart cities. Metro systems provide an efficient form of public transport that reduces road congestion, lowers exhaust emissions, and promotes sustainable mobility. In cities with well-developed metro systems, dependence on combustion vehicles is reduced, which favors the promotion of alternative, eco-friendly transportation modes, such as electric vehicles. Additionally, in cities with a well-established public transportation network, electric vehicles can complement the system, for example, in the form of electric buses or taxis. Therefore, the development of public transportation in the form of metro systems supports electromobility by improving air quality and reducing traffic congestion.

Cities with a high Environmental Performance Index (EPI) tend to invest more in environmentally friendly technologies, including electromobility. Good environmental practices promote the implementation of electric transport solutions that are more sustainable. High levels of air pollution (e.g., PM10, PM2.5) can motivate the development of electromobility. In cities with severe air pollution, the introduction of electric vehicles becomes a key solution for improving air quality. Electromobility contributes to the reduction of exhaust emissions, which can help enhance air quality and decrease pollution.

High municipal waste production can indicate inefficient resource management within a city. In cities where waste is not properly segregated, recycling is limited, and material reuse is insufficient, this can lead to greater consumption of natural resources, including those essential for the production of electric vehicles, such as batteries. Moreover, waste management that does not consider recycling can lead to increased energy and fossil fuel consumption, ultimately diminishing the benefits of electromobility development. In cities with high per capita waste production, effective implementation of electromobility-related technologies may be hindered by insufficient infrastructure for sustainable resource management.

High climate change risks, such as floods, droughts, heatwaves, and rising sea levels, can present significant challenges to the development of electromobility. Cities that must address climate change impacts often need to redirect resources toward adaptation measures, which can delay or limit investments in electromobility-related technologies. Additionally, climate change can lead to energy instability, affecting the availability of power for charging electric vehicles. For example, cities prone to frequent flooding may face challenges in developing electric vehicle charging infrastructure. Furthermore, climate change may affect the generation of renewable energy sources, such as solar and wind power, which are critical for powering electric vehicles.

An increase in the number of commercial vehicles within a city can intensify traffic congestion and exhaust emissions, potentially hindering the growth of electromobility. A greater number of combustion

vehicles increases demand for fossil fuels and may discourage investments in electric vehicle charging infrastructure, as the transportation system remains dominated by internal combustion engines.

A high number of airplane arrivals indicates significant air traffic, resulting in high greenhouse gas emissions. Although air transportation and electric transportation are distinct sectors, high emissions from aviation can negatively impact urban sustainability and hinder the ability to implement low-emission technologies such as electromobility.

A higher Environmental Performance Index indicates the effectiveness of a city's efforts in environmental protection, sustainable resource management, and emission reduction. On the other hand, a high CO_2 emission index indicates a substantial amount of carbon dioxide emissions resulting from industrial activities, transportation, and other factors. In cities with high CO_2 emissions, the development of electromobility may be challenging, as it requires an increase in the number of electric vehicles to reduce greenhouse gas emissions. High emissions may also indicate a lack of pro-environmental policies, which can lead to insufficient investment in infrastructure supporting electromobility.

Indicators related to sustainable transportation, such as the availability of urban bicycles, metro systems, and environmental performance (e.g., EPI, renewable water resources), act as stimulants for the development of electromobility. Conversely, indicators related to air pollution, greenhouse gas emissions, and traffic intensity, which highlight issues with transportation efficiency, function as deterrents.

Analyzing Table 2 reveals that 10 indicator positions are considered deterrents—desired values are those decreasing in magnitude—while the remaining 12 are stimulants. The characterization of variables and their assigned ratings serve as the basis for further analysis.

4. RESULTS

The set of indicators obtained in the research became the basis for establishing rankings of smart cities in Poland in the analyzed time period - 5 years, which is considered statistically acceptable, using the linear ordering method. The prepared rankings concern the predispositions of the development of electromobility in smart cities due to the number of low-emission cars in use over the years 2019-2023. The positioning results are presented in figures 1-5.

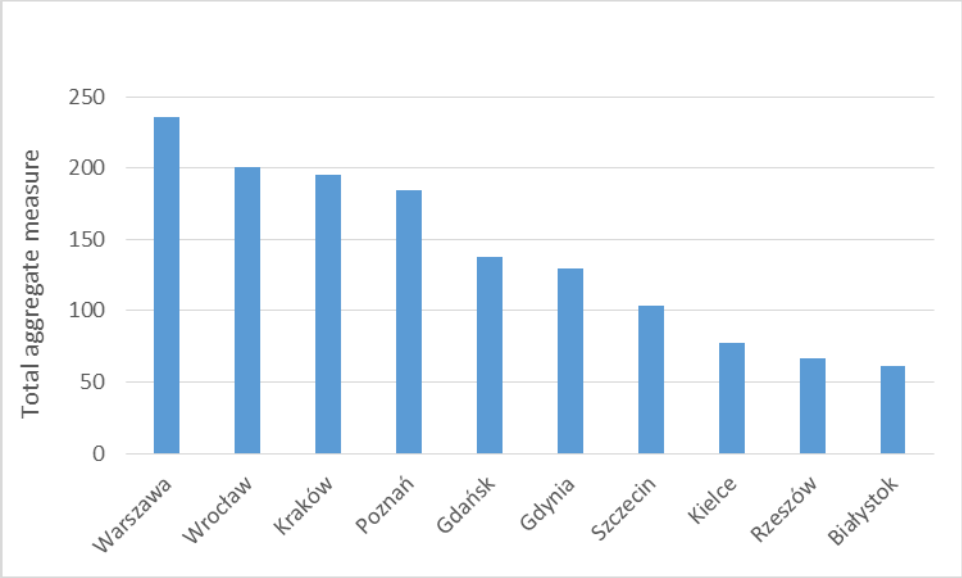


Figure 1. Predispositions for the development of electromobility - results for 2019
Source: own elaboration.

In cities such as Warsaw, Wrocław, Kraków, Poznań, and Gdańsk, we observe a significantly higher aggregate index measure. This may suggest that these cities are more advanced in terms of electromobility development.

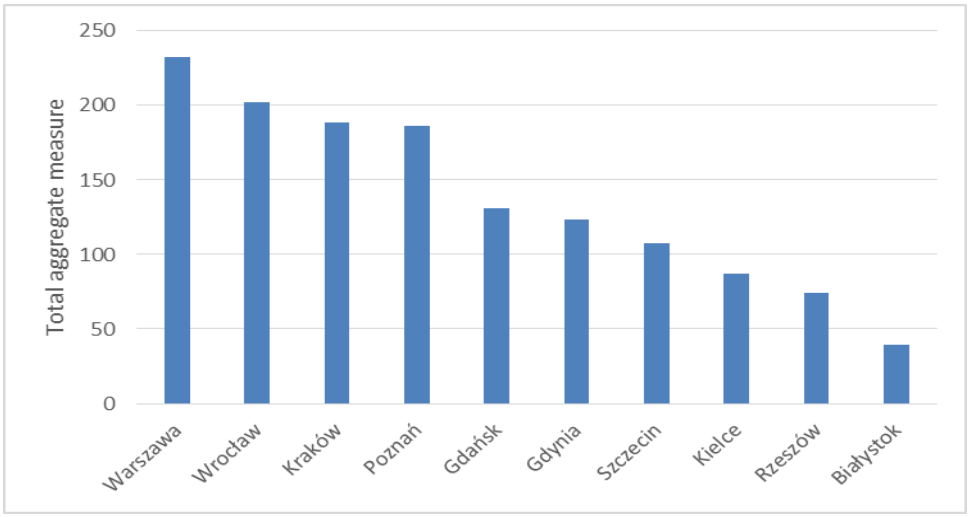


Figure 2. Predispositions for the development of electromobility - results for 2020
Source: own elaboration.

Warsaw (232.5) remains the leader, indicating that the capital is home to the largest investments and developments in electromobility. It is likely that Warsaw has the highest number of charging stations, electric vehicles, and initiatives related to electric transport and smart city projects. Wrocław (201.9), Kraków (188.7), and Poznań (186.3) also rank among the top cities, suggesting that these cities are intensively developing their infrastructure and supporting the growth of electric vehicles. In cities with larger populations and better infrastructure, such as Gdańsk (131.4) and Gdynia (123.2), electric mobility is developing steadily, although it may not yet be at the same level as in the largest cities. However, we observe a growing investment in eco-friendly infrastructure here. Szczecin (107.9) is also among the cities that may focus on the development of electric mobility, given its geographical location and the increasing pro-environmental trend. Cities such as Kielce (87.3), Rzeszów (73.9), and Białystok (39.7) are beginning to recognize the benefits of electric mobility. Although the figures in these cities are lower, the trend towards introducing electric transport solutions is still rising, and smaller cities may benefit from the development of new technologies and changing regulations that support investments in electric vehicles. Białystok (39.7), despite having a noticeably lower index, may be in the initial phase of electric mobility development. This could be due to smaller investments compared to larger cities, but over time, the number of electric vehicles and charging stations may increase.

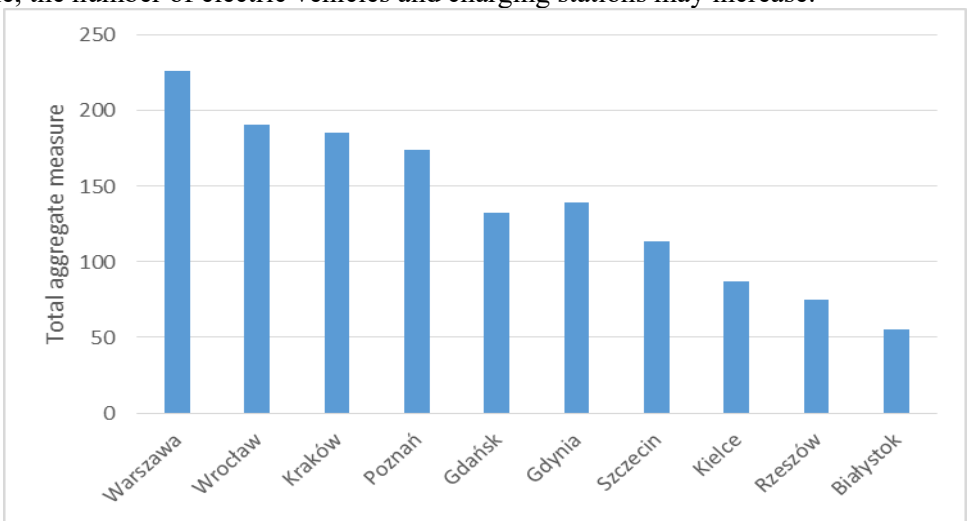


Figure 3. Predispositions for the development of electromobility - results for 2021
Source: own elaboration.

Warsaw (226.2) remains at the forefront, indicating its strong dominance in the development of electromobilty in Poland. The capital is investing in charging infrastructure, electric vehicles, and eco-friendly transport solutions. Wrocław (190.5), Kraków (185.7), and Poznań (174.2) also exhibit

significant growth in electric mobility, driven by increasing ecological awareness, improved air quality, and a growing number of investments in modern transport technologies. Cities like Gdańsk (132.3) and Gdynia (139.2) also report solid progress, showing that more urban areas have invested in electric vehicles and charging stations. Gdańsk and Gdynia benefit from their port locations, which may foster the implementation of eco-friendly transport solutions. Szczecin is seeing growth in electric mobility, but it has not yet reached the levels of larger cities like Wrocław or Kraków. This may suggest that the city is gradually introducing more charging stations and initiatives, but the development process is slower compared to larger centers. Kielce (87), Rzeszów (75), and Białystok (55) are examples of cities that are gradually introducing electric mobility solutions. While their figures are lower than those of larger cities, there is a noticeable increase in interest in eco-friendly transport solutions, which may soon result in further growth in the number of electric vehicles and charging stations.

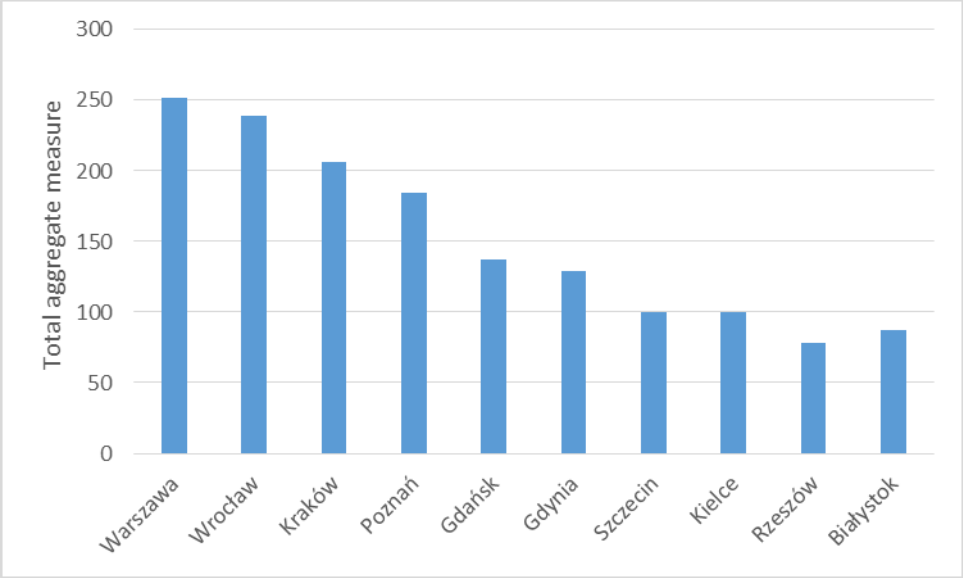


Figure 4. Predispositions for the development of electromobility - results for 2022
Source: own elaboration.

Warsaw (252.2) remains in the lead and shows a clear increase compared to previous data. This suggests that the capital continues to invest in the development of charging infrastructure, electric vehicles, and eco-friendly transport solutions. Wrocław (239), Kraków (206), and Poznań (184.2) also maintain high scores, indicating that these cities continue to advance electric mobility. The increasing demand for electric vehicles and the growing number of charging stations are key drivers in these urban centers. Gdańsk (137.3) and Gdynia (129.2) may be experiencing rapid development in electric mobility, which could be linked to their port characteristics and the growing interest in eco-friendly transport. These cities are likely investing in modern infrastructure that supports the growth of electric mobility in regions with high transport traffic. Szczecin (100.3) and Kielce (99.7) are still in the development phase, but noticeable progress in electric mobility can be observed. We can expect further growth in the number of electric vehicles and charging stations in these cities, especially as ecological awareness increases and local authorities support pro-environmental initiatives. Rzeszów (78) and Białystok (87) still show lower results compared to other cities, but their figures are gradually rising. Both cities are beginning to recognize the benefits of electric mobility and are investing in charging infrastructure and electric vehicles. The pace of electric mobility development in these cities may be slower, but it is expected to increase as it gains in popularity.

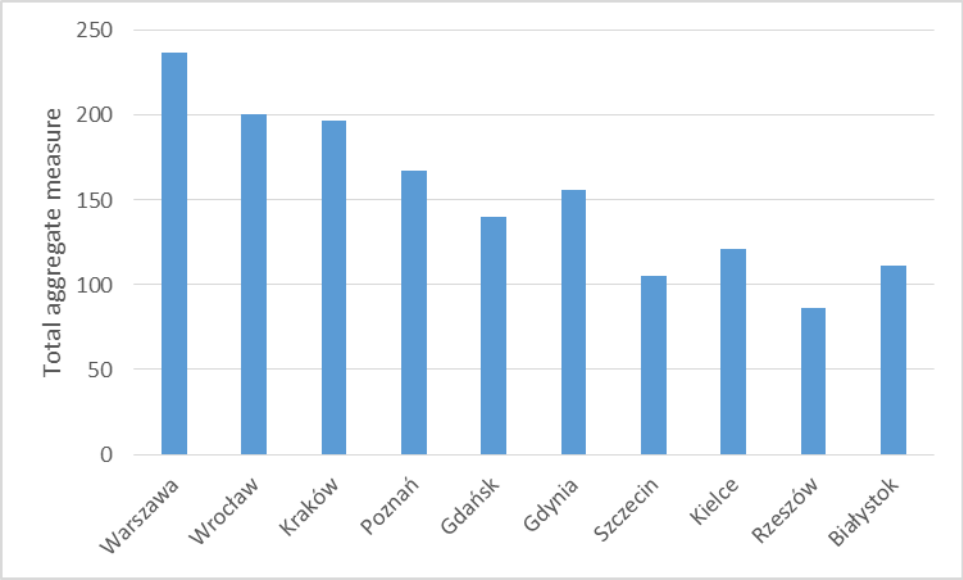


Figure 5. Predispositions for the development of electromobility - results for 2023
Source: own elaboration.

In cities such as Warsaw, Wrocław, Kraków, and Poznań, we observe a continued increase in the number of electric vehicles, driven by growing ecological awareness, pro-environmental policies, and the availability of charging infrastructure. In larger cities, the further development of the charging station network is evident. At the same time, cities like Gdańsk, Gdynia, Szczecin, Kielce, and Białystok are also beginning to invest heavily in the development of this infrastructure to increase accessibility and facilitate the use of electric vehicles for their residents.

In cities with a higher aggregate index, such as Warsaw, Wrocław and Kraków, electric vehicles are becoming increasingly common thanks to the support of local governments and their intelligent management. Emission-reducing regulations and tax incentives are being introduced, which is conducive to further development of electric mobility. Moreover, in cities with higher levels of air pollution, such as Warsaw and Kraków, electric vehicles are becoming a natural solution in the fight against smog. Local governments often implement policies to promote the development of electric mobility, such as bans on older combustion vehicles from city centers. The growth of electric mobility may also depend on the demographic and economic diversity of cities and the skills of their intelligent management. Large cities with higher per capita income, such as Warsaw and Wrocław, may have a larger population ready to invest in electric vehicles. Although larger cities such as Warsaw and Wrocław are leading the development of electric mobility, smaller and medium-sized cities such as Szczecin, Kielce, Rzeszów and Białystok are also starting to see the benefits of this technology and are intensifying their efforts to develop this sector. Gdańsk and Gdynia continue to develop electric mobility, probably due to their port features and the growing demand for sustainable, intelligent transport in the region. The development of charging infrastructure, as well as pro-ecological initiatives in these cities, make them significant players in the electromobility sector in Poland. In cities where more companies are involved in electric vehicle rental (e.g. Gdańsk and Gdynia) or where electric bikes, scooters and other forms of micromobility are offered, we observe a greater increase in electromobility. Smaller cities, such as Rzeszów or Białystok, may have lower demand for electromobility due to smaller populations and weaker infrastructure. The lower combined indicator in Białystok (compared to larger cities) may indicate a lower level of environmental awareness of residents or a lack of appropriate programs encouraging electromobility.

5. DISCUSSION

The development of electromobility is a complex process that includes the implementation of electric vehicle technology, the development of appropriate infrastructure, the transition to renewable energy sources and changes in society and governance aimed at creating a more

sustainable, intelligent transport system that contributes to environmental protection and improves the quality of life of its inhabitants. Electromobility is one of the key elements of sustainable development strategies for cities and entire regions, as well as for intelligent transport. Increasing the number of electric vehicles, expanding charging infrastructure, integrating renewable energy sources, supporting technological innovations and intelligent solutions will be crucial for the further widespread adoption of electric mobility. Electric mobility has the potential to transform transport systems worldwide, contributing to the fight against climate change, improving the quality of life and creating new economic opportunities. Its implementation enables the reduction of exhaust emissions, improves air quality and brings economic, social, governance benefits, while solving challenges related to infrastructure, costs and recycling.

6. CONCLUSION

Electromobility is a key element in the pursuit of smart cities and intelligent transport management contributing to the reduction of greenhouse gas emissions and the improvement of air quality. In the context of smart city management, the integration of technology and data enables more effective management of both public and private transport. The implementation of multi-criteria analysis allows for a comprehensive assessment of electric mobility as a key step towards becoming a smart city. The multidimensional comparative analysis method is undoubtedly an appropriate tool for assessing smart cities in Poland in terms of their development of electromobility. In future research works, the authors will focus on further examination of the level of electromobility implementation in cities in Poland, including in the structure of the work a comparison of metropolises in Europe.

Future work in this area must focus not only on solutions for individual motorization, public transport and micromobility, but also freight transport. Initial work on the assessment of electromobility in all areas is already underway. In addition, the decision criteria for the development of electromobility will be analyzed in detail, taking into account technical, economic, environmental and social aspects.

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STUDY OF EMISSIONS, ENERGY CONSUMPTION, AND OPERATING COSTS OF CITY BUS FLEET: EXPLORING THE ROLE OF AI AND TECHNOLOGICAL SOLUTIONS IN SUSTAINABLE URBAN TRANSIT.

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ABSTRACT

Purpose: *The purpose of this article is to conduct a comparative analysis of city buses included in the public transport fleet in Szczecin, with a focus on evaluating the economic and ecological performance of conventional, hybrid, and electric vehicles.*

Need for the study: *With growing environmental concerns and the increasing need for cost-effective urban mobility solutions, there is a strong demand to identify the most sustainable and economically viable types of buses for public transport systems. This study addresses this need by assessing actual operating data across different vehicle technologies.*

Methodology: *The analysis conducted in the article covers energy consumption and associated costs (fuel or electricity, depending on the vehicle type) for each month over the span of one year. The data accounts for seasonal variations in energy demand, driven by the use of additional vehicle systems such as heating and air conditioning. The study also includes a brief theoretical consideration of how artificial intelligence systems could enhance operational efficiency of city buses.*

Findings: *Electric buses demonstrated the most favorable outcomes from both ecological and economic perspectives, while conventional diesel buses showed the least advantageous performance. Hybrid vehicles ranked between the two. The study also identified specific operational areas where the integration of AI technologies could further optimize efficiency and reduce costs.*

Practical Implications: *The results offer valuable insights for municipal decision-makers and transport operators considering the transition to more sustainable fleets. Moreover, the potential of AI-based systems to support operational improvements highlights a possible strategic direction for future development in urban public transport.*

Keywords: Urban logistics; City buses; Energy consumption; Transport; AI; Sustainable development

Jel codes: L320; L910; Q550; R400

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1. INTRODUCTION

Social costs of transportation in the form of pollution (Grazieschi et al., 2023) or noise (Muralikrishna and Manickam, 2017) are increasingly being considered on a par with internal costs such as fuel consumption (Persyn et al., 2022). This is encouraged, among other things, by the EU's transport policy ("Clean and sustainable mobility," 2023) which is based on the assumption of achieving climate neutrality by the Member States. The most important document speaking on this matter is the European Green Deal presented by the European Commission in December 2019 (Communication From The Commission to The European Parliament, The European Council: European Economic and Social Committee and The Committee of The Regions - The European Green Deal, 2019), which sets the year 2050 as the date for achieving climate neutrality in Europe. At the same time, it assumes a net reduction in greenhouse gas emissions of at least 55% compared to 1990 by 2030. According to Eurostat data ("Statistics | Eurostat," n.d.), in the period 2010 to 2023, cumulative greenhouse gas emissions [Greenhouse gases (CO2, N2O in CO2 equivalent, CH4 in CO2 equivalent, HFC in CO2 equivalent, PFC in CO2 equivalent, SF6 in CO2 equivalent, NF3 in CO2 equivalent)] by the transport sector (category: Transportation and storage) fell by only ≈0.06% from 2010 to 2023. Despite the fact that transport in the first quarter of 2023 accounted for only ≈10% of total European greenhouse gas emissions, it is the only sector of the economy where progress in reduction is so insignificant. The above obliges to carry out intensifying actions aimed at reducing emissions in the transport sector, otherwise, with maintaining the current trend, it will not be possible to achieve the goals of the climate policy adopted by the EU. According to Eurostat data ("Statistics | Eurostat," n.d.), in 2010, Poland was responsible for approximately 10% of air pollutants and greenhouse gases (expressed as CO2 equivalent) of the total value for 27 EU member states. By 2021, Poland's percentage share in this category had already risen to 12%. It should be mentioned here that the above may be the result of many things, such as the fact that Polish transport companies are responsible (as of 2022) for approximately 26% of the total intra-EU road freight transport (255,798 thousand tons of goods compared to a total of 976,436 thousand tons of goods for 27 EU member states) ("Statistics | Eurostat," n.d.). However, the role of Polish transport companies in reducing total EU emissions is indisputable. Taking this into account, it was decided to conduct research and analysis on the example of this country.

One of the basic actions taken to achieve climate neutrality is to eliminate the acquisition of energy from non-renewable sources (like mining) in favor of renewable energy sources such as wind or solar energy. Two sectors of the economy seem to be the most important in this respect, namely: energy production and transport (McPherson et al., 2023; Upham et al., 2023; Zhang et al., 2024). In 2020, road transport was responsible for 78.4% of global CO2 emissions (Santos and Smith, 2023). Therefore, during the conducted research, it was decided to focus on this branch of transport. At the same time, due to the possibility of applying the conducted research and analysis in practice, it was decided to narrow the field of research to urban passenger transport and the replacement of current means of transport with electric vehicles. Electric buses are becoming an increasingly large percentage of the urban public transportation fleet in many cities. Based on the state of urban transportation in Poland, a drastic change in their quantity can be observed among the bus fleets of transport companies. In 2016, among newly purchased buses, those with electric drive accounted for 1%, while in 2021: 37% of newly purchased vehicles (Jagiełło et al., 2023), which emphasizes how significant electric buses have become in recent years. Given the sustainable development goals promoted by the European Union and the economic and ecological factors (Souza and Dantas, 2020), it can be stated that the number of electric buses used in public urban transportation will increase year by year. When conducting research and analysis on changes in the transport fleet, the differences between corresponding technological solutions are a necessary and often overlooked issue. Examples of such differences are presented in the next section and are included in the final summary and conclusions. A large part of the available publications (Dębowski et al., 2021; Sparber et al., 2023; Teoh et al., 2018) focuses on the transfer of telemetry and costs for individual specific cases of replacing conventional transport solutions with a modern electric vehicle in order to possibly further extrapolate the obtained data. This approach has the advantage of being able to focus on many elements related to one specific case, but the disadvantage is the method of extrapolating the results that does not take into account variables resulting from the operation of the entire fleet of vehicles (in particular, the accumulation of problems assuming a domino effect). It was therefore decided not to focus on an extensive description of one case, but rather

to specify and average the authentic results of the entire fleet of vehicles in terms of energy demand and the resulting average operating cost and its change depending on the influence of the seasons. Such results can be used for a comparative assessment of the results obtained thanks to extrapolation models. After obtaining the final values and conducting field research, it was also possible to indicate areas of the company's and transport fleet's operation where the use of artificial intelligence-based solutions would increase the efficiency of the entire transport system.

2. LITERATURE REVIEW

For the purposes of the classic basic literature review, the Scopus database was used to select relevant publications. The basic keyword was “bus” in combination with “electric”, then the search was limited to the keywords: “buses”, “costs”, “electric bus”, “bus systems”, “energy efficiency”, “hybrid vehicles” and “electric power utilization”. After defining the basic search, 10,666 results were obtained. The search was then narrowed by limiting the results to: Article, Conference paper and final version in English, which reduced the results to 9,557. It was limited to articles from 2020 (3,543 results), then the subject area was limited to: “Energy”, “Environmental Science”, “Social Sciences”, “Business, Management and Accounting”, “Economics, Econometrics and Finance” and “Multidisciplinary” (2,176 results). At the above stage, the articles were assessed. First, after evaluating the titles and keywords, 2094 items were eliminated, then the abstracts were analyzed, which led to the elimination of another 44 papers and leaving 38 for analysis of the possibility of accessing the content and reviewing the full texts. Finally, 18 papers were selected for the literature review presented in Table 1.

Table 1. Literature review of electric bus exploitation costs in current studies

No.	References	Approach	Description	Average Cost per km
1	(McCluskey et al., 2025)	Model, Literature review	The article examines the economic aspects of introducing electric buses in the UK. The authors point out that the total cost of electric buses is generally similar to diesel buses. An important argument in the discussion is the size of the batteries, which are often smaller than would be justified, due to the lower cost of the initial purchase.	EV - £1.739 Diesel - £1.744
2	(Moradi et al., 2024)	Model	The article presents a study on the optimization of charging infrastructure and strategies for an electrified public transport system. Dynamic programming (DP) was used to optimize costs, battery degradation and system efficiency. In addition to standard elements (such as route length, number of trips, etc.), the model used assumes, among others, battery wear and the forecasted number of years of operation of the vehicle charging infrastructure. The obtained result shows that with good optimization, the possible reduction of the total cost is 35%.	n.d.
3	(Wagner and Walther, 2024)	Model, Case Study	The analysis was carried out on the example of a bus network in Northern Italy with a diverse terrain (urban/rural and mountain routes). The authors indicate that the combination of BEB and FCEB bus technologies in mixed fleets can meet various operational needs. The above combination will be most profitable when the purchase cost of FCEB buses drops below 625 thousand euros. Or the price of hydrogen drops below 4.33 euros/kg.	n.d.

No.	References	Approach	Description	Average Cost per km
4	(Chamier-Gliszczynski et al., 2024)	Literature review, Mathematical analysis, Case Study	The article focuses on the process of changing from conventional city bus technologies to more advanced technological solutions in order to reduce pollutant and noise emissions generated by public transport. The paradigm shift assumes replacing combustion buses with electric, hydrogen or trolleybuses. An analysis of the costs associated with fleet replacement and infrastructure construction was conducted.	n.d.
5	(Batóg et al., 2024)	Literature review, Mathematical analysis	The article discusses the electrification of public urban transport in Poland, focusing on financing options, forecasts for the electric bus fleet and demand for electricity. The authors indicate low efficiency of the batteries used, lack of charging infrastructure and high energy demand as significant barriers in the above process.	n.d.
6	(Avenali et al., 2024)	Model, Real Options analysis	The article describes an analysis based mainly on the Real Options method to support decision-making on replacing bus fleets with more ecological technologies. The authors show that the costs per mile using their method taking into account uncertainties in the case of electric buses (BEB) can be lower than in the case of other solutions, but the differences between max. and min. are also the largest in this case.	Urban enviroment BEB – 2,63 (+/- 0,71) $/mil DF – 2,97 (+/- 0,23) $/mil CNG – 3,17 (+/- 0,16) $/mil
7	(Ginting et al., 2024)	Literature review, Life Cycle Assessment analysis	The article discusses the environmental impact of electrification of public buses in Jakarta, Indonesia, using life cycle analysis (LCA). The authors point out the short battery life and the life cycle of electric buses, which should be over 32 years for the best effect. It is indicated that BEBs have a greater environmental impact than diesel buses in Indonesia's current energy mix, which is mainly based on fossil fuels, and that changes in this area should be made.	n.d.
8	(Siddiqui et al., 2024)	Mathematical analysis (economic)	The main assumption of the article is to compare four types of buses: solar, electric, hydrogen and diesel, in terms of social, environmental, and economic costs and benefits. The authors indicate that solar buses have the highest net value (NPV per seating capacity) at the level of PKR 79.46 million (approximately EUR 260,500), which means the greatest benefits in relation to costs, while the lowest value (-PKR 5.87 million, approximately -19,242 EUR) was obtained by hydrogen buses. Electric buses in this study obtained a result of PKR 57,154, which due to the lack of need to build solar infrastructure places them as a desirable alternative to other technologies.	n.d.
9	(Kügemann and Polatidis, 2024)	Multi-criteria analysis, Case Study	In this paper, a multi-criteria analysis (MCDA) methodology including Life Cycle Sustainability Analysis (LCSA) was used to evaluate alternative fuel buses, taking into account their application in the public transport system on the island of Gotland (Sweden). Evaluations were performed on bioethanol, biodiesel, biogas, hybrid (biodiesel and biogas), battery electric and hydrogen fuel cell hybrid buses. For the presented Case study, biogas and biogas hybrid buses were the most preferred (which is related to local biogas production).	n.d.

No.	References	Approach	Description	Average Cost per km
10	(Chung and Chiou, 2024)	Mathematical analysis (economic)	The article discusses the economic aspects of city bus operations for a mixed fleet (different technological solutions operating in parallel), especially taking into account the impact of electric buses. The comparison and calculations are based on the data of entire companies. As one of the main results, it can be indicated that when the number of electric buses in the fleet reached a certain level, the operating cost decreased, which indicates the possibility of achieving savings by increasing the share of these vehicles. The authors also talk about the economies of scale and the increase in costs in the case of small operators in contrast to large ones where they were reduced.	n.d.
11	(Åslund and Pettersson-Löfstedt, 2023)	Case Study, Semi-structured interviews	The article focuses on the transition of Swedish public transport to electric buses, analyzing the positive aspects, expectations and interests of different groups involved in this process, such as public transport authorities (PTA), transport operators (PTO) and local governments. The authors present the advantages and disadvantages of electric buses in the context of the discussed case study. One of the most important conclusions is the need for cooperation between entities and their effective communication. It is indicated that Sweden has already made great progress in the electrification of rolling stock and intends to continue on this path.	n.d.
12	(Topal, 2023)	Model, Mathematical analysis	This paper focuses on the financial analysis of the use of hybrid fuel cell, electric and conventional (diesel) buses in the metrobus system in Istanbul (Turkey). It discusses the importance of these technologies for the development of sustainable urban mobility, potential implementation challenges and environmental benefits of individual solutions.	EV (BOB) – 0,31 eur/km (fuel) and 0,11 eur/km (maintance) Diesel – 0,62 eur/km (fuel) and 0,24 eur/km (maintance)
13	(Liu et al., 2023)	Model, Mathematical analysis	The article discusses the study of drivers' behavior in the context of savings in driving electric buses, the analysis was based on large data sets. The CRITIC (Criteria Importance Through Intercriteria Correlation) model was used to assess drivers' behavior. The proportion of low economic efficiency on weekends was 4.5 times higher than on weekdays, which is associated with the greater "aggressiveness" of drivers' driving on these days. A new method of constructing driving cycles for weekdays and weekends was shown, using Principal component analysis (PCA) and k-means clustering method.	n.d.

No.	References	Approach	Description	Average Cost per km
15	(Muñoz et al., 2022)	Mathematical analysis	The authors of the article compare different city bus technologies in terms of costs, energy consumption and environmental impact (Case Study: Argentina). The basic method used was the "Well-to-Tank" (WTT) analysis, where the processes related to the production, transport, and distribution of energy carriers (e.g., diesel, hydrogen, electricity) are analyzed. In the next stage, the focus is on the "Tank-to-Wheel" (TTW) analysis, where energy consumption and greenhouse gas emissions were calculated during the vehicle use stage, using different drive configurations and dynamic simulations for two driving cycles. In terms of data, historical data were adopted along with a forecast until 2030. The best results were achieved by CNGV (Compressed natural gas vehicle) vehicles.	n.d.
16	(Stec, 2021)	Literature review, Mathematical analysis (statistics)	The article assesses the economic efficiency of using low-emission and zero-emission vehicles in public transport in the Visegrad Group (V4) countries. The author devotes much attention to the issue of sustainable mobility and points out that one of the strategic goals of the EU is to reduce transport emissions. Among the analyzed vehicles, the cheapest to operate in the perspective of 15 years are electric buses, and the most expensive are hydrogen buses (due to high purchase costs). The year 2035 was indicated, in which the development of technology should reduce the costs associated with hydrogen technologies to a level that will increase their use for economic reasons..	Chechia: Diesel – 1,56 eur/km Electric – 1,51 eur/km Hybrid (electric) – 1,47 eur/km Hydrogen – 1,82 eur/km Hungary: Diesel – 1,62 eur/km Electric – 1,53 eur/km Hybrid (electric) – 1,49 eur/km Hydrogen – 1,85 eur/km Poland: Diesel – 1,65 eur/km Electric – 1,60 eur/km Hybrid (electric) – 1,53 eur/km Hydrogen – 1,85 eur/km Slovakia: Diesel – 1,57 eur/km Electric – 1,53 eur/km Hybrid (electric) – 1,48 eur/km Hydrogen – 1,82 eur/km

No.	References	Approach	Description	Average Cost per km
17	(López-Ibarra et al., 2020)	Model, Mathematical analysis	The paper focuses on the issue of transport network optimization, focusing on the total cost of ownership of the fleet, while ensuring that certain basic established values are not exceeded. For the purposes of the applied model, a Case Study of a fleet of 10 Plug-In Hybrid Electric Buses was used.	n.d.
18	(Borén, 2020)	Literature review, Case Study, Mathematical analysis	This article addresses the topic of sustainable transport, focusing on electric buses in the context of the Swedish public transport system. It discusses the costs in financial and social terms compared to other types of propulsion such as diesel or biogas. It is found that the energy efficiency of electric buses in the use phase is three times higher than that fossil fuel buses.	n.d.

Source: own elaboration.

3. METHODOLOGY

3.1. Overview of the Study Area

Firstly, when researching the change of conventional fleets to electric vehicles, it is necessary to take into account the differences between the models of electric buses in use and the solutions used in them, as well as how they affect carbon dioxide emissions or energy consumption. One of the available solutions are lithium-ion batteries, which are used by companies such as Solaris ("Urbino electric," n.d.). Unfortunately, the manufacturer does not specify exactly what type of lithium-ion batteries are used. A different approach can be seen with company Yutong, which uses lithium-ion batteries, specifically lithium-iron-phosphate cells. (U12 E-bus YUTONG, n.d.). The most common solutions (in terms of battery technology selection) used in electric vehicles are three-component lithium batteries and lithium-iron-phosphate (LFP) batteries. The first one is characterized by higher energy density, higher charge, and better performance, but this type of battery is susceptible to thermal runaway in the event of battery damage and has low resistance to high temperatures. The LFP battery, on the other hand, is cheaper, safer due to its high temperature resistance, and has a better lifespan, but it also has low energy density and charging efficiency. In addition, its performance at low temperatures is worse than that of a three-component lithium-ion battery (Liu et al., 2022; Su, 2022). In the case of LFP batteries, the advantages are much more important than the disadvantages, which is why these batteries are becoming more and more often chosen solutions in the automotive industry. (Yang et al., 2021).

One of the key factors when purchasing an electric bus for a company is choosing the appropriate battery capacity. Depending on the dimensions of the vehicle, engine power, or maximum number of passengers, the battery capacity should be selected accordingly so that the vehicle can be used in an optimal way. However, it is important to calculate or estimate the required maximum capacity, as the weight of the battery increases with its capacity, which translates into increased electricity consumption (Pielecha and Pielecha, 2020). Another significant difference between individual electric buses is their adaptation to various battery charging methods, which include: charging in depots using plug-in chargers, fast charging (e.g., via pantograph), wireless charging or replacing batteries after they are discharged. (Alamatsaz et al., 2022). It is also worth noting that some electric buses are actually low-emission vehicles, not zero-emission vehicles, due to the central heating system which is not powered by electricity, but by diesel fuel (Čulík et al., 2021). Opting for such solutions leads to greater environmental pollution than in the case of vehicles using entirely electricity, especially in winter, when the demand for heating in the bus is the highest.

3.2. Subject of the study

As a basis for the calculations and research aimed at obtaining real values of operational data for the bus fleet, the Polish city of Szczecin located in the northwestern part of the country was chosen. This city was chosen because it is the only one in Poland that has zero emission buses and at the same time

conducts continuous tests of new technological solutions, hence it was possible to obtain data on both diesel buses and hybrids or electric buses. Another argument for choosing this city to conduct the research is the fact that hybrid buses such as the Solaris Urbino 18 Hybrid (the first mass-produced hybrid bus in Europe) are used in Poland (this model) only in eight cities. Moreover, due to many years of Polish, German and Scandinavian influences, the city of Szczecin has an extensive spatial structure based on the concentric model, during many modernizations and reconstructions changing towards a star corridor model (city center with a complex of squares in various shapes and radially intersecting streets) often found in the case of European agglomerations of strategic or commercial importance. The terrain is lowland, hilly with a large number of elevations and the Odra River flows through the center of the city. The average temperatures are shown in Figure 1 in the section showing the condensed results of annual energy consumption measurements of the tested vehicles. The city has one main urban transport administrator, which is a separate organizational unit of the Municipal Office. The above-mentioned budgetary unit was established in 2002 and is called the „Road and Urban Transport Administration in Szczecin (pol. Zarząd Dróg i Transportu Miejskiego w Szczecinie)". The Road and Urban Transport Administration in Szczecin is responsible for planning and organizing public transport in Szczecin and neighboring municipalities, while the transport process itself is the responsibility of dependent entities in the form of operators serving a given type of transport. The data obtained and the research carried out were conducted at one of the above operators, which has the highest qualifications in the subject of this research, the company „Szczecińskie Przedsiębiorstwo Autobusowe "Klonowica" Spółka z o.o." (SPAK). The company has been operating since 1999, providing passenger bus transport services in the area mentioned above. The company uses vehicles from Man and Solaris, with 14 electric buses from the latter manufacturer in its fleet. Their electric bus fleet includes vehicles with a length of 12 and 18 meters, which, depending on the model, use batteries (Solaris High Power) with a capacity of 60 or 90 kW. Most often, two 60 kW batteries are used per bus, which allows them to be charged simultaneously using the available 120 kWh charging stations (plug-in) built in the city, at the end stops and bus depots. ("Sześć nowych elektrobusów już w Szczecinie," n.d.). The design of the units also allows for charging buses using a pantograph using the wires of the existing extensive tram network in the city. With an average (defined for the purposes of this study) route length of approximately 15 km (full route, in both directions), assuming increased road traffic, a bus with two 60 kW batteries is able to make 4 trips until the battery is discharged. During practical tests, a driving format assuming 3 trips per 1 charge was estimated and started to be used. The company purchases several electric buses annually with the aim of a complete fleet replacement. The number of units purchased depends on the amount of funding under local government, national and EU programs aimed at reducing transport pollution. The buses currently in use were co-financed, among others, by the „GEPARD - Zero-emission public transport (eng. CHEETAH - Emission-free public transport)" program ("GEPARD - Bezemisyjny transport publiczny - Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej - Portal Gov.pl," n.d.) as well as from the funds of the National Fund for Environmental Protection and Water Management under the priority program „Green public transport" ("Autobusy elektryczne dla Szczecina. Miasto otrzyma ponad 6 mln zł dotacji z NFOŚiGW na rozwój elektromobilności - Agencja Restrukturyzacji i Modernizacji Rolnictwa - Portal Gov.pl," n.d.). Current and future investments focus on the use of funds from the "Green Public Transport" program, however, the amount of funding has been reduced in recent years, which, with the current settlement, only allowed for the purchase of 2 of planned 8 new vehicles. According to tender data, the new vehicles will be low-floor and air-conditioned, adapted to the needs of people with physical disabilities, buses with a power of 145 kW (category M3 - BEV: Battery Electric Vehicle). Both vehicles are designed to accommodate at least 120 passengers (minimum 35 seated). It should be noted that Szczecin, as the only city in Poland, has a fleet of fully emission-free electric buses in which both heating and air conditioning are battery-powered. This should be taken into account when making comparisons, as the difference in energy efficiency and power consumption of individual vehicle models can often result from an incorrect combination of unsuitable variants, which is difficult to verify when using literary sources.

3.3. Research Methodology

The emission and energy consumption studies were conducted based on data (telematics data and actual operating costs available to the operator) obtained in cooperation with and from the urban public transport operator in Szczecin - SPA Klonowica. Table 2 shows the fleet of vehicles owned by the

company and key information about these vehicles that directly affect carbon dioxide emissions and energy consumption of buses. It is noteworthy that the average age of the vehicles in the fleet is provided. A noticeable change in the company's approach to ecological solutions can be observed, as it initially decided to purchase low-emission vehicles and later switched to zero-emission buses.

Table 2. The status of SPA Klonowica's bus fleet as of 24.02.2025 (Spak.pl, 2025; Mkm.szczecin.pl, 2019; Solarisbus.com; n.d.)

Vehicle type	Engine type	Engine power	Dimensions (length x width)	Maximum number of passengers (including seats)	Number of vehicles in the company's fleet	Average age of vehicles
MAN A21	Diesel	235 kW (320 KM)	11,95m x 2,5m	107 (30-39)	1	18,00
MAN A23	Diesel	228 kW (310 KM)	17,95m x 2,5m	175 (45)	3	18,00
Solaris Urbino 10	Diesel	176 kW (239 KM)	9,94m x 2,55m	81 (19-23)	4	14,00
Solaris Urbino 12	Diesel	188 kW (256 KM)	12m x 2,55m	86-94 (28-39)	26	15,46
Solaris Urbino 12 Electric	Electric	200 kW	12m x 2,55m	99 (39)	6	3,00
Solaris Urbino 12 Hybrid	Hybrid	151 kW	12m x 2,55m	94 (30)	8	7,00
Solaris Urbino 18	Diesel	231 kW (314 KM)	18m x 2,55m	136-168 (41-47)	36	14,03
Solaris Urbino 18 Electric	Electric	240 kW	18m x 2,55m	123 (41)	10	3,40
Solaris Urbino 18 Hybrid	Hybrid	220 kW	18m x 2,55m	147 (42)	8	7,00

Source: own elaboration.

In scientific literature, various approaches can be found regarding the study of energy consumption, fuel combustion, and cost-effectiveness of operating vehicles with specific types of engines. In one of the analyzed publications, authored by G. Zając and S. Jurga (Zając and Jurga, 2017), energy consumption studies of public transport vehicles were conducted, and megajoules per passenger-kilometer [MJ/pas.km] were used as the unit for conventional vehicles, while kilowatt-hours per passenger-kilometer [kWh/pas.km] were used for electric buses. However, among others, authors such as W. Gis, S. Kruczyński, S. Taubert and A. Wierzejski (Gis et al., 2017) conducted a standardized road test for urban traffic (SORT-2) using buses powered by compressed natural gas, diesel, and electric power. To show the final results of the study, the authors used the unit of fuel/electricity consumption per kilometer [kWh/km]. After taking into account the prices for the appropriate sources of energy, authors obtained the cost of driving one kilometer for each type of vehicle. After analyzing the obtained results, a possible theoretical application of AI-based systems to increase the efficiency of urban transport in the studied context was also proposed.

4. RESULTS

Due to the potential universality of the obtained results, in the further part of the article, where the analysis of energy consumption results of vehicles belonging to SPA Klonowica was carried out, the results are presented in kilowatt-hours per kilometer [kWh/km], and the cost of fuel/energy (and AdBlue solution for buses powered by diesel) per 1 vehicle-kilometer [vkm] is presented. The use of these two units will allow for obtaining uniform results for vehicles with different types of engines,

which will facilitate their comparison. On the other hand, the cost of fueling a vehicle per 1 vkm will allow for taking into account all additional factors (current energy prices, amount of used AdBlue solution), and as a result, will enable obtaining a clear answer to the question of which type of buses is the most efficient in terms of operating costs. The study used the actual heating value, which is 10,7 kWh per liter for diesel (MacKay, 2008). Due to the previously indicated differences in energy consumption related to periods of variable temperatures, the data from each month is shown.

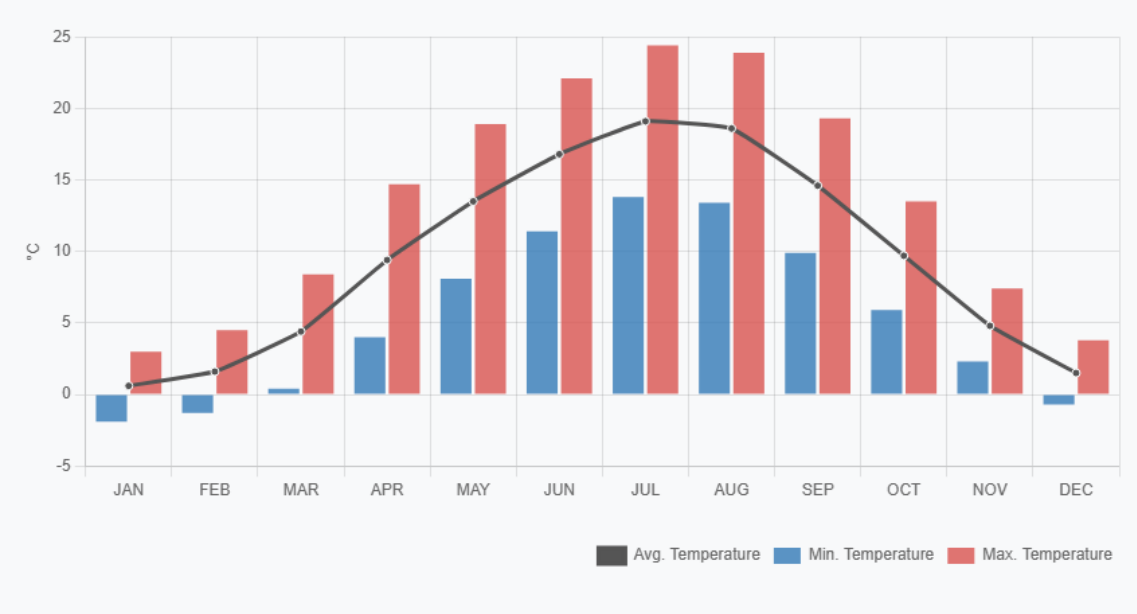


Figure 1. Temperature chart for the city of Szczecin from January 1 to December 31, 2024
Source: based on: https://meteostat.net/en/place/pl/szczecin?s=12205&t=2024-01-01/2024-12-31

Figure 1 presents the average, minimum and maximum temperatures for the city of Szczecin in year 2024. Temperatures are crucial for fuel or electricity consumption due to the use of heating or air conditioning systems. Extremely high or low temperatures can also negatively affect battery capacity, which in the case of electric buses affects their operational capabilities.

In the study, data presenting the energy consumption of vehicles with different types of engines (diesel, hybrid, electric) based on data from invoices provided by SPAK, which included the following values (all monetary values shown below are converted to the European common currency using the exchange rate from March 12, 2025 (4.20 PLN = 1 EUR):

- for diesel buses: fuel consumption and consumption of the water-based AdBlue solution, which is required in this type of vehicle
- for hybrid buses: fuel consumption (the hybrid vehicles in question do not have a charging function, the electricity is obtained in them through recuperation, which means that the invoices do not include the consumption of electricity)
- for electric buses: electricity consumption

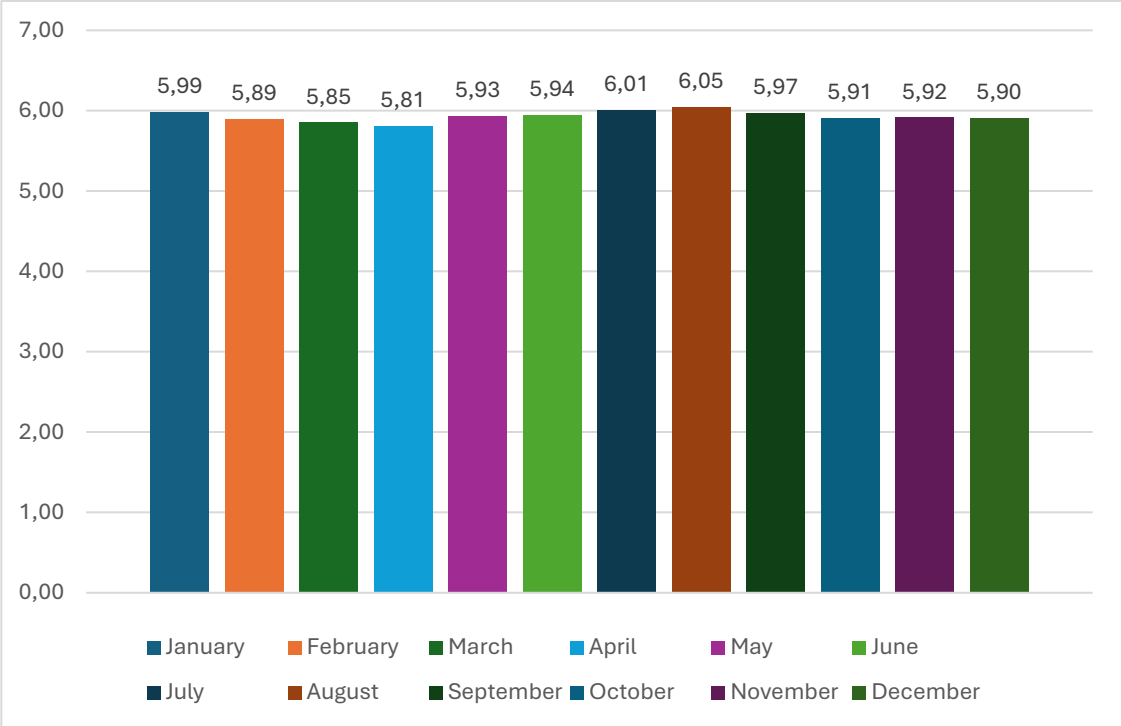


Figure 2. Energy consumption of diesel vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

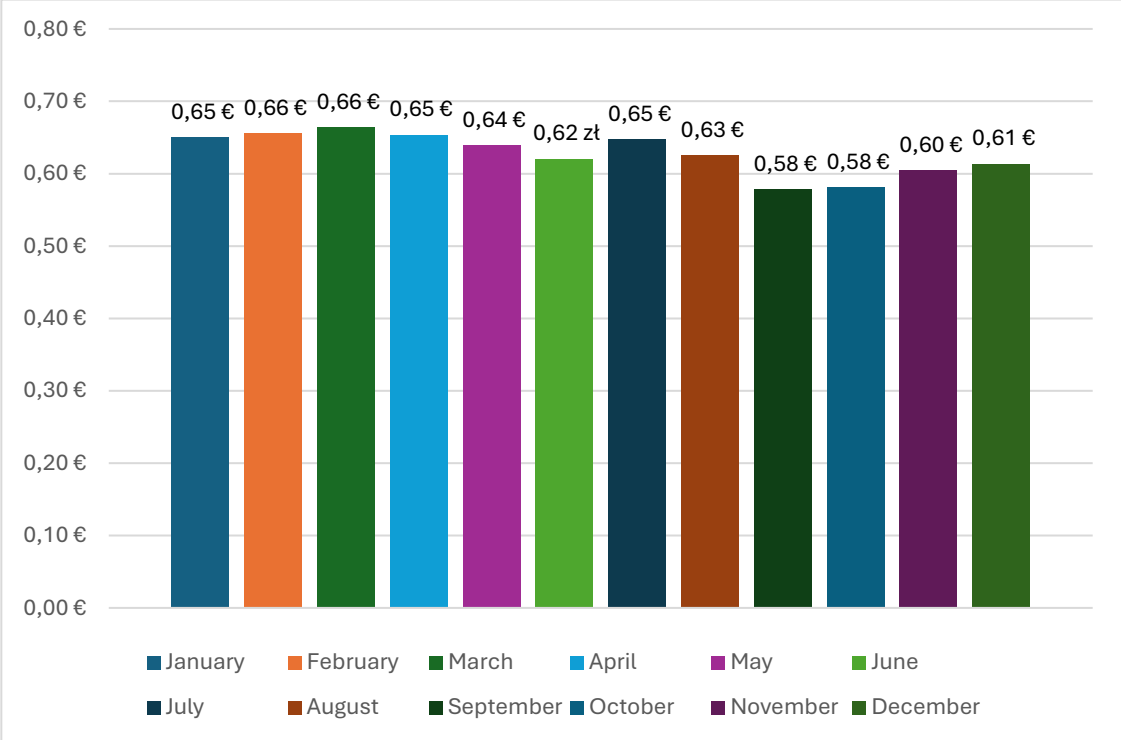


Figure 3. Fuel cost of diesel vehicles per 1vkm in the studied period
Source: own elaboration.

Figure 2 and 3 show the energy consumption and cost per 1 vkm for diesel vehicles. It can be seen that in the case of this type of bus, the differences between months are insignificant and there is no clear trend of changes depending on the studied periods.

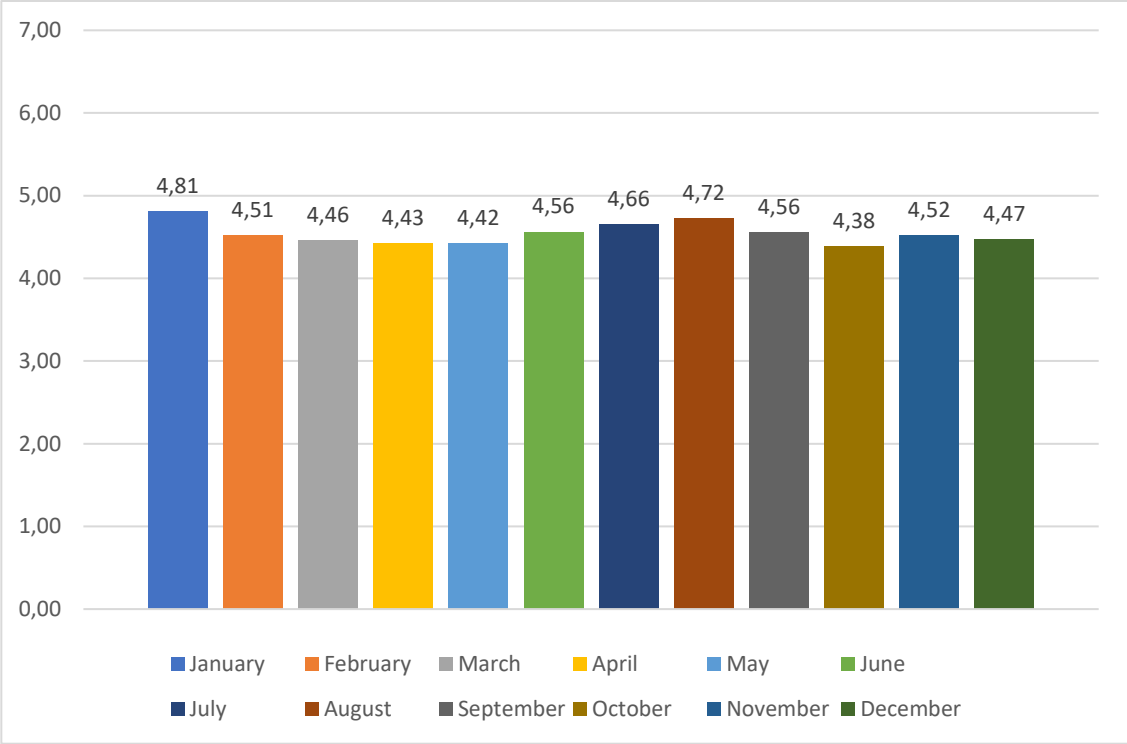


Figure 4. Energy consumption of hybrid vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

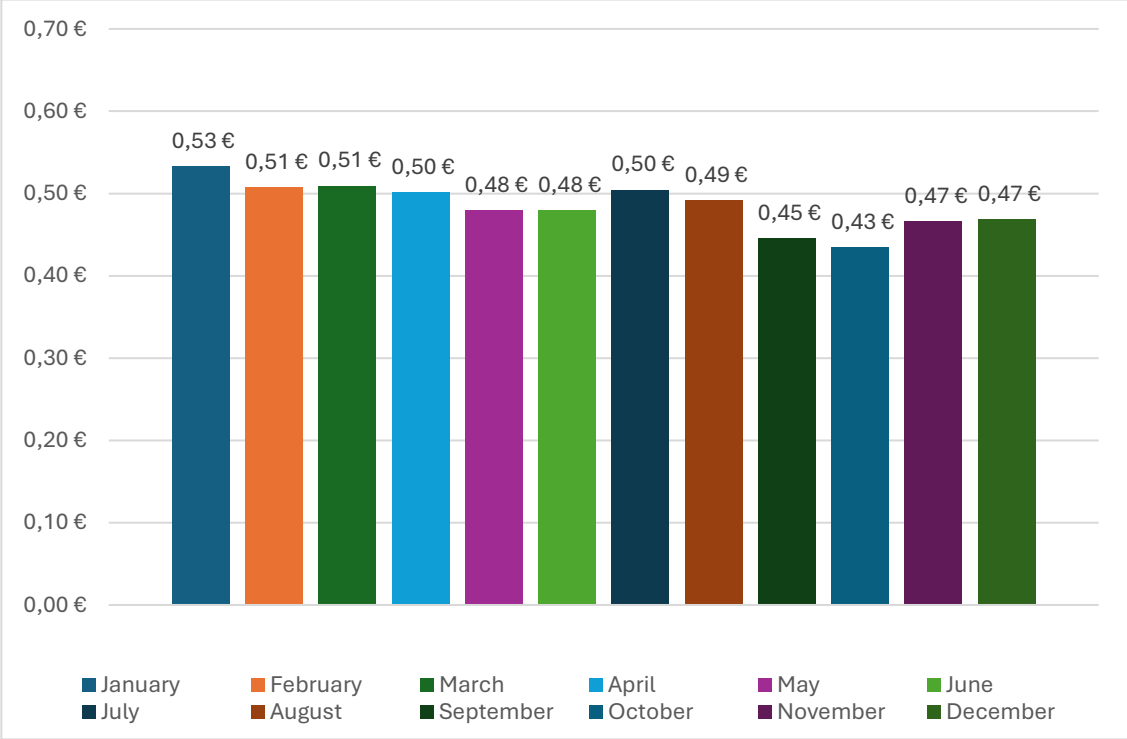


Figure 5. Fuel cost of hybrid vehicles per 1vkm in the studied periods
Source: own elaboration.

Figure 4 and 5 show energy consumption and cost per 1 vkm for hybrid engine vehicles. As in the case of diesel buses, monthly differences in energy consumption and costs are not significant and do not show clear trends. However, both energy consumption and cost are much lower compared

to a conventional engine. Such dependencies may result from the fact that in a hybrid bus, the main engine is also a diesel engine, which is why monthly dependencies may be similar to the previous case. On the other hand, the use of an electric engine as a supporting system, obtaining energy through recuperation, allows for a significant reduction in fuel consumption, and thus a reduction in operating costs and energy consumption.

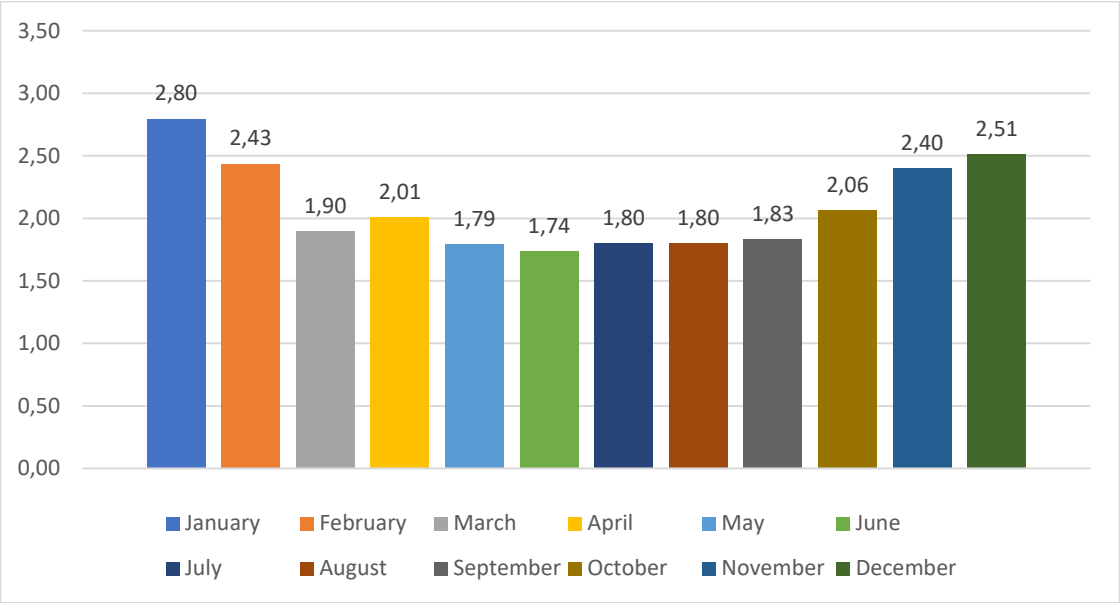


Figure 6. Energy consumption of electric vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

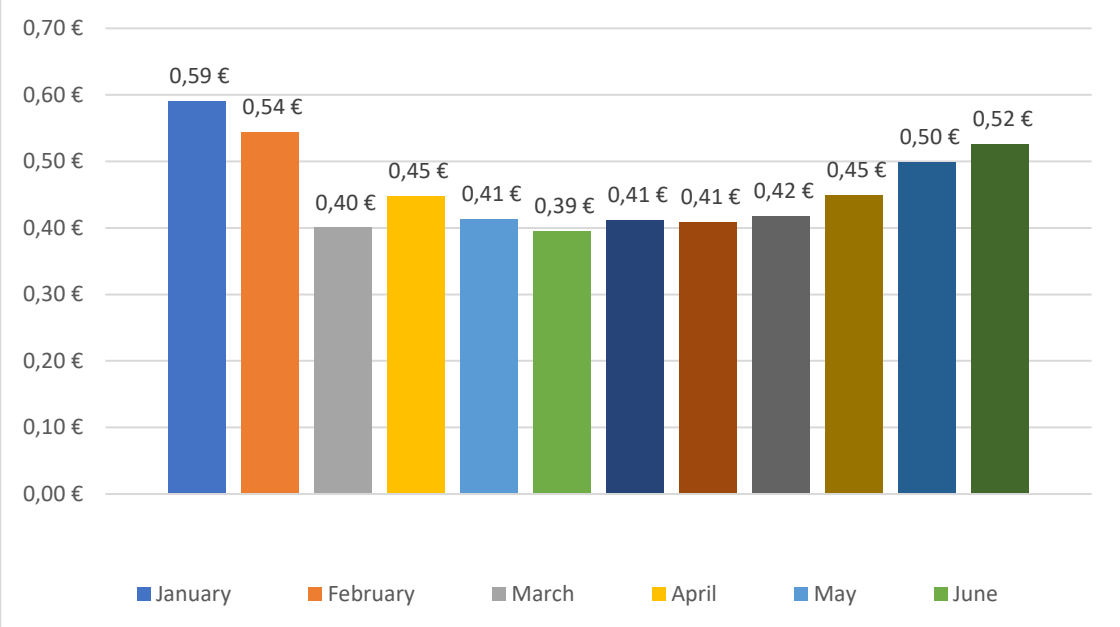


Figure 7. Fuel cost of electric vehicles per 1vkm in the studied periods
Source: own elaboration.

Figure 6 and 7 show energy consumption and cost per 1vkm for electric vehicles. The presented graphs show that both operating costs and energy consumption are the lowest in months with moderate and warm temperatures, while in winter months, when temperatures are relatively low, there is a clear increase in costs and energy consumption. This is consistent with common knowledge about batteries and research conducted in this area (Torbus et al., 2017).

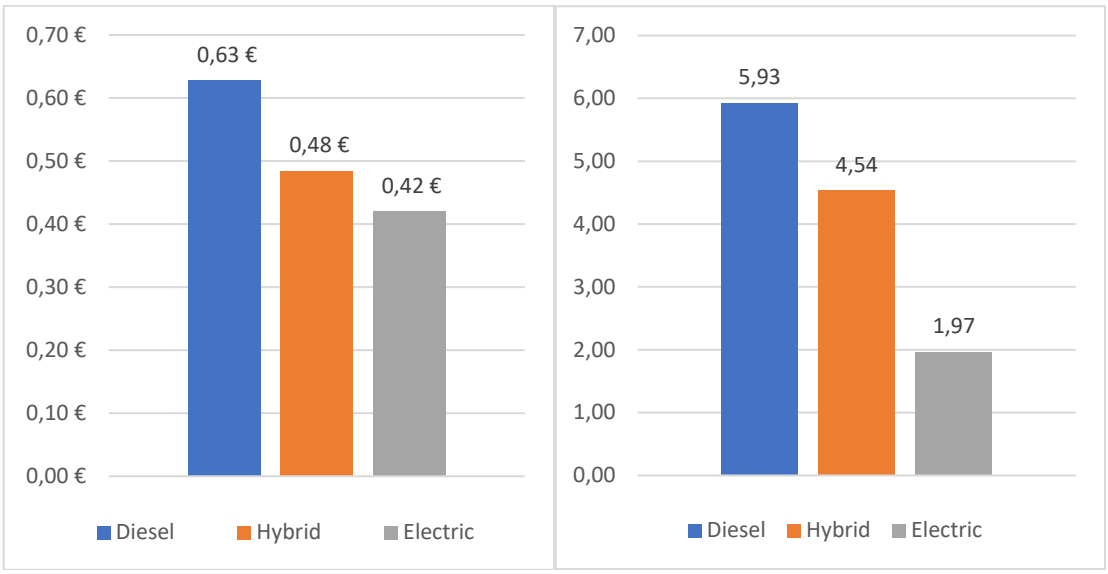


Figure 8. Energy consumption (kWh) and fuel cost of studied vehicles per 1vkm in 2024
Source: own elaboration.

Shown results clearly indicate the advantage of modern, ecological transport technologies over conventional solutions. In the case of the conducted study, it can be concluded that the cost of fuel/energy for hybrid buses is approximately 24% lower than for analogous vehicles using conventional combustion technologies, and for fully electric vehicles, the cost is approximately 33% lower.

It is obvious that in the scope of fleet operation, the cost of energy/fuel consumption is not the only operating cost of the company. However, other costs such as depreciation, repairs or service are similar in the case of any selected buses from those used in Szczecin and examined for the purposes of this article. In the case of electric vehicles, a drop in performance or the possible need to replace the battery after a certain period of time must be taken into account, however, in this case the operational buses did not experience any significant reduction in performance up to the time of the research and the form of management and organization adopted at SPAK (including not using the full capacity of the batteries) provides sufficient margin for this reduction in performance to occur without any impact on the operation of the fleet. For a company starting its business, in contrast to the case under study, there are also costs associated with building plug-in chargers or charging lines. In Szczecin, the charging infrastructure is already well-developed and plug-in chargers are located at the end stops of bus routes. There is also, as previously indicated, an extensive tram network, the power supply of which has been made available to electric buses. Buses can be and are recharged during mandatory stops related to the regulations on drivers' working hours and waiting time in accordance with the timetable. The design of the units used and the stations built in accordance with all safety procedures allows the batteries to be charged when passengers are present in the vehicle. Taking into account the above, the costs of energy/fuel itself and their consumption in selected periods were presented, taking into account the adopted variables and the fact that the electric units used are zero-emission vehicles in the full sense, which is not true in the case of a large number of publications (usually low-emission solutions are studied because the indicated units use diesel generators to provide heating and/or air conditioning). Additionally, the presented data concern the entire network of connections and the full fleet used by the company, which is also rare and the results of published studies are being often extrapolated from individual cases on single lines.

There are few publications proposing the use of AI solutions in fleet management and improving the efficiency of public transport buses. There are individual applications in the field of energy optimization management of used batteries (Jondhle et al., 2023), but there are issues where models using AI, whether as transformers or expert models, could have some application. In the opinion of the authors of this article, it would be possible to distinguish 3 basic groups where current systems could bring the greatest benefits:

- Route optimization: Application of AI to analyze traffic data, predict travel patterns and optimize routes, which leads to lower energy consumption and emissions.
- Energy management: AI can monitor energy consumption in real time and introduce recommendations for energy efficiency.
- Failure prediction: Application of AI algorithms in diagnostics of the technical condition of vehicles, which reduces repair costs (by quickly detecting faults) and increases operational efficiency, sometimes also reducing the cost of repairs.

At the same time, in the area of urban intelligent logistics systems, the same tool that could theoretically deal with route optimization in the area of public transport companies, when integrated with urban systems, could be responsible for demand prediction. Which would mean predicting by the AI expert system increases or decreases in transport demand depending on the time of day, level of road traffic, weather, road condition or accidents or other types of traffic flow obstructions. This would allow for adjusting the operating time of traffic lights or informing transport companies according to current needs in real time and overall reducing the environmental and energy costs of the entire system.

5. CONCLUSION

The results presented in the article indicate that choosing a fleet of electric vehicles, in addition to reducing greenhouse gas emissions, especially carbon dioxide, is also the most cost-effective solution for transport companies (and municipal companies) in terms of operating costs. This means that there are more arguments for introducing electric vehicles to the fleets of transport companies than just aspects related to environmental protection. The presented comprehensive results containing practical information and based on a network of connections instead of one line can encourage companies to use solutions consistent with the EU transport policy, which in turn will accelerate the process of achieving climate neutrality in Europe. The presented data can also serve further research in the field of urban transport and sustainable development. At the same time, the theoretical directions of development of supporting the operations of urban bus fleets with the help of systems using artificial intelligence, proposed in the article, may serve as an inspiration for further research and development of this type of systems.

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TRAVELLERS' MULTICRITERIA DECISIONS AS CONDITIONS FOR SUSTAINABLE URBAN TRANSPORT DEVELOPMENT: THE EXAMPLE OF POLAND

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ABSTRACT

Purpose: *This study identifies the determinants that influence ecological behaviours among travellers in Poland when choosing transport modes—specifically shifts toward sustainable options such as public transport and electric vehicles—and examines the cognitive decision-making processes underpinning these choices.*

Need for the study: *In the Polish context, economic, infrastructural and psychological factors shape travellers' ecological decisions. Understanding these determinants—and integrating principles of intelligent mobility management—enables policymakers to design targeted interventions that foster environmental responsibility.*

Methodology: *A nationwide CAWI survey was conducted in late 2023 with 1,117 respondents aged 18, stratified to reflect demographic distributions across Poland. The questionnaire probed both external influences on travel choices and internal decision-making factors.*

Findings: *The study shows that electric vehicle adoption is most responsive to lower purchase costs, expanded charging infrastructure, and environmental awareness—especially when supported by intelligent tools like AI-powered digital twins. Public transport and walking gain popularity through unified ticketing, service upgrades, and price reductions. Travellers make decisions based on convenience, cost, and environmental concerns, while intelligent management systems enhance choices by delivering real-time data on congestion, emissions, and expenses.*

Practical Implications: *To support sustainable mobility, policymakers should promote electric vehicles through financial incentives and invest in charging networks and public transport improvements. Integrated ticketing across transport modes can simplify multimodal travel. The use of intelligent management tools—such as AI-driven planners and digital twins—can optimise route selection, reduce external costs and support sustainable transport objectives.*

Keywords: decision making, ecology, electromobility, green transport, intelligent mobility management travellers' choices

Jel codes, O18, Q01, R40, R49, Z30

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5. INTRODUCTION

The global passenger transport market in the early 21st century is characterized by significant dynamism and continuous transformations primarily driven by environmental shifts. The rapid growth in consumerism has led to environmental degradation, prompting the need to redefine environmental protection policies and emphasize sustainable consumption (Kamińska, 2019; Kos, Krawczyk, & Tomanek, 2020). Many countries have responded to this challenge by implementing coordinated sustainable development strategies, particularly within the transport sector, emphasizing the reduction of emissions, noise, energy consumption, and land occupancy (Holden, Linnerud, & Banister, 2017; Kos, Krawczyk, & Tomanek, 2020). The negative externalities of transport–such as congestion, pollution, noise, and compromised road safety–have predominantly been attributed to private car use compared to public transportation (Kos, Krawczyk, & Tomanek, 2018; Kos, Krawczyk, & Tomanek, 2020; Kos, Krawczyk, & Tomanek, 2022).

To effectively mitigate these adverse effects, influencing travellers' decisions toward eco-friendly alternatives such as public transportation and electric vehicles becomes crucial. The increasing competitiveness of rail transport, driven by improvements in infrastructure and modernization, further supports the potential for changing traveller preferences. However, the COVID-19 pandemic significantly disrupted this trend, shifting passenger preferences temporarily back toward individual transportation due to health concerns and public transport restrictions.

Beyond traditional incentives, emerging intelligent mobility management tools–such as AI-powered digital twins, predictive congestion models and integrated multimodal trip-planning platforms offers real-time, personalized insights into traffic, emissions and energy use, empowering both planners and passengers to make more sustainable choices (Di et al., 2024; Nguyen, 2024). The concept of intelligent management, understood as the integration of advanced technologies (such as AI, digital twins, and real-time data systems) into strategic decision-making, is increasingly relevant in urban transport systems. In this context, intelligent mobility management becomes a key operational dimension, enabling data-driven planning, monitoring, and optimisation of mobility services. The findings of this study contribute to the broader discourse on intelligent management by highlighting how user behaviour insights, when combined with digital tools, can support sustainable and adaptive transport governance in smart cities. Intelligent mobility management refers to the strategic use of digital technologies, real-time data, and AI-based tools to plan, monitor, and optimise urban mobility systems. It encompasses not only infrastructure and vehicle management but also the behavioural dimension of mobility—understanding and influencing how users make transport decisions. Through tools such as predictive analytics, digital twins, and integrated trip planners, intelligent mobility management supports cities in dynamically adjusting services to user needs, improving system efficiency, and reducing environmental impact. Embedding such approaches into transport policy enables more responsive and sustainable urban governance.

Given these transformations, a thorough understanding of the factors shaping travellers' decision-making processes becomes essential to rebuild demand for public transport or redirect it towards environmentally sustainable options. This study specifically examines travellers' preferences and decision-making factors in Poland to determine what influences their environmental awareness and transport mode choices, emphasizing shifts from combustion-engine vehicles to electric vehicles or public transport. The aim is to identify key determinants shaping these decisions, thereby providing insights to develop targeted policies aligned with sustainable urban transport objectives.

6. LITERATURE REVIEW

In recent years, increasing importance has been placed on ecological aspects when making purchasing decisions. More and more consumers are aware of the impact of their choices on the natural environment and want to make purchases that align with the principles of sustainable development. Ecological aspects relate to issues such as:

- cleaner and organic production,
- minimising energy consumption,
- reducing CO_2 emissions,
- reducing water usage,

- recycling and reusing products, minimisation of transport needs (Krajnc & Glavič, 2003).

Consumer environmental awareness plays a crucial role in reducing consumption imbalances (Khan, 2024). It can be defined as a set of information and beliefs regarding the environment and the connections between the state of the environment and the conditions and quality of life (Becla, 2016). Environmental awareness and concern for the natural environment are becoming increasingly important factors influencing consumer decisions and behaviours. With the development of issues related to environmental pollution, climate change, and the depletion of natural resources, consumers are increasingly considering the impact of their consumption decisions on the environment. The growth of environmental awareness is the result of many factors, such as social campaigns, environmental education, the availability of information about the impact of products on the environment, and increasing interest in sustainable development topics. All these contribute to changing consumer attitudes and behaviours (Han, 2021; Morrison & Beer, 2017).

Consumers who are aware of the negative impact of consumption on the environment strive to make informed choices that take into account sustainable development aspects. One of the primary causes of natural environment degradation is unsustainable consumption. The degree of imbalance is greater the higher the level of industrialization. The development of consumerism also threatens the environment in Poland. This also applies to the modernization of transport means, road and highway networks, and the development of rail transport as an alternative to road transport (Holden et al., 2013).

Transport is the only sector in which emissions increased by 30% between 1990 and 2019 in the EU, while they decreased in other sectors such as agriculture, industry, energy, residential, and commercial buildings. The most responsible for the rise in emissions was international aviation, which more than doubled. Road transport emissions also increased by more than 20% during the examined period (EEA, 2022). This trend is not unique, as the USA saw a 19% increase from 1990 to 2021, also with a decrease in other sectors (US Environmental Protection Agency, 2024). According to data presented by the EU, transport accounts for nearly a quarter of greenhouse gas emissions in Europe. Almost 73% of transport emissions are generated by road transport, with passenger cars, small delivery vans, and trucks having the largest share. Cars account for about 12% of total CO_2 emissions in the EU, and this number is continuously growing. Transport is also the main source of air pollution in cities (European Climate Pak, 2024).

The importance of actions in the field of road transport is well illustrated by data from the European Environment Agency. It shows that road transport accounts for 71.7% of total greenhouse gas emissions in the EU-27 in 2019 by sector, water transport 14.1%, rail 13.4%, and air 0.4%. It should be noted, however, that emissions related to the production of electricity for railways are not included in this study. Nevertheless, of these 71.7% GHG emissions, passenger cars account for as much as 60.6%. Therefore, improving or reducing emissions related to the use of this means of transport or changing societal habits is so important (Schwanen et al., 2012; Marsden et al., 2014).

In Poland, the GHG emission structure is different, with transport also playing a significant role. In a report prepared for the Ministry of Climate and Environment, the following categories of emission origins were specified: fuel combustion – 78.3%, agriculture – 8.5%, industrial processes and product use – 6.1%, fugitive emissions from fuels – 5.8%, waste – 1.2%, indirect CO_2 emissions – 0.1%. In the fuel combustion category, as much as 17.1% was transport, making it the second most emission-intensive sector after energy, which in Poland is still based on fossil fuels, including mainly hard and brown coal. The measurements show that transport accounts for 13.39% of total GHG emissions in Poland (Krajowy Raport Inwentaryzacyjny, 2023).

Finding a solution to the problem of emissions from transport, including passenger transport, is widely known and recognized (Kamińska, 2021; Kos et al., 2022; Kos et al., 2020; EEA, 2022; Mercure & Lam, 2015; Mercure et al., 2018; Ritchie, 2020; Betta et al., 2021). Alongside the increasingly widespread social awareness based on both scientific or journalistic reports and empiricism related to experiencing the negative impacts of transport, particularly noise, air pollution, or congestion, we have legal regulations enforcing accelerated actions aimed at change. One of them is the European Green Deal, aimed at making Europe a climate-neutral area by 2050, and the Fit for 55 package of assumptions. This means that by mid-century, we will not be able to produce more carbon than our ecosystems – forests and oceans – can naturally remove from the atmosphere. To achieve this goal, CO_2 emissions from transport must be reduced by 90% (Transport and Green Deal, 2024).

Although most cited studies are based on GHG emissions levels or their equivalents, it is essential to remember that transport also has a significant impact on other aspects, i.e., external costs, those not borne by the user but by society or the environment. Transport activities give rise to environmental impacts and accidents. An external cost is a cost not included in the market price of the goods and services being produced, i.e., a cost not borne by those who create it. External costs are costs generated by transport users and not paid by them but by society as a whole, such as congestion, air pollution, climate change, accidents, noise, but also up- and downstream processes, costs for nature and landscape, or additional costs in urban areas. There is a market failure because transport prices do not reflect their costs, and transport users choose their transport mode with the wrong price signal. These costs are extremely difficult to calculate, depending on many factors such as emission standards met by a given vehicle, driving style, weather conditions, terrain, power source, or fuel source and path before being used. An important issue is also the problem of valuing and indicating areas that are the environment affected by external costs. Among them, one can include air pollution, climate change, noise, accidents, congestion, air, water resources, land, solid pollution, noise, accidents, and others such as reducing the investment attractiveness of a given area (EEA, 2024; Reiner & Bickel, 2001; Mostert & Limbourg, 2016).

The EU's horizontal documents and regulations, followed by national strategies and legislation, recognize this problem and are generally aimed at promoting solutions that are friendly or perhaps more accurately described as less burdensome to the external environment, i.e., society and the environment. Since the CAWI method survey was conducted in Poland, it is necessary to cite the key Polish legal act in this area, the Act of January 11, 2018, on electromobility and alternative fuels (Journal of Laws 2023.875, as amended). In the context of the research, particular attention should be paid to the definitions of hybrid cars and electromobility consistent with EU documents. It differs slightly from the one used in common language. In Article 2, points 12 and 13, we find the following definitions: "electric vehicle – a motor vehicle within the meaning of Article 2, point 33 of the Act of June 20, 1997 – Road Traffic Law, using exclusively electrical energy accumulated by connecting to an external power source for propulsion" and "hybrid vehicle – a motor vehicle within the meaning of Article 2, point 33 of the Act of June 20, 1997 – Road Traffic Law, with a combustion-electric drive, in which electrical energy is accumulated by connecting to an external power source." This indicates the introduction of a certain systematics where combustion cars are both cars with only a combustion engine and commonly known as hybrid cars, i.e., very popular vehicles produced by, among others, Toyota (Hybrid Electric Vehicle – HEV, including Mild Hybrid Electric Vehicle – mHEV), i.e., without the possibility of charging the battery from an external source—practically charged from the grid. Therefore, these types of power sources are treated equally, although the use of HEV drive significantly reduces fuel consumption both in passenger vehicles and public transport (Sher et al., 2021; Drożdż et al., 2022).

According to the regulations, a hybrid car is considered a Plug-In Hybrid (PHEV), i.e., with a combustion engine and additional electric power supply charged from the grid. They most often enable driving a few dozen kilometres without using a combustion engine, thus theoretically allowing daily transport needs to be met without emissions or with very little fuel consumption. Meanwhile, an electric car will be a vehicle equipped only with such a drive, i.e., without a combustion engine but with an electric motor. According to the previously mentioned systematics, such cars are called Battery Electric Vehicles (BEVs), sometimes EVs. The authors are aware of hydrogen cars, and they are mentioned in the legislation, but vehicles powered by hydrogen fuel cells, from which energy is generated (FCEVs), were not the subject of research due to the lack of both a wide offer of such vehicles and their presence on the roads or the counted number of charging points in the country.

By creating a real-time virtual replica of urban transport and environmental systems, digital twins give travellers personalised insights into congestion, air quality and energy use—empowering them to choose the most efficient and sustainable routes. As noted by Nguyen (2024), many cities—including Houston, Singapore and Amsterdam—are leveraging digital twins and AI to enhance climate resilience and manage urban challenges such as flooding, air pollution and heat islands, optimising energy systems and waste flows to boost climate resilience (Nguyen, 2024).

7. MATERIALS AND METHODS

The aim of the study conducted on a nationwide sample was to gather information about travellers' choices and decisions regarding the abandonment of combustion-engine cars in favour of public transport and electric vehicles, aligning with the ideas of sustainable urban transport development.

To reliably achieve this formulated goal, the following research questions were posed:

- What can influence ecological behaviours of travellers and raise their environmental awareness?
- What factors could cause the respondents to give up traveling by private car in favour of public transport?
- What factors could influence the change in travellers' habits/preferences towards electric vehicle?

The study was conducted using the CAWI method on the Poznaj.to company panel between November and December 2023. Sample Description – the study population comprised individuals aged 18 and over residing in Poland. A total of 1117 interviews were conducted. The quantitative method and sampling technique used in the study allow for generalization of the results to the entire adult population with a margin of error of +/- 3.0% (95% confidence level). The study was conducted on a random sample, thanks to a proprietary respondent selection system and a tool for maintaining participation intervals in surveys. The results were generalized based on the selected representative sample from the population. Additionally, the sample was subjected to a weighting procedure to adjust the results in relation to the general population structure.

Survey Control of the study was carried out in two ways:

- Field Control: During the survey, the received responses were monitored in real time, allowing for the identification and elimination of cases where the data was questionable, such as overly short questionnaire completion times, undesirable tendencies, inconsistencies, or discrepancies in responses. The questionnaire script prevented respondents from skipping key questions presenting significant content from the survey's perspective.
- Non-field Control: Substantive analysis allowed for the elimination of incomplete or unreliable material. Quality control covered 100% of the collected material, during which response consistency, response patterns, and answers to semi-open questions were analysed.
- The research tool was designed by the authors and consulted with the research firm conducting the survey. It included 18 single-choice questions, 14 multi-item questions, 18 multiple-choice questions, and 10 demographic questions regarding socio-demographic characteristics.

Data Weighting - before analysis, the dataset underwent a weighting procedure to correct discrepancies in empirical distribution compared to the general population structure regarding gender, age, and place of residence. The iterative weighting methodology (RIM) was applied using these characteristics.

Description of the Selected Test to analyse the significance of differences in responses among various respondent groups, statistical analyses were conducted using IBM SPSS Statistics 26. Chi-square tests and comparisons of significant column proportion differences were performed, with a significance level of $\alpha = 0.05$. The Bonferroni correction was also applied to adjust significance values.

Presentation of Results - most of the results in the report are presented for the entire sample and broken down by health status, gender, age, and size of the locality. An exception is multiple-choice questions, which are presented only for the entire sample. The text includes descriptions of significant differences between fractions compared in pairs based on the mentioned demographic variables.

Characteristics of the Respondents

- Gender: A slightly higher percentage of respondents were women (52.4%) compared to men (47.6%).
- Age: The largest age groups were those between 31 and 60 years old (52.9%) and those over 60 years old (30.2%).
- Residence: About 40% of the respondents were rural residents, while one in five lived in towns with populations between 20,000 and 100,000 (19.1%). Residents of cities with over 400,000 inhabitants made up 13.6% of the sample.
- Education: Nearly 40% of the respondents had a secondary education, and a quarter (26.6%) had higher education.

- Income: The largest group of respondents had a household income per person between 3,000 and 5,000 PLN (26.8%), followed by those with an income between 2,000 and 3,000 PLN (24.8%). Nearly 30% indicated an income below 2,000 PLN (27.9%).
- Housing: A slightly higher percentage of respondents lived in multi-family buildings.

8. RESULTS

Almost all respondents (85.9%) travel by car, with one-third using this mode of transport daily. Men statistically significantly more often than women reported traveling daily or several times a week (69.8% of men vs. 56.9% of women, $p<0.05$). Age also differentiates the distribution of responses. Statistically, respondents over 60 years old were significantly more likely to report not traveling by car at all (24% in this group) compared to younger respondents. For respondents aged 18-30, this percentage was 16.3%, and for those aged 31-60, it was 10.8%.

The size of the place of residence also influences the differences between groups. Residents of villages and towns with up to 400,000 inhabitants were significantly more likely to report traveling by car daily compared to residents of larger cities (14.1% in this group, $p<0.05$). Education, income, household size, and type of property also differentiated the results ($p<0.05$). People with higher and secondary education were significantly more likely to report traveling by car sever-al times a week compared to those with other levels of education. Respondents with an income of more than 3,000 PLN per person were significantly more likely to report traveling daily by this mode of transport compared to those with lower incomes. Daily car travel was also significantly more frequently reported by residents of single-family houses.

Nearly one-fourth of respondents do not travel by bus, and 26.5% use them sporadically. One in five uses this mode of transport several times a month, and one in ten uses it daily. Respondents aged 18-30 were significantly more likely to report traveling by bus daily (15.7% in this group) compared to those over 60 years old (7.2% in this group). The size of the place of residence also differentiated the responses. Residents of villages and towns with up to 100,000 inhabitants were significantly more likely to report not traveling by bus at all compared to residents of larger cities (31.9% of village residents, 31.2% of residents of towns up to 20,000 inhabitants, 22.6% of residents of towns with 20,000-100,000 inhabitants, 9.7% of residents of towns with 100,000-400,000 inhabitants, 7.4% of residents of cities with more than 400,000 inhabitants, $p<0.05$). Education, income, household size, and type of property also differentiated the results ($p<0.05$). People with elementary education were significantly more likely to report traveling by bus daily compared to those with other levels of education. Daily bus travel was also significantly more frequently reported by respondents with an income between 3,000 and 5,000 PLN, and by respondents from single-person households compared to those from two- and three-person households. Daily bus travel or travel several times a week and month was significantly more frequently reported by residents of multi-family buildings.

Nearly 60% of respondents reported not traveling by tram daily. Those who use this mode of transport most often re-ported traveling several times a month or less frequently (18.3%). Women were significantly more likely than men to report this response (61.8% of women vs. 53.6% of men, $p<0.05$). Similarly, respondents over 60 years old were significantly more likely to report not traveling by tram daily (65.5% in this group) compared to younger respondents. For respondents aged 18-30, this percentage was 49.2%, and for those aged 31-60, it was 56.4%. The size of the place of residence also influenced the differences between groups. Residents of cities with more than 400,000 inhabitants were significantly more likely to report traveling by tram several times a month or more frequently compared to residents of smaller towns (73.4% of residents of the largest cities, while in other classes of towns this percentage did not exceed 26%).

Education and type of property also differentiated the results ($p<0.05$). People with higher education were significantly more likely to report traveling by tram several times a week compared to those with lower education. Daily tram travel or travel several times a week was significantly more frequently reported by residents of multi-family buildings.

One-third of respondents do not travel by train (36.3%), and half use this mode of transport once a month or less frequently (50.45%). Women were significantly more likely than men to report not traveling

by train (39.5% of women vs. 32.7% of men, $p<0.05$). Age also differentiated the responses. Respondents over 60 years old were significantly more likely to report not traveling by train at all (46% in this group) compared to younger respondents. For respondents aged 18-30, this percentage was 32.4%, and for those aged 31-60, it was 32%. Education and type of property also differentiated the results ($p<0.05$). People with elementary education were significantly more likely to report traveling by train daily compared to those with other levels of education. Residents of single-family houses were significantly more likely to report not traveling by train at all.

Nearly half of the respondents reported using a bicycle at least several times a month (45.2%), and one-third reported not traveling by bicycle. Women were significantly more likely than men to report not traveling by bicycle (38.1% of women vs. 24.7% of men, $p<0.05$). Age also differentiated the responses. Respondents over 60 years old were significantly more likely to report not traveling by bicycle at all (45.7% in this group) compared to younger respondents. For respondents aged 18-30, this percentage was 25.9%, and for those aged 31-60, it was 25.6%. The size of the place of residence also influenced the differences between groups. Residents of villages and towns with up to 100,000 inhabitants were significantly more likely to report traveling by bicycle daily compared to residents of larger cities (8.1% of village residents, 8.2% of residents of towns up to 20,000 inhabitants, 11.4% of residents of towns with 20,000-100,000 inhabit-ants, 3.4% of residents of towns with 100,000-400,000 inhabitants, 1.3% of residents of cities with more than 400,000 inhabitants, $p<0.05$). Education, income, household size, and type of property also differentiated the results ($p<0.05$). People with vocational education were significantly more likely to report traveling by bicycle daily compared to those with higher education. Daily bicycle travel was also significantly more frequently reported by respondents with an in-come below 1,000 PLN.

Further analysis presented the results of respondents who reported traveling by car (N=999).

What Can Influence Eco-Friendly Behaviours of Travelers? Factors That Could Lead Respondents to Give Up Traveling by Car in Favor of Public Transport (Table 1).

The main factors that could lead respondents to give up traveling by car in favour of other means of transport are the introduction of discounts and incentives for travellers, price promotions (43%), and a single ticket for all means of transport in the city or municipality (35.5%). Approximately 27% of survey participants also indicated that they could be convinced by the expansion of road infrastructure, the modern public transport options, and care for the environment and personal health. One in ten respondents believed that nothing could convince them to switch from car travel to other means of transport. Figure 1 presents the factors that could influence the change in transport habits from car transport to public transport or walking in general and broken down by age, and place of residence.

Men were statistically significantly more likely than women to indicate that they could be convinced by competitive price offers from various organizers/carriers/means of transport (18.3% of women vs. 24.4% of men, $p<0.05$).

Age is also a variable that differentiates the distribution of responses. Respondents over 60 years old were significantly more likely to state that nothing could convince them to switch from a car to another means of transport (20.4% in this group) compared to younger people (7.9% in the 31-60 group and 9.7% in the 18-30 group, $p<0.05$). The youngest respondents were significantly more likely to choose factors such as improving the quality of road infrastructure (30.5% in this group) and a single ticket for all means of transport (43.7% in this group) compared to respondents over 60 years old (16.7% and 30.4% in this group, $p<0.05$).

The size of the place of residence also influences the differences between groups. Residents of cities with more than 400,000 inhabitants were significantly more likely to point to factors such as improving the quality of road infrastructure (33.3% in this group) and the modernity of public transport means and forms (38.2% in this group) compared to rural residents (17.9% and 22.6% in this group, $p<0.05$). Education also differentiates the results, people with primary education were significantly more likely than those with vocational education to choose "care for the environment" and "a single ticket for all means of transport in the city/municipality" ($p<0.05$). Factors that could influence the change in transportation habits/preferences of travellers regarding the shift from combustion engine cars to electric cars (Table 2) The main factor that could lead respondents to switch from combustion engine cars to electric cars is financial considerations – 43% cited lower prices of electric vehicles. Approximately one in four participants also indicated that they could be persuaded by the availability of electric vehicle charging infrastructure (26.4%), introduction of incentives

and discounts for buyers, price promotions (26.2%), competitive travel costs, lower operating expenses (25.7%), and environmental concerns (25.5%). Nearly one in four respondents also stated that nothing could convince them to switch from a combustion engine car to an electric car (23.3%). Figures 4-7 depict the factors that could influence changes in transportation habits regarding the switch from combustion engine cars to electric cars in general and broken down by gender, age, and place of residence. Men statistically significantly more often than women indicated that lower prices of electric vehicles could persuade them (46.4% of male responses vs. 36.2% of female responses, $p<0.05$). Age also differentiated response distributions significantly. Individuals aged 60 and above statistically more frequently indicated that nothing could persuade them to give up a combustion engine car for an electric car (30.2% in this age group) compared to those under 30 years old (15.4%, $p<0.05$). Conversely, younger individuals more significantly preferred easily accessible information systems about the benefits of offers and promotions (16.6% in the 31-60 age group and 15.6% in the 18-30 age group) compared to those over 60 years old (7.6%, $p<0.05$). Place of residence also influenced differences between groups. Rural residents significantly less frequently mentioned factors such as environmental concerns (21% in this group) and availability of electric vehicle charging infrastructure (21.3% in this group, $p<0.05$).

Table 1. Factors that could influence the change in transportation habits regarding the abandonment of private car use

Total n=999	Women n=510	Men n=489	18-30 years old n=184	31-60 years old n=544	61 and older n=271	Village n=416	City up to 20k n=129	City 20k - 100k n=181	City 100k - 400k n=148	City over 400k n=125
Introducing discounts and incentives for travellers - price promotions										
43.0	44.0	42.0	37.7	45.8	40.8	37.2	45.8	39.3	55.0	50.7
Unified ticket for all means of transport in the city/municipality										
35.3	34.4	36.3	43.7	34.9	30.4	37.7	29.1	32.2	35.3	38.8
Expansion of road infrastructure										
27.7	29.0	26.4	29.9	30.6	20.3	27.3	25.9	31.1	26.2	28.0
Modernity of public transport means and forms										
27.5	26.6	28.4	33.2	26.0	26.5	22.6	27.3	28.1	31.4	38.2
Environmental care										
27.0	26.1	28.0	27.3	26.7	27.6	23.9	34.3	27.4	27.4	28.7
Personal health care										
26.4	25.1	27.8	27.9	27.7	22.7	28.4	32.1	27.8	21.2	17.5
Improvement in the quality of road infrastructure										
23.2	24.8	21.6	30.5	24.0	16.7	17.9	29.1	22.4	25.3	33.3
Competitive price offers from different operators/means of transport										
21.3	18.3	24.4	18.7	23.0	19.5	20.1	20.5	22.7	19.2	26.4
Easily accessible information system about the range of offers, promotions										
14.7	13.1	16.2	16.9	13.9	14.6	14.7	13.9	15.7	13.6	14.9
Regular, cyclical marketing activities										
7.8	7.9	7.7	10.4	8.4	4.8	5.8	12.0	9.9	9.1	5.3
Greater availability of public transport in the place of residence										
2.5	2.6	2.3	1.2	2.9	2.5	4.4	0.5	0.9	3.1	
Something else										
0.8	0.9	0.7	1.8	0.5	0.8	1.5	0.8		0.2	0.7

Source: own research (N = 999).

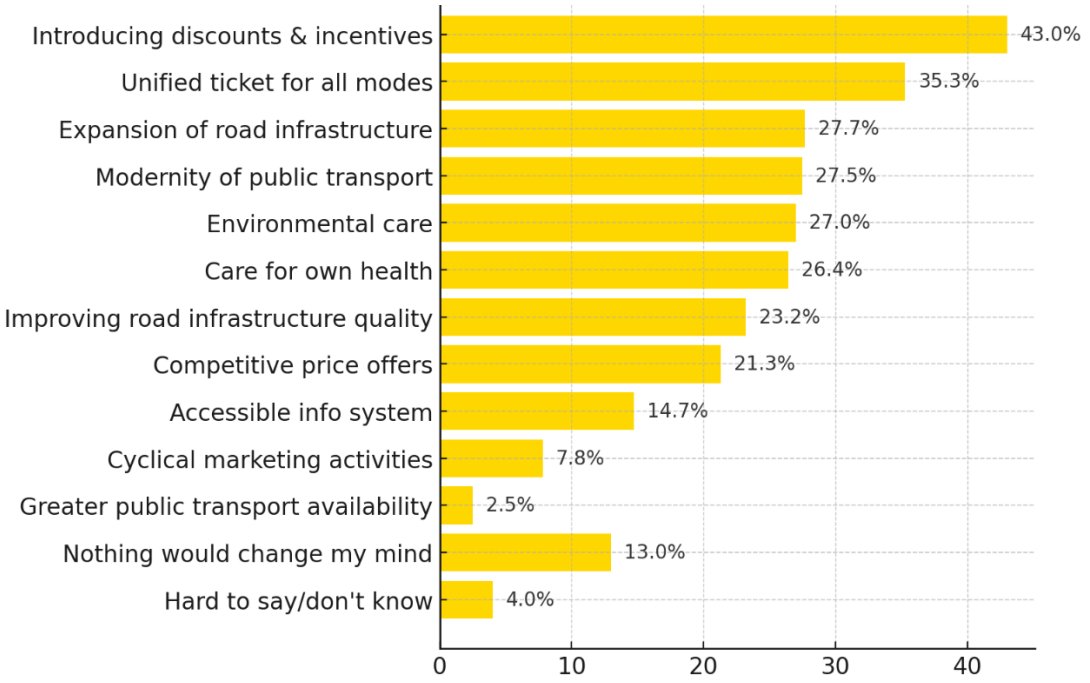


Figure 1. Factors that could influence a change in transportation habits from using private cars to public transport or walking

Source: own studies.

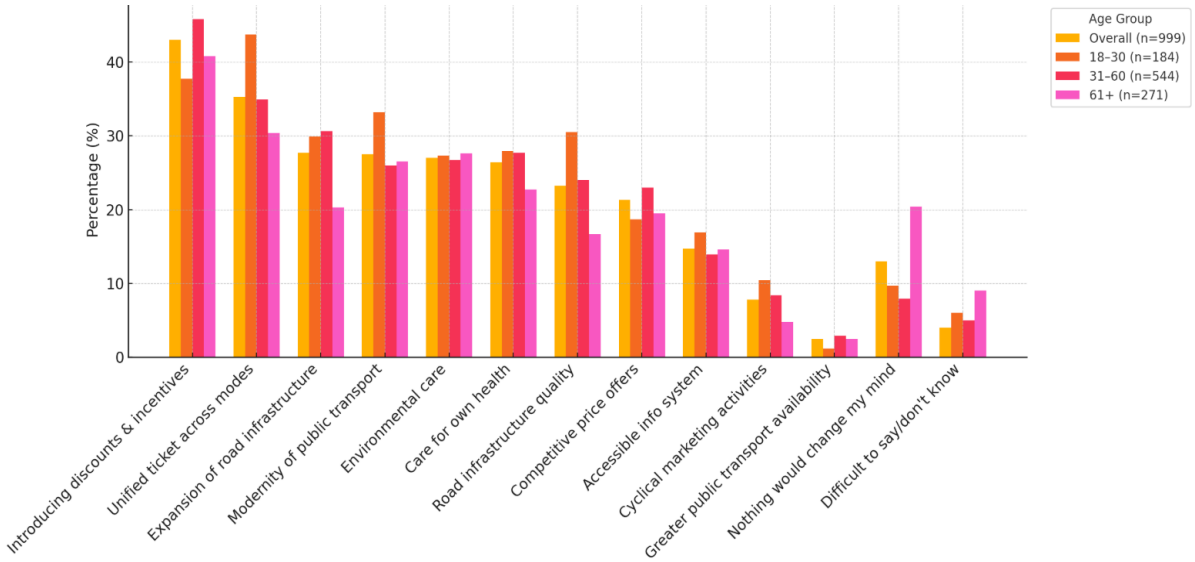


Figure 2. Factors that could influence changes in transportation habits regarding the shift from car transport to public transportation or walking based on the criterion of passengers' age

Source: own studies.

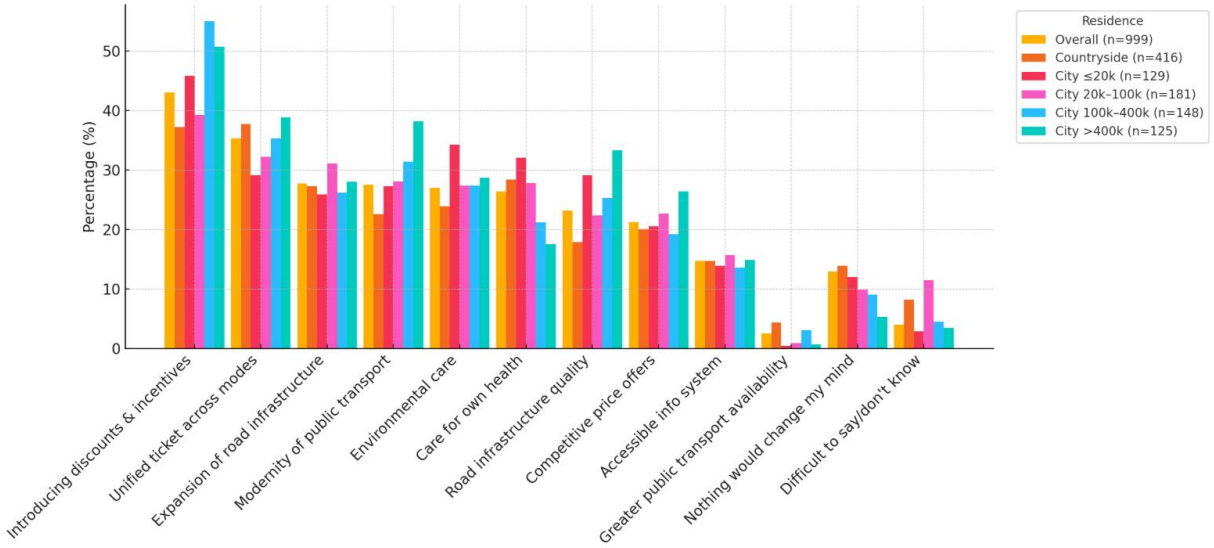


Figure 3. Factors that could influence the change in transportation habits regarding the shift from car transport to public transportation or walking based on the criterion of residential area size

Source: own studies.

Table 2. What could influence changes in your transportation habits/preferences regarding switching from combustion engine cars to electric cars?

Total n=999	Woman n=510	Man n=489	18-30 years n=184	31-60 years n=544	61 and above n=271	Village n=416	City up to 20K n=129	City 20K-100K n=181	City 100K – 400K n=148	City above 400K n=125
Lower prices of electric vehicles										
41.2	36.2	46.4	44.3	41.2	39.0	38.8	37.6	41.4	44.0	49.4
Availability of electric vehicle charging infrastructure										
26.4	26.9	25.9	32.3	26.0	23.3	21.3	26.7	30.9	22.7	40.9
Introduction of incentives and price promotions										
26.2	25.0	27.6	27.7	25.2	27.4	23.2	34.2	27.1	22.5	30.9
Price competitiveness of travel - lower operating costs										
25.7	23.0	28.5	32.5	24.2	24.2	22.9	31.1	27.9	21.9	30.5
Environmental concerns										
25.5	24.9	26.1	28.0	23.6	27.6	21.0	35.8	26.8	21.0	32.6
Availability of repair service										
17.2	19.3	15.0	22.0	16.4	15.4	13.8	20.6	21.2	17.2	19.0
Concern for personal health/environmental choices										
16.0	14.8	17.2	19.5	16.3	13.0	14.2	16.0	21.3	12.8	18.1
Easily accessible information system about offers, promotions										
14.0	12.5	15.6	15.6	16.6	7.6	12.5	14.9	12.7	19.4	14.0
Something else										
0.5	0.6	0.3		0.6	0.5	0.4		0.1	0.7	1.2
Nothing could change my mind										
23.3	24.9	21.6	15.4	22.6	30.2	26.4	18.0	18.0	28.3	21.1
I own an electric vehicle										
0.5	0.8	0.2	0.5	0.7		0.2		1.6		0.7
Difficult to say/do not know										
7.0	9.0	4.8	4.9	6.1	10.3	8.2z	2.9	11.5	4.5	3.5

Source: own research (N = 999).

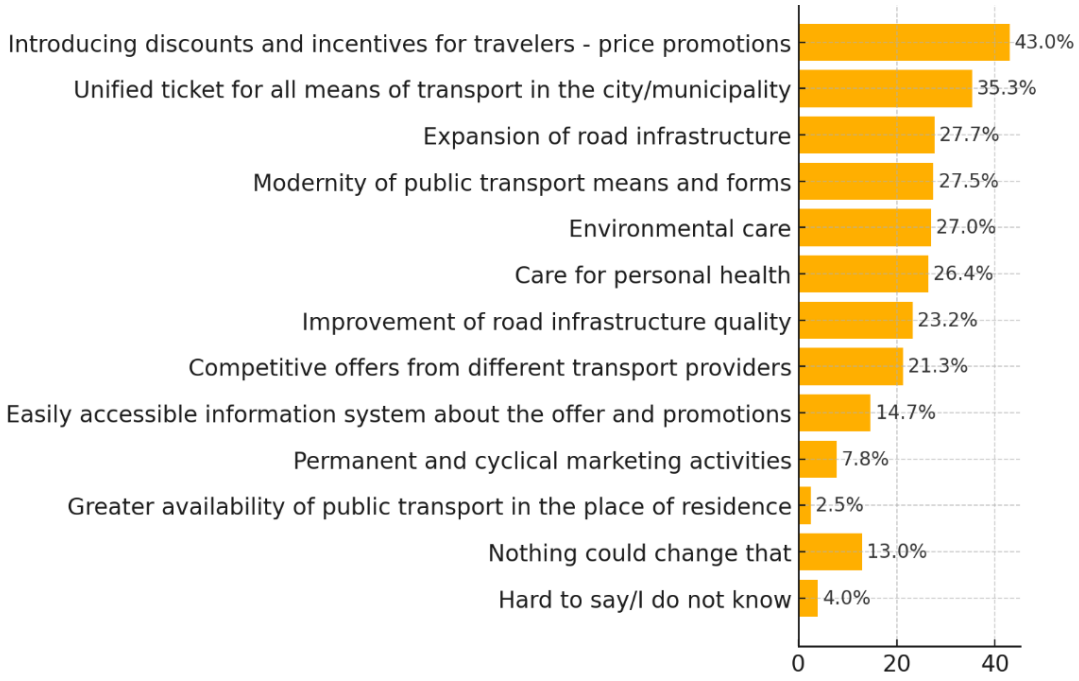


Figure 4. Factors that could influence changes in transportation habits regarding the shift from combustion engine cars to electric cars

Source: own studies.

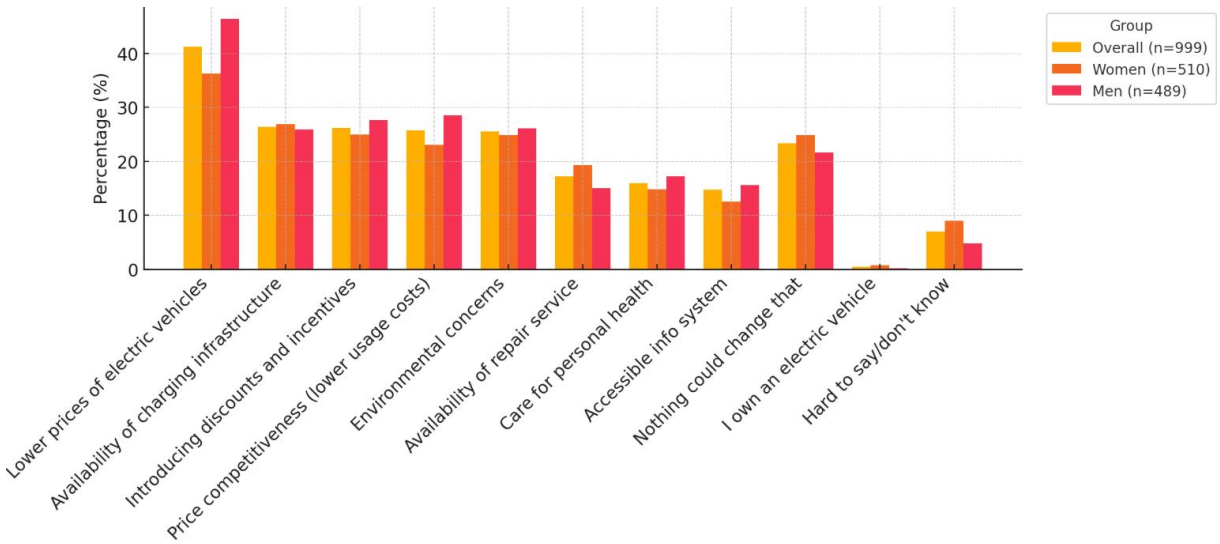


Figure 5. Factors that could influence changes in transportation habits regarding the shift from combustion engine cars to electric cars according to gender criteria

Source: own studies.

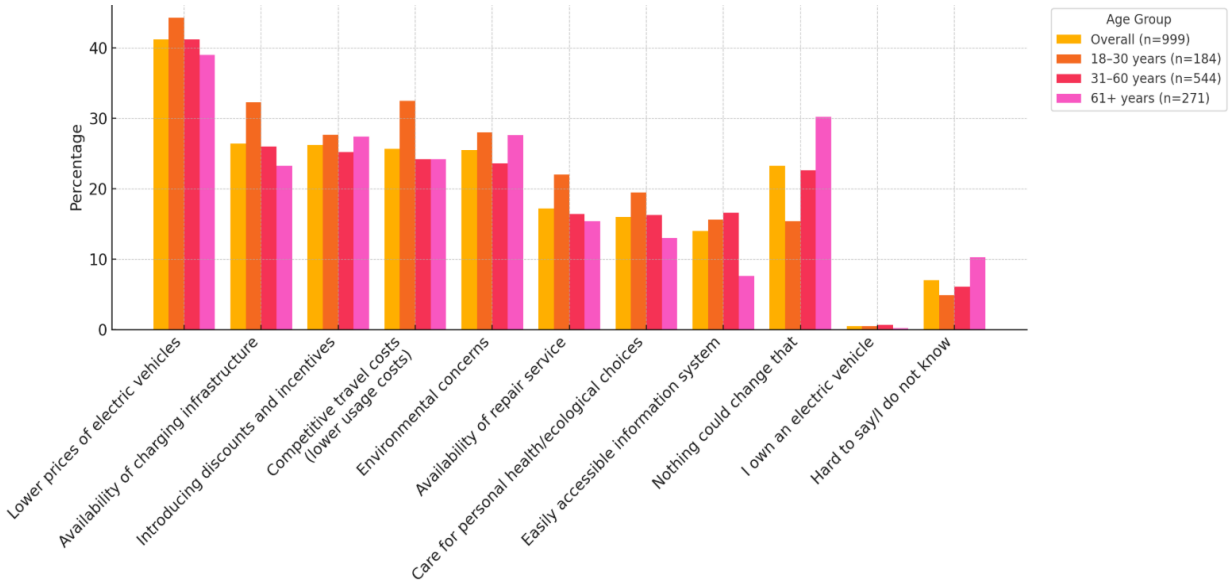


Figure 6. Factors that could influence changes in transportation habits regarding the shift from combustion engine cars to electric cars according to age criteria

Source: own studies

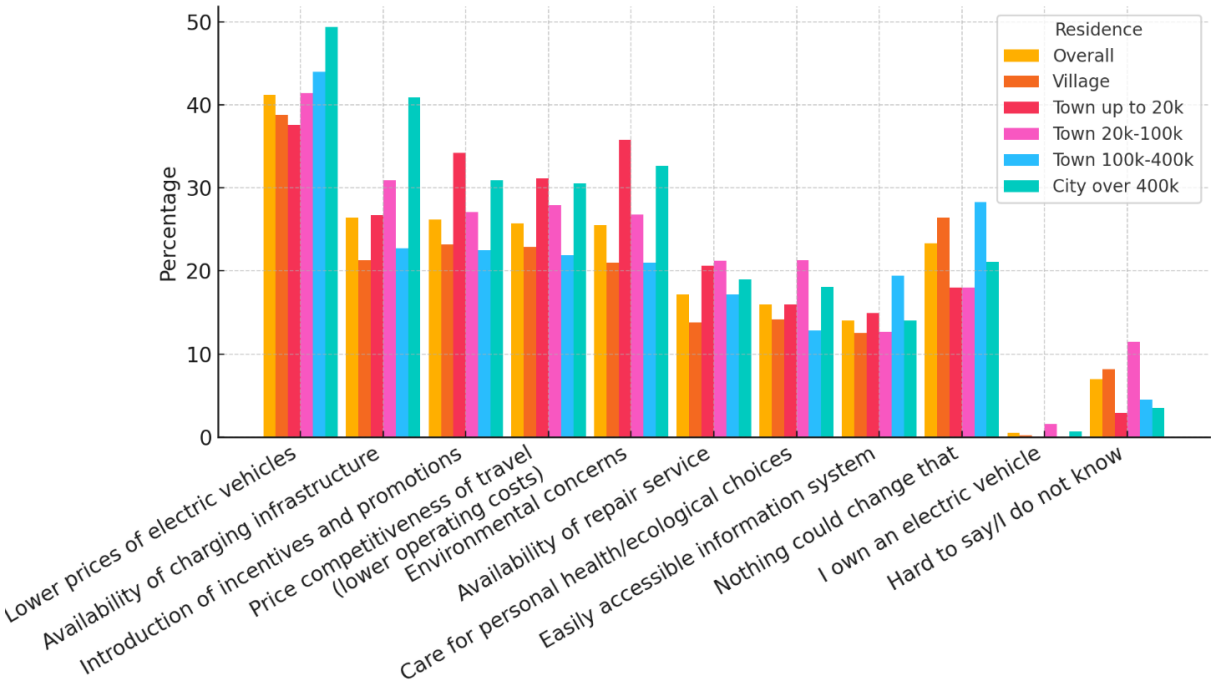


Figure 7. Factors that could influence changes in transportation habits regarding the shift from combustion engine cars to electric cars based on the criterion of residential area size

Source: own studies.

The results also vary based on respondents' education and income. Individuals with higher education significantly more often than those with vocational education chose lower prices of electric vehicles, availability of electric vehicle charging infrastructure, and price competitiveness of travel. Respondents whose net income per person ranged between PLN 2.000 to PLN 3.000 significantly more frequently than those with incomes up to PLN 1.000 indicated factors such as "Environmental concerns," "Price competitiveness of travel - lower operating costs," and "Lower prices of electric vehicles" ($p<0.05$).

9. DISCUSSION AND CONCLUSIONS

The presented studies and research results indicate that the issue of environmental choices and decisions made by travellers is highly important, both across the EU and specifically in Poland (EEA, 2022; Mercure & Lam, 2015; Mercure et al., 2018; Ritchie, 2020; Betta et al., 2021). Research highlights that ecological considerations increasingly influence travellers' purchasing decisions, reflecting growing consumer awareness about their impact on the environment (Khan, 2024; Morrison & Beer, 2017). According to Krajnc and Glavič (2003), ecological considerations include aspects such as cleaner and organic production, minimizing energy consumption, reducing CO_2 emissions, reducing water usage, recycling and reusing products, and minimizing transport needs. Considering the progress of AI it is worth noticing that Digital Twin Travellers frameworks can synthesise individual travel patterns from aggregated mobile-phone data, providing highly detailed inputs for passenger decision modelling and accurately reflecting traveller behaviours" (Anda, Ordonez Medina & Axhausen, 2021).

Consumer environmental awareness significantly reduces consumption imbalances (Khan, 2024). It involves recognizing the relationships between the environment's condition and the quality of life (Becla, 2016). Increased environmental awareness influences consumer decisions, driven by environmental education, social campaigns, availability of product information, and the rising importance of sustainable development issues (Han, 2021; Morrison & Beer, 2017).

Consumers aware of the negative impacts of consumption on the environment strive for sustainable choices. Unsustainable consumption, heightened by industrialization, is one of the primary causes of environmental degradation, including in Poland (Holden et al., 2013).

Transport emissions increased by 30% between 1990 and 2019 in the EU, contrasting with reductions in other sectors (EEA, 2022). International aviation and road transport significantly contributed to these increases, with road transport emissions rising by over 20% during the same period (EEA, 2022; US Environmental Protection Agency, 2024). Road transport alone is responsible for approximately 73% of Europe's transport emissions, with passenger cars accounting for around 12% of total EU CO_2 emissions (European Climate Pak, 2024).

Road transport's significant contribution to greenhouse gas (GHG) emissions in the EU highlights the importance of actions aimed at reducing emissions or changing travel habits (Schwanen et al., 2012; Marsden et al., 2014). In Poland, transport is responsible for approximately 17.1% of emissions from fuel combustion, making it the second largest emission-intensive sector after energy (Krajowy Raport Inwentaryzacyjny, 2023).

The authors see a substantial opportunity in applying AI-driven solutions to intelligent mobility management, "What really distinguishes a digital twin from a traditional simulator is its 'brain'—predictive and decision-making capabilities that allow it to extract patterns from real-time data and support intelligent traffic management and travellers' choices" (Di et al., 2024).

The application of intelligent management tools—such as AI-based modelling, integrated mobility platforms, and behavioural analytics—can significantly enhance the effectiveness of urban transport policies. By incorporating real-time user data and multi-criteria decision-making frameworks, city authorities are better equipped to design flexible, efficient, and sustainable mobility systems. This study provides a foundation for linking individual travel behaviours with system-level planning, demonstrating the potential of intelligent management in aligning personal choices with public transport goals."

Traveler choices reflect socio-economic and personal factors (Mostert & Limbourg, 2016). These decisions have become more pronounced due to experiences during the COVID-19 pandemic, where personal safety and convenience gained priority, thus influencing the preference for individual car transport over public options (Sher et al., 2021; Drożdż et al., 2022).

The study indicates two potential pathways to influence traveller choices:

a) Switching from combustion engine cars to electric vehicles (EVs):
- Lowering prices of electric vehicles,
- Improving charging infrastructure,
- Promoting environmental education and awareness.

b) Shifting from private cars to public transport or walking through:
- Incentives and price promotions,

- Unified ticket systems,
- Expansion of infrastructure,
- Modernization of public transport,
- Environmental education (Kamińska, 2021; Kos et al., 2022; Kos et al., 2020).

About 20% of travellers declared that nothing could persuade them to abandon car use, indicating deep-rooted behavioural preferences. The findings reflect principles such as the Inverted Mobility Pyramid, recommending selecting transportation modes with the least environmental impact (Kos et al., 2020).

Research limitations include its timing during a period of uncertainty related to the pandemic, possibly influencing respondents' conservative attitudes towards transport mode change. Further investigation into the underlying reasons for resistance to change is recommended to support future policymaking and strategic interventions (Mercure et al., 2018; Transport and Green Deal, 2024).

These results can inform policymakers and planners in developing effective strategies aligned with Poland's sustainable transport policy, ultimately addressing traveller expectations and achieving sustainable development goals. The growing availability of artificial intelligence solutions also opens up new possibilities for smart mobility management. Tools powered by machine learning can detect patterns in travel behaviour, predict demand, and offer recommendations that align with both individual convenience and environmental targets. These systems, when integrated into urban transport policies, can bridge the gap between sustainability goals and the actual decisions made by travellers. Research indicates that using artificial intelligence tools such as ChatGPT influences travellers' decisions regarding tourist destinations Simultaneously, there is considerable potential in AI. Research indicates that using artificial intelligence tools such as ChatGPT influences travellers' decisions regarding tourist destinations (Kim, Kim, Kim, & Hailu, 2023). At the same time, it is both desirable and expected to popularize tools and applications used by tourists, which would not only suggest what to see and how to book good accommodation at affordable prices but would also clearly and reliably show travellers how to reach these places and what external costs or environmental consequences are associated with their transport choices.

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QUANTIFYING THE CREATIVE CLASS–SUSTAINABILITY LINK: A COMPARATIVE EU ANALYSIS WITH AI INSIGHTS

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ABSTRACT

Purpose: *This study aims to indicate that contemporary development depends on the proper generation of the creative class (CC^{UE}) and the environment supporting its absorption in the perspective of sustainable development (SD^{UE}). It also highlights the significant potential of artificial intelligence for a positive impact.*

Need for the study: *Although theories and considerations about the creative class vary, emphasizing different research contexts, recognizing creativity as a determinant of innovation in many territorial areas seems unquestionable. Artificial intelligence has and will significantly impact these development processes in the near future, providing the creative class with new tools previously unused.*

Methodology: *Therefore, to determine the areas of these dependencies, several stages of analysis were carried out in the study part of the work, i.e.: standardization of variables describing selected research areas for EU countries; determination of weights for individual diagnostic variables (wj) CRITIC method; determination of an aggregate measure for sustainable development or creative class using the TOPSIS method, and the assessment of the degree of compliance of the obtained rankings were made using the Kendall's Tau coefficient (τ).*
Findings: *The results have shown a relationship between the development of the creative class and sustainable development in general, but also in selected areas of the so-called environmental and economic dimensions.*

Practical Implications: *The research results are particularly important for innovation, as they support the creative class, the sustainable development of countries, and the creation of suitable conditions that enhance their competitiveness.*

Keywords: creative class, sustainable development, EU countries, regional development, artificial intelligence, AI, culture

Jel codes: Q01; R11; Q56

1. INTRODUCTION

An attempt to present the historical process of shaping the concept of creative class (CC^{UE}) and its usefulness for the development of sciences is complex and ambiguous. Initially, attention was

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focused on the issues of the economics of creativity or the creative economy. The multitude of definitions created and their multi-layered use make it ultimately challenging to indicate the time from which the use of this term as an indicator of specific economic values dates back. This is because until recently economists have been discussing the issue of creativity, considering issues regarding the impact of the creative class on the economic development of countries or regions (Howkins 2001; Florida, 2002; Hartley, 2004; Hesmondhalgh, 2002; after Kloudov'a 2010; Florida, 2017; Ambrosino and Guillon, 2018; Gill et al., 2019; KEA, 2019; Bacsi, 2020, unfortunately, often treat them as a marginal phenomenon.

As a result of these considerations, two main scientific trends were formed, which can be defined as areas of activity and influence: sectoral and professional (Johansson & Karlsson, 2012). The primary representative of the sector approach is Howkins (2001), while the resource approach is represented by Florida (2002). Hence, Florida's (2002) research on creativity and its impact on economic development focuses on, among others, man, and specifically the creative class. The latter is the subject of interest in this article. According to its creator, R. Florida (2002), the feature of creativity is that members of the creative class perform the type of work that allows for the creative creation of new products or services. However, the creator of this theory did not examine members of the creative class in terms of their level of creativity, which we do not do in this article. Additionally, it should be noted that in this article the authors do not analyze other aspects of creativity, i.e. the participation of representatives of the creative class in the creative process (you can read more about the creative process: Rossman (1931), Osborn (1953), Tolkamp et al., 2023 or the features of the created creative work (what work can be considered creative in the literature on the subject was presented by: Hlavsa and Jurčová, 1978; Cropley, 1999; van Woerkum et al., 2007; Mayer, 2008; Nathan, 2019; Czerwińska, Lubszczyk, et al. 2022).

Therefore, the article's subject is the study of the development of the creative class and its relationship with the sustainable development of European Union countries. The article distinguishes between cognitive and empirical trends to show and analyze a specific scientific area. The first one is focused on a qualitatively comprehensive assessment of the literature on the subject, which allowed for critical analysis and shaped the research framework. On this basis, it is believed that research in the field of the development of the creative class has significantly evolved, influencing the development of the researched scientific discourse. This can be seen in the diversity of many thematic contexts regarding the issues discussed in the literature, for example, the analysis of creative cities or regions and the development of the creative class (for example Pratt, 2008), the development of modern enterprises and the influence of the creative class on them (for example Fang and Slaper, 2022), or the role of the creative class in the context of rural development (e.g. Kiminami et al., 2023). The research carried out in the article concerned concepts related to the development of concepts regarding the creative class and its connections with sustainable development and its distinguished components, i.e., economic, social, and environmental areas, concerning selected European Union countries. Additionally, the analysis concerned the demonstration of differences in the above-mentioned experiment regarding the division of 27 European Union countries, using the term so-called countries of the old EU and countries that joined the EU after 2004, calling them new countries. The old EU countries included: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, and Sweden (hereinafter described as category A), and the new EU countries are: Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia (described later in the article as category B). Moreover, it was assumed that the countries examined were treated as regions in this case. Aspects available in the literature on the subject were analyzed regarding the use of various proprietary methods allowing for the best assessment of the creative class and the components of sustainable development so that one could constructively conclude what should be done to develop it as best as possible, and then generate added value for sustainable development in surveyed countries belonging to the European Union.

The second study stream is focused on research on the importance of the creative class (CC^{UE}) and its relationship with the components of sustainable development (SD^{UE}) at the national level, taking into account the connotations related to the development of artificial intelligence (old and new EU countries). The article presents research on a new approach taking into account the authors' indicator for measuring the creative class, which was constructed by analyzing the availability of data in the Eurostat database for all EU countries and the years examined, as well as the following studies: Hong Kong's Creativity Index; Euro-Creativity Index (ECI); Silicon Valley's Creative Community Index; Sharpie's Creativity

Index; European Creativity Index (ECI) (KEA European Affairs, 2009); Design, Creativity and Innovation Scoreboard; Creative Space Index (CSI); Global Creativity Index (GCI); Washington's Creative Vitality Index (now: Creative Vitality Suite) (ArtsWA - Washington State Arts Commission and WESTAF - Western States Arts Federation) (Florida & Tinagli, 2004; Montalto et al., 2019). Moreover, sustainable development was prepared based on Ding et al. (2014), Rezende and Sinay (2016), and Pravitasari et al. (2018.

This part of the article presents the results of research using methods included in the Multidimensional Statistical Analysis, i.e. CRITIC (Criteria Importance through Inter-criteria Correlation method), which allows determining the importance of individual diagnostic variables, and the TOPSIS method, which allows obtaining an aggregated measure describing the level of sustainable development (SD^{UE}) or creative class (CC^{UE}) in the analyzed countries, and the degree of compliance of the obtained rankings was assessed using the Kendall's Tau coefficient (τ). Additionally, research was carried out taking into account time and comparison of the existing relationships and changes over ten years (the analysis includes variables describing sustainable development in the years 2010-2022, while in the case of data describing the creative class, the data covered the years 2013-2022). The research was conducted using measurable indicators, considering analytical data from Eurostat. It should be noted that Eurostat data on the cultural and creative industries (CCI) are extensive but not exhaustive, which has limited the analytical possibilities in this article. Although Eurostat provides a basic overview of the creative class and sustainable development, its data have scope, depth, and context limitations. To gain a more comprehensive understanding, it would be necessary to complement Eurostat statistics with qualitative research, case studies, and data from national or regional sources that reflect the intangible and evolving aspects of the creative economy. Despite the imperfection of Eurostat data for the studied groups of European Union countries, taking into account the time and space, the adopted data best reflected the research needs of the article. Hence, the decision was made to use them in the research methodology.

Then, the obtained results were analyzed by starting a thematic discussion, commenting on the research, pointing out limitations, and suggesting further research directions. Attempts were also made to refer to the development of artificial intelligence, which creates vast possibilities for developing tools that the creative class can use in their work. Thus, enriching the market with innovations. However, due to the lack of data indicating the development of artificial intelligence in European regions, the article will only present conclusions and thoughts in this regard, and implications for the development of the areas studied.

The conclusion of the research conducted in the article is to obtain answers to the following questions: *during the research period, did the creative class develop in the European Union countries, divided into the old and new EU countries? What scope of changes has occurred in the development of the creative class? Which components of sustainable development are the most appropriate determinants of the development of the creative class in EU countries (in categories A and B)? Will artificial intelligence influence the development of the creative class and the number of generated innovations, and thus the development of the studied regions?* Moreover, the research results allow for the presentation of recommendations for European Union countries, indicating to what extent and in which countries actions should be consistently taken to create conditions favorable to the creative class.

2. LITERATURE REVIEW

Fragmentary research conducted worldwide by various researchers dealing with the issues of human capital and its creativity constituted a theoretical and practical basis as an integrating whole to create a definition describing the creative class. However, the agreement on constructing a uniform definition remains unresolved in science and practice. This article will attempt to discuss the definition of the creative class and the preferences for its development, which became the basis for creating the original indicator used in the presented research.

2.1. Definition of the Creative Class

The creative class is defined as those individuals who perform professions, "whose function is to create meaningful new forms" (Florida, 2012), and who are generally highly mobile. It consists of people who co-create economic value through their creativity and creative activity, not only in the labor market but

also in the sphere of consumption, particularly purchasing behavior. The theory predicts that the creative class accumulates in areas with four attractive features: talent, tolerance, technology, and territoriality (4 T) (Florida, 2012). The author stated that this class derives its identity from its role in the economy as a creativity provider. Assuming that creativity is the driving force of economic growth, this class has become dominant in society (Florida, 2010). Therefore, the creative class is a group of individuals performing a closed list of professions, with specific characteristics and preferences regarding their work and residence.

The creative class can also be divided into two subgroups:

- super creative core, which includes people fully engaged in creative processes, working innovatively to develop new concepts and solve problems;
- employees are defined as creative professionals who use knowledge to a significant extent in their work (knowledge-intensive employees).

It should be emphasized, however, that Florida does not promote the artificial creation of elites or the division of communities into creative and non-creative ones. His considerations aimed to point out that every person is creative to some extent, but only a tiny part of society has the opportunity to receive remuneration for the effects of their creativity. In the era of the creative workforce (Florida, 2010), which is often situated within the creative industries (Caves, 2002) and in the broader context of the creative economy (Howkins, 2002), it is emphasized that some people working in creative professions, they have abilities that enable them to gain great economic benefits. These abilities include (Bridgstock, 2011): creativity, emotional intelligence, a predisposition to work in a team, and problem-solving skills.

In his works, Florida did not analyze the differences in the creative potential of representatives of the creative class. However, Eysenck (1993), researching the relationship between intelligence, creativity, and personality since the beginning of the 1980s, notes that people differ in their position on the dimension of characteristics determining creativity. Hence, at one extreme, some people have a negligible level of features that predispose them to be creative, while at the other extreme, there are people who have an outstanding amount of them (Sterlau, 2014). When examining the creative class in European Union countries, the authors of the article also did not research the intensity of creative traits in representatives of the creative class, because the following analysis used Eurostat statistical data, which did not consider such assessment criteria.

2.2. Development preferences of the creative class

A characteristic feature of people performing creative professions is the strong involvement of their members in professional activity. It should be noted that most studies focused primarily on factors attracting employees at the scale of a country, region, city (Andersen et al., 2010), or nation (Houston et al., 2008). However, little research has been done into the preferences of particular parts of the urban region among the 'creative class', whether this is the city centre, the outskirts, or the periphery. Moreover, R. Florida's theory of the creative class has been criticized due to its exclusive application in urban environments and neglect of rural areas (e.g., Gülümser et al., 2010; Hansen and Niedomysl, 2009 as cited in Rodrigues et al., 2024). M. Rodrigues et al. (2024) point out that in response to this criticism, there are selective studies by several authors who tried to extend them in the presented scope to rural areas (for example, these are the following works: McGranahan et al., 2001; Carruthers & Vias, 2005; McGranahan & Wojan, 2007; Nuur & Laestadius, 2009; Ström & Nelson, 2010; Xiong et al., 2020; Bjerke and Mellander, 2022 after (Rodrigues et al., 2024).

When reviewing the literature in the field of the presented scientific trend, which is the development preferences of the creative class, it is worth noting that the research primarily concerns cities and spaces where representatives of the creative class gather. The authors also present preferences in this area because cities constitute part of countries and regions. Therefore, researchers emphasize that for the development of creators and intellectuals, the factors of the socio-economic environment that stimulate this market segment in the area of work and the forms of spending free time are of great importance. Moreover, the main factors attracting the creative class usually include affluent labor markets, active social, cultural, and entertainment scenes, and a tolerant atmosphere, approximated by diversity indices (Clark et al., 2002; Florida, 2002; Florida, 2005; Florida et al. 2008 after Bereitschaft and Cammack, 2015). Among this rich assortment of territorial assets, diversity is often the most controversial in terms of its ability to attract creative class workers and catalyze economic growth (Anderson et al., 2010). Also important for developing the creative class is the so-called "quality of place" amenities. Features

that define the quality of a place include what is there (built and natural environments), who is there (diverse people), and what is happening (vibrant streets, café culture, art, music, and outdoor activities; Florida, 2012, after Natekal, 2023). There has been much discussion and research in recent years on the impact of place quality on attracting the creative class to these areas. For example, Zenker (2009) stated that the already mentioned "urban planning and diversity" play a unique role in attracting the creative class; Bereitschaft and Cammack (2015) found that this would be the proportion of same-sex households in a given location and income inequality; Bereitschaft & Cammack, 2015; pointed out that access to open spaces plays a role in attracting the creative class; Wood and Dovey (2015) would be fine-grained (lot size), post-industrial, hospitality and bohemian buildings, while Spencer (2015) found that creative industries were most likely to be located in dense, mixed-use neighborhoods close to the city center (Natekal, 2023).

It should be noted, however, that there is still a lack of significant research on the classic location factors determining the development of the creative class, such as living costs, and the individual's position in the life cycle (Clark et al., 1984) or accessibility to the workplace (Prashker et al., 2008). Also contrary to Florida's claims that the creative class is moving away from strong family ties, most findings indicate that closeness to family and friends and factors related to a creative worker's trajectory are important to their development (Chow, 2017).

It should also be noted that Florida's work cannot be transferred directly and entirely to Europe, because there are many suggestions and requirements regarding CIT facilities in Europe. European cities have, on average, higher population densities than American ones, and the European community shows greater diversity in culture, recreation, and entertainment infrastructure. Despite these limitations and partially justified criticism, the Florida method contributed to greater awareness of creative industries and the role of creativity in development. Hence, the authors of the article created their indicator for measuring the creative class in European Union countries (it was presented in the research part). Considering the availability of data, it has some limitations in this respect. However, the authors' task allows them to indicate trends and directions of development that may shed light on new research in this area and indicate new conclusions.

In addition, it should be emphasized that in the context of the changes taking place, including the development of the concept of intelligent management, it should be noted that it enables better use of the potential inherent in the creative class, for example by supporting local clusters, access to digital infrastructure, and investments in education. Intelligent management can create better conditions for its development. For example, these can be: access to co-working spaces, supporting culture and startups, good spatial planning, etc. The creative class and intelligent management are interconnected: the creative class needs intelligently managed spaces, and good management uses the knowledge and activity of this group of employees.

The concept of sustainable development has been developing worldwide for almost 50 years. During this time, both the concept and its approach have evolved. (Mebratu, 1998; Grober, 2007; Mensah, 2019; Ametepey et al., 2023). Nowadays, research topics related to sustainable development are discussed in the literature of various scientific disciplines: in the context of enterprises, cities, and regions, at the international level, and at various points in time (ex-ante, simultaneous, ex-post). (Lazaretti et al., 2019). There are many definitions and contexts of use. This means that sustainable development is interpreted ambiguously, and there is a risk that no one can precisely define this issue (Mensah & Enu-Kwesi, 2018). Many definitions show this is a multidimensional and complex problem (Kiselakova et al., 2020). Despite many doubts, the article's authors will attempt to analyze this phenomenon in the context of the issues considered in this study. It should be noted that the foundations for sustainable development in the EU were created in the early 1990s in Community law and scientific and research programs in environmental protection. The starting point for the contemporary discussion on sustainable development is primarily the work of the World Commission on Environment and Development (WCED). In 1987, the Commission published the report "Our Common Future", also known as the Brundtland Report, according to which "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Our Common Future, 1987). Brundtland's definition has an anthropocentric character, which is expressed by placing man and his needs at the center of attention (Speed, 2006). Moreover, in 2001, UNESCO (after Levickaitė, 2015) defined the concept of sustainable development not only as economic growth but also as the pursuit of adequate intellectual, emotional, moral, and spiritual existence. This change was

accelerated by the UNDP Human Development Reports, which began publication in 1991 through the work of economist Amartya Sen, who characterized the development as "expanding human capabilities", i.e., strengthening people's ability to lead lives as they want, including access to cultural resources and participation in culture. The world paid attention to the role of culture in thinking about development policy (WCCD, 1995 after Yang and Černevičiūtė (2017). In this regard, cultural diversity is the fourth element of sustainable development and embodies the concept of universally sustainable development (*Culture for Sustainable Development*, 2019; Bacsi, 2020). The first agenda, i.e. "Agenda 21" (2002, 2012), adopted at the United Nations Conference on Environment and Development (Rio de Janeiro, Brazil, June 3-14, 1992) presented an updated approach to the key pillars of sustainable development - economy, ecology, politics, and culture. Table 1 contains the history of the path to building Sustainable Development Goals.

Table 1. Genesis of building SDGs

Event	**Place, Year,**	**Actions**
The United Nations Conference on Environment and Development (UNCED), also known as the 'Earth Summit'	Rio de Janeiro, Brazil, 1992	More than 178 countries adopted Agenda 21, a comprehensive plan of action to build a global partnership for sustainable development to improve human lives and protect the environment.
Millennium Summit	New York, 2000	The Summit led to the elaboration of eight Millennium Development Goals (MDGs) to reduce extreme poverty by 2015.
World Summit on Sustainable Development	South Africa, Johannesburg, 2002	The Johannesburg Declaration on Sustainable Development and the Plan of Implementation. Reaffirmed the global community's commitments to poverty eradication and the environment, and built on Agenda 21 and the Millennium Declaration by placing more emphasis on multilateral partnerships.
United Nations Conference on Sustainable Development (Rio+20)	Rio de Janeiro, Brazil, in June 2012	Member States adopted the outcome document "The Future We Want," in which they decided, inter alia, to launch a process to develop a set of SDGs to build upon the MDGs and to establish the United Nations High-level Political Forum on Sustainable Development (HLPF). The Rio +20 outcome also contained other measures for implementing sustainable development, including mandates for future programmes of work in development financing, small island developing states, and more.
Open Working Group	2013	The General Assembly set up a 30-member Open Working Group to develop a SDG proposal.
UN Sustainable Development Summit	New York, 2015	The General Assembly began the negotiation process on the post-2015 development agenda. The process culminated in the subsequent adoption of the *Transforming Our World: the 2030 Agenda for Sustainable Development*, with 17 SDGs at its core.
The first SDG Summit – the High-level Political Forum on Sustainable Development (HLPF) under the auspices of the General Assembly	New York, 2019	It resulted in the adoption of the Political Declaration, “Gearing up for a decade of action and delivery for sustainable development.” World leaders called for a decade of action to deliver the SDGs by 2030 and announced accelerated actions to advance the agenda. The General Assembly endorsed the Political Declaration on 15 October 2019.
The second SDG Summit (HLPF) Acceleration and Accountability Platform	New York, 2023	To review progress and accelerate the 2030 Agenda for Sustainable Development implementation. *Documents:* "Times of Crisis,

Event	Place, Year,	Actions
		Times of Change: Science for Accelerating Transformations to Sustainable Development" (Global Sustainable Development Report (GSDR) 2023)**;** Report: **'**Progress towards the Sustainable Development Goals: towards a rescue plan for people and planet'

Source: *The 17 Goals*, 2023; *SDG the Summit*, 2023; *Documentation,* 2023.

The concept of sustainable development assumes achieving goals in three most important dimensions: economic (services, household needs, agricultural development, industrial development, effective use of labour), social (equality, participation, social mobility, cultural protection, empowerment), and environmental (McGill, 2013; Grayson & Kjellerena, 2015) after (Akkartal & Aras, 2021; Sokół & Mempel-Śnieżyk, 2022). Sustainable development can also be considered for economic and social reasons (McGill, 2013, after Akkartal and Aras, 2021). This requires a holistic approach due to the connections and dependencies between these areas. These three areas, domains, or pillars are widely described in the literature, and on this basis, a set of indicators was constructed and used in the calculations later in the article (Kates et al, 2005; Hasna, 2007; Elliott, 2013; Purvis et al., 2019). However, since the beginning of the 21st century, scientists and policymakers have been calling for missing pillars that could connect or be as important as these three. The literature mentions additional pillars, such as institutional (Spangenberg et al., 2002; Turcu, 2012), cultural (Soini & Birkeland, 2014), and technical (Purvis, Mao, Robinson, 2019).

In 2015, the United Nations 2015 adopted 17 Sustainable Development Goals (SDGs) in the '2030 Agenda'. Those global goals are for people and the planet; they have been set to improve lives, without leaving anyone behind (*The SDGs Explained for Business,* 2024). The 17 SDGs and 169 targets (*Transforming our world: the 2030..*, 2024) are the roadmap for how to build a better, sustainable world. Those 17 goals can be categorized into the five Ps: People (SDG1-6), Prosperity (SDG7-10), Planet (SDG11-15), Peace (SDG16), Partnership (SDG17) (Lekagul et al., 2022). Indicators of sustainable development are used to review the progress of each goal. To realize the '2030 Agenda' vision, monitoring a set of indicators at the global and EU levels is necessary. There are different sets of indicators depending on the nation and organisation. A set of global indicators is complemented at the regional and national levels. The UN indicators are used globally and hence are not always appropriate for the European Union (*EU SDG Indicator set,* 2023. The result of the review is in preparation for the 2023 edition of the EU SDG monitoring report – the final version of 24/05/2023. Eurostat has been making reports annually since 2017 to assess and monitor SDG progress. The EU indicator set comprises **102 indicators** structured along the 17 SDGs, and each goal has six exclusively attributed indicators. 34 of the 102 indicators are multipurpose, meaning they monitor more than one SDG (*Sustainable Development Goals Information on Data*, 2024). The global SDG indicators framework comprises 248 indicators, including 13 multipurpose ones. The United Nations Conference on Trade and Development (UNCTAD) encourages companies and has been working on SDG sustainability reporting by companies. To support governments in measuring the private sector's contribution to the implementation of the SDGs. It has developed its *Guidance on core indicators for entity reporting on the contribution towards implementation of the Sustainable Development Goals (GCI) and updated the second guidance: Core Indicators for Sustainability and SDG Impact Reporting: Training Manual* (UNCTAD/DIAE/2020/2/Rev.1; 21 July 2023). The core SDG indicators cover the economic, environmental, social, and institutional areas (see Table 2).

Table 2. Areas of core SDG indicators

Economic area indicators	Social area indicators
• Revenue	
• Value added (gross value added, GVA)	• Share of women in managerial positions
• Net value added (NVA)	• Hours of employee training
• Taxes and other payments to the Government	• Expenditures on employee training
• Green investment	• Employee wages and benefits
• Community investment	• Expenditures on employee health and safety

• Expenditures on research and development • Share of local procurement	• Incidence rate of occupational injuries • Share of employees covered by collective agreements
Environmental area indicators • Water recycling and reuse • Water use efficiency • Water stress • Waste generation • Waste is reused, re-manufactured, and recycled • Hazardous waste generation • Greenhouse gas emissions • Ozone-depleting substances and chemicals • Share of renewable energy • Energy efficiency • Land used adjacent to biodiversity-sensitive areas	Institutional area indicators • Board meetings and attendance • Share of female board members • Board members by age range • Audit committee meetings and attendance • Compensation per board member • Corruption incidence • Management training on anti-corruption

Source: *Core Indicators for Sustainability and SDG Impact Reporting: Training Manual, 2023.*

In the literature, a critical reflection on a global set of SDG indicators appears among researchers (Mair et al., 2018; Diaz-Sarachaga et al., 2018; Brussel et al., 2019; Lyytimäki et al., 2020; Kasztelan, 2022; Lepenies et al., 2023; Gebara et al., 2024). Creating and constructing a unique indicators framework is essential for monitoring progress toward SD, considering specific areas. That is why, for the creative class, authors create their own set of SD indicators.

The creative class and creativity are indispensable aspects of sustainable development (Shu et. al. 2020) as they contribute to economic growth, social stability, and environmental protection through innovation and creative solutions. The creative class attracts innovative talent and technological investment to regions, thereby increasing economic prosperity. As highlighted by Zhao et al. (2020), according to Lim (2016), it contributes to greater economic efficiency and minimizes environmental impacts. The creative class and creativity are both a source of new products and services and a catalyst for broader social and economic change toward a more sustainable future. Through creative processes and innovation, it is possible to significantly contribute to developing a more sustainable society, support global efforts to protect the environment and increase economic efficiency and social justice.

According to Lozano (2011), creativity leads to the creation of new knowledge and approaches needed to find solutions to increase sustainability and minimize environmental impacts (De Lucia et al., 2016). The creative class influences sustainability from individual creativity that sparks new sustainable ideas to organizational changes that institutionalize those ideas to broader societal changes toward sustainability (Brem & Puente-Díaz, 2020). Learning in these organizations involves acquiring new knowledge and unlearning outdated models and practices that are not environmentally sustainable. This continuous process of learning and adaptation is essential to achieve long-term sustainability goals (Lozano, 2011). In Puglia, young entrepreneurs benefit from support from Principi Attivi in implementing start-ups that focus on sustainability. This initiative shows how creative projects can contribute to regions' economic and social development (De Lucia et al., 2016). Firms that use their creative resources effectively can achieve a better market position and are often able to grow more sustainably (Srikalimah et al., 2020).

3. METHODOLOGY

In this study, we developed a creative class (CC^{UE}) index to assess sustainability (SD^{UE}) and its old and new sub-indexes in European Union countries. Based on the critical analysis of the literature on the subject, the authors concluded that *there are relationships between the development of the creative class and sustainable development in general in the old and new countries of the European Union*. To verify the adopted research hypothesis, several stages of analysis were carried out, i.e.:

- analyzes the development of the creative class and their relationship with SD^{UE} at the level of the countries surveyed;

– analysis of CC^{UE} and SD^{UE} growth rates to confirm the relationship in the analyzed years in the countries of the old and new European Union (in categories A and B).

To this end, the first methodology step focused on the data necessary for the analysis. In our case, the choice of indicators is primarily determined by their availability, as most indicators come from Eurostat sources. The subject of the analysis was the 27 countries currently part of the European Union. For all countries, data were collected on 26 variables describing sustainable development and 11 variables describing the creative class (Figure 1). For the above variables, data was collected, as mentioned above, based on Eurostat. However, in the case of variables describing sustainable development, the data covered the years 2010-2022, while in the case of data describing the creative class - CC^{UE}, the data covered the years 2013-2022. In the case of missing data for a given year, the value of the nearest different year was assumed. In contrast, in the case of the $SD^{UE}24$ and $SD^{UE}25$ variables, these values were converted to one million inhabitants of a given country. In the case of Malta and Romania, for the $SD^{UE}2$ and $SD^{UE}21$ variables, their level was assumed to be the arithmetic mean of the other countries due to the complete lack of data.

When examining the level of sustainable development and the state of the creative class of specific EU countries, it should be borne in mind that it is a specific multidimensional characteristic, not directly measurable, but described by several diagnostic variables that should be substantively related to this concept. The countries are ordered from the "best" to the "worst" based on the value describing individual countries, obtained from the function aggregating the information in the adopted diagnostic variables. The main stages of the procedure aimed at obtaining a synthetic variable based on previously adopted diagnostic variables included:

- normalizing the variables in the interval [0,1]:
- in the case of a stimulant, according to the formula:

$$z_{ij} = \frac{x_{ij} - \min\limits_{i} x_{ij}}{\max\limits_{i} x_{ij} - \min\limits_{i} x_{ij}} \tag{1}$$

- in the case of destimulants:

$$z_{ij} = \frac{\max\limits_{i} x_{ij} - x_{ij}}{\max\limits_{i} x_{ij} - \min\limits_{i} x_{ij}} \tag{2}$$

- determination of weights for individual diagnostic variables (wj) CRITIC method (Criteria Importance through Inter-criteria Correlation method) (Diakoulaki et al., 1995), which requires standardization of variables following formulas (1) and (2), then determining the standard deviation σj for each normalized variable and the linear correlation coefficients rij between all variables. The values of individual weights are determined based on formula (3):

$$w_j^5 = \frac{C_j}{\sum_{k=1}^{n} C_k} \tag{3}$$

where:

$$C_j = \sigma_j \cdot \sum_{k=1}^{m} (1 - r_{ik})$$

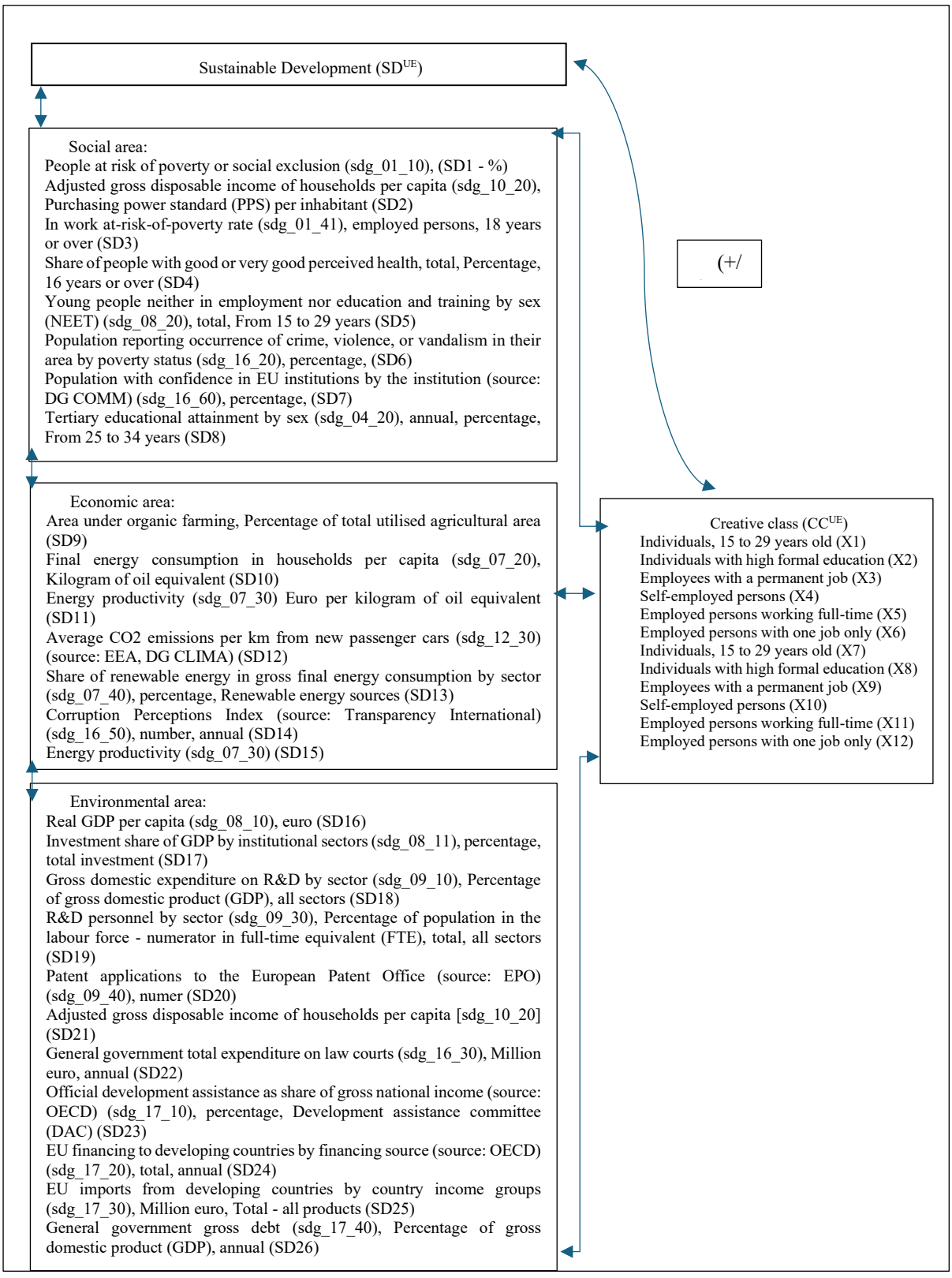


Figure 1. Research model
Source: own elaboration.

- determining an aggregate measure for sustainable development or creative class using the TOPSIS method (a *technique for order preference by similarity to ideal solution*) (Hwang & Yoon, 1981, pp. 130-132), according to which the ranking of objects is created based on the values determined according to the formula:

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-}, \tag{4}$$

where:

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(z_{ij}\cdot w_j - z_0^+\right)^2},\ \text{i=1,2…m}$$
$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(z_{ij}\cdot w_j - z_0^-\right)^2},\ \text{i=1,2…m} \tag{5}$$

$$z_0^+ = \begin{cases} \max\limits_i z_{ij}\cdot w_j & in\ the\ case\ of\ stimulants \\ \min\limits_i z_{ij}\cdot w_j & in\ the\ case\ of\ destimulants \end{cases} \tag{6}$$
$$z_0^- = \begin{cases} \min\limits_i z_{ij}\cdot w_j & in\ the\ case\ of\ stimulants \\ \max\limits_i z_{ij}\cdot w_j & in\ the\ case\ of\ destimulants \end{cases}$$

The degree of agreement of the obtained rankings was assessed using Kendall's Tau coefficient (τ). This coefficient takes values in the range <-1, 1>, and a value of 1 means full compliance, a value of 0 means no compliance with the orderings, and a value -1 means complete opposition. To verify the hypothesis about the consistency of the obtained rankings, the Kendall's Tau significance test was used, for which the test statistic was defined as:

$$Z_\tau = \frac{\tau}{\sqrt{\frac{2(2n+5)}{9n(n-1)}}} \tag{7}$$

for n>=10 it is asymptotically normally distributed (Abdi, 2007).

4. RESULTS

To determine any possible time shift between the level of the creative class (CC^{UE}) and the degree of sustainable development (SD) of individual countries, a preliminary analysis of the relationship between the position in the ranking describing the level of the creative class in 2013 and the results of the study on the level of sustainable development in 2013, 2012, 2011 and 2010 was carried out. The same procedure was repeated in the case of determining the level of the creative class (CC^{UE}) in 2022, comparing the results with the obtained sustainable development (SD) rankings in 2022, 2021, 2020, and 2019. The research results were presented for individual countries but also taking into account division into so-called countries old EU, which include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden (hereinafter described as category A), and the countries that joined the EU after 2004, the so-called new EU countries and these are: Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia (hereinafter described as category B).

In each case, statistically significant negative relationships were obtained between the level of the creative class (CC^{UE}) and the degree of sustainable development (SD) (in the case of the level of the creative class in 2013: τ = -0.31; p-value = 2.31E-02 for development sustainable in 2013; p-value=6.32E-03 for sustainable development in 2012; p-value=9.16E-03 for sustainable development in 2011; τ=-0.35; p-value=1.03E-02 for sustainable development in 2010; in the case of the creative class level in 2022: τ=-0.37; p-value=7.16E-03 for sustainable development in 2022; τ=-0.38; p-value=5.56E-03 for sustainable development in 2021; τ=-0.36; p-value=8.11E-03 for sustainable development in 2020; τ=-0.34; p-value=1.17E-02 for sustainable development in 2019).

Table 3. Relationships between CC^{UE} and SD^{UE} (2013, 2023)

	CC^{UE} 2013		CC^{UE}2023	
	Kendall's Tau	**p-value**	**Kendall's Tau**	**p-value**
SD^{UE} total	-0.3732	6.32E-03	-0.3789	5.56E-03
SD^{UE} social	-0.2137	1.18E-01	-0.0997	4.66E-01
SD^{UE} economic	-0.4121	2.50E-03	-0.4758	4.99E-04
SD^{UE} environmental	-0.2479	6.97E-02	-0.3618	8.11E-03

Source: *own research.*

On this basis, it was assumed that a given country's sustainable development (SDUE) level translates into the creative class (CCUE) level with a one-year delay. A detailed analysis of the impact of sustainable development on the level of the creative class, even taking into account a one-year delay, indicates that individual areas of this development, i.e., the social, economic, and environmental areas, influence the development of the creative class in different ways. Analyzing the results of the creative class (CCUE) development in 2013 against the background of individual areas of sustainable development (SD^{UE}) in 2012, it can be noted that the economic area had only a statistically significant impact on the development of the creative class. In 2022, the level of development of the creative class of individual EU countries depended not only on the degree of sustainable development in the economic area in 2021 but also significantly on the environmental area (see Table 3).

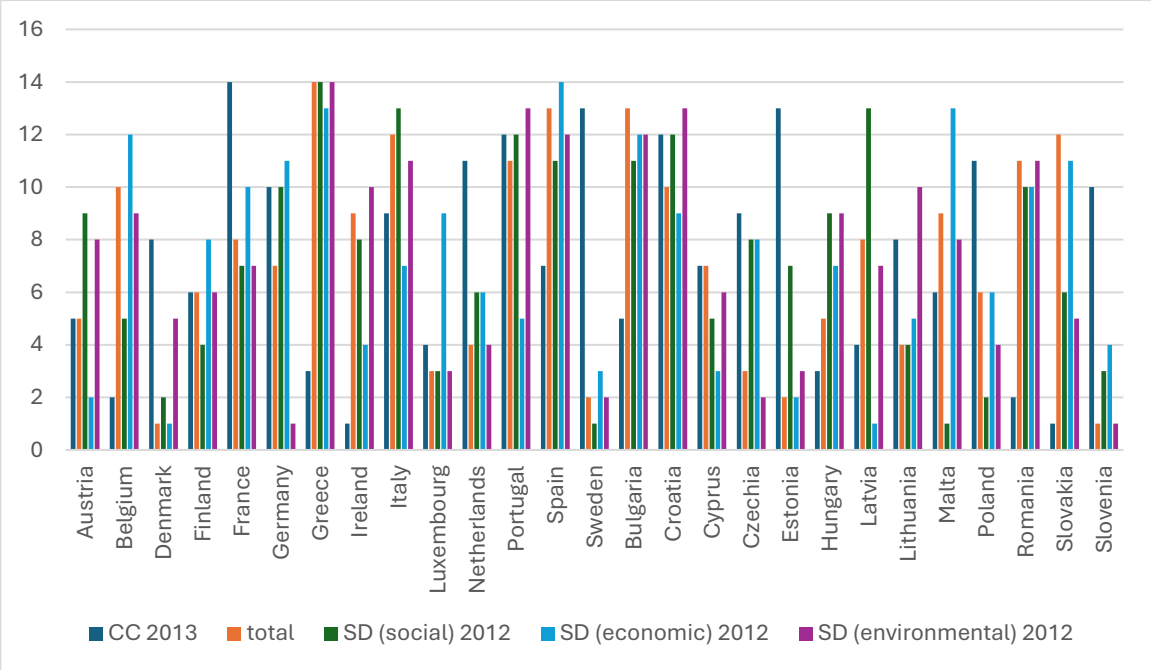


Figure 2. Positions of individual EU countries in the CC^{UE} and SD^{UE} rankings (2012 and 2013)
Source: *own research.*

Carrying out a separate analysis for the countries of the so-called old European Union (category A), i.e. countries that formed the European Union before 2004, and new members of the European Union, i.e. countries that joined the European Union after 2004 (category B), it can be concluded that in terms of the creative class (CC^{UE}) in the top ten in both analyzed periods there were only two countries of the old European Union (category A), while in terms of sustainable development, there were nine such countries (see chart 1 and 2).

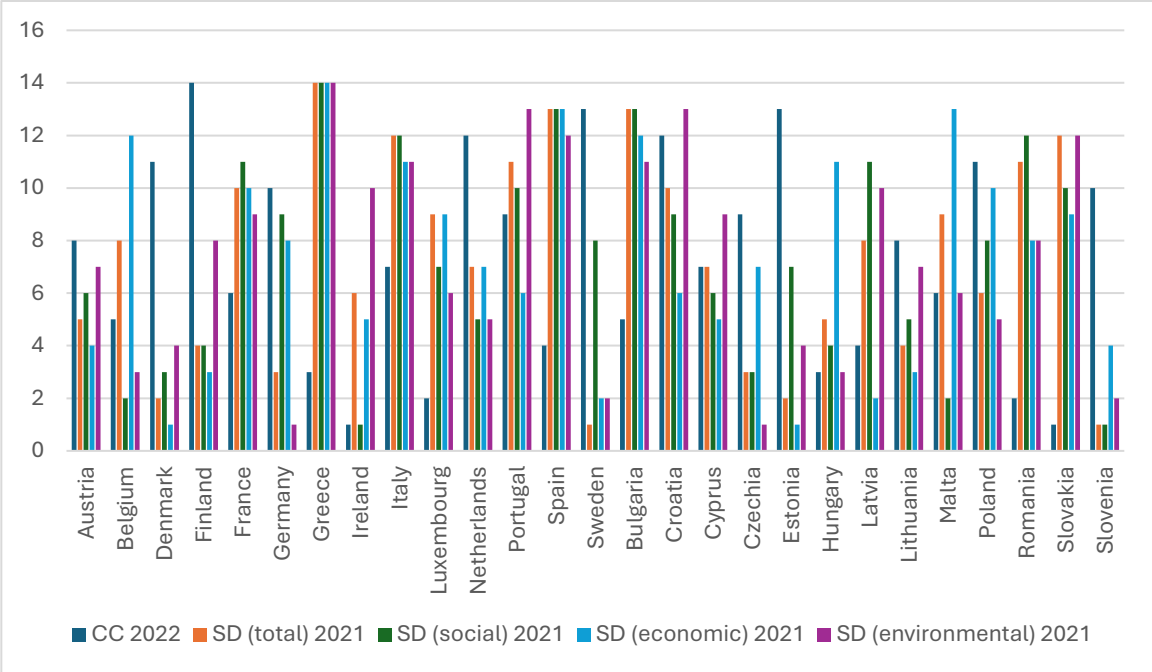


Figure 3. Positions of individual EU countries in the CC^{UE} and SD^{UE} rankings (2021 and 2022)
Source: *own research.*

Analyzing separately the so-called old European Union (category A) and countries that joined the European Union after 2004 (category B), it can be seen that in 2013 the level of the creative class (CC^{UE}) in the case of new European Union countries depended only and exclusively on total sustainable development (SD^{UE}), but there was no dependence on individual areas describing this development. However, there was no relationship between the level of the creative class and individual areas describing sustainable development in 2012 in the case of the old EU countries (category A). In 2022, the level of the creative class among the countries of the old European Union depended not only on the total sustainable development but also on the environment describing this development and the economic area. In the case of new European Union countries (category B), sustainable development had a significant overall impact on the level of the creative class (see Table 4).

Table 4. Study of the relationship between CC^{UE} and SD (including the division into the so-called old EU countries - category A and new EU countries - category B)

		CC^{UE}2013		CC^{UE}2022	
		Kendall's Tau	**p-value**	**Kendall's Tau**	**p-value**
SD^{UE} total	A	-0.1429	2.96E-01	-0.4505	9.78E-04
	B	-0.4615	7.32E-04	-0.4615	7.32E-04
SD^{UE} social	A	-0.0546	6.88E-01	-0.1868	1.72E-01
	B	-0.1795	1.89E-01	-0.2051	1.33E-01
SD^{UE} economic	A	-0.1648	2.28E-01	-0.4725	5.45E-04
	B	-0.2308	9.13E-02	-0.2564	6.06E-02
SD^{UE} environmental	A	-0.2308	9.13E-02	-0.2967	2.99E-02
	B	-0.2308	9.13E-02	-0.2564	6.06E-02

A – Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden

B - Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia

Source: *own research.*

Such significant differences between the obtained rankings for the old and new European Union countries may result, to a large extent, from the entirely different meaning of the adopted variables describing the creative classes of these two groups of countries. Analyzing the importance of individual variables separately for the group of old European Union countries and separately for the group of new European Union countries, higher importance can be noticed, among others: variables x1, x3, and x10 for the old countries compared to the new countries in 2013, and on the other hand, a significantly higher importance for the new European Union countries compared to the old European Union countries of such variables as x2 or x11 (see Table 7 in the annex). In 2022, however, variables such as x1, x7, and x9 were of much greater importance for the countries of the old European Union, and for the new countries of the European Union, such variables as x2, x3, x8, and x11 (see Table 8 in the appendix). Different values of weights in individual groups of countries could result, among other things, from a different level of development of those describing the creative classes of these countries. The numerical characteristics describing the basic statistical parameters for the variables describing the creative classes adopted in the study for all 27 European Union countries, and divided into countries that formed the European Union before 2004 and joined the European Union after 2003, are presented in Tables 9 and 10 in the Annex.

Analyzing the relationship between the level of the creative class (CC^{UE}) and the level of sustainable development (SD^{UE}) at the level of individual countries in the years 2012-2022 (taking into account the previously discussed one-year delay), it is impossible to talk about a typical statistically significant relationship in this respect, both among new and old EU countries. In the case of the group of "old" EU members (category A), general sustainable development had a significant impact on the development of the creative class only in the case of Spain ($\tau = 0.64$, p-value = 9.49E-03), where there was also a significant influence of the environment ($\tau = 0.60$, p-value=1.57E-02), social factors significantly influenced the creative class only in the case of Finland and Portugal ($\tau = -0.47$, p-value=6.03E-02), economic factors only in the case of Belgium ($\tau = -0.47$, p-value=6.03E-02).

Table 5. Study of the relationship between CC^{UE} and SD^{UE} (the so-called old EU countries were included - category A)

		SD^{UE} (total)	**SD^{UE} (social)**	**SD^{UE} (economic)**	**SD^{UE} (environmental)**
	Kendall's Tau	0.0667	0.0222	0.2000	0.1111
Austria	p-value	7.88E-01	9.29E-01	4.21E-01	6.55E-01
	Kendall's Tau	-0.0667	0.1111	-0.4667	-0.0667
Belgium	p-value	7.88E-01	6.55E-01	6.03E-02	7.88E-01
	Kendall's Tau	0.0222	0.2889	-0.1556	0.0222
Denmark	p-value	9.29E-01	2.45E-01	5.31E-01	9.29E-01
	Kendall's Tau	0.0222	-0.4667	-0.2444	0.2444
Finland	p-value	9.29E-01	6.03E-02	3.25E-01	3.25E-01
	Kendall's Tau	0.2000	0.3333	0.2444	0.0222
France	p-value	4.21E-01	1.80E-01	3.25E-01	9.29E-01
	Kendall's Tau	-0.3778	-0.0667	-0.4222	-0.4222
Germany	p-value	1.28E-01	7.88E-01	8.92E-02	8.92E-02
	Kendall's Tau	0.2444	-0.1111	-0.2444	0.5111
Greece	p-value	3.25E-01	6.55E-01	3.25E-01	3.97E-02
	Kendall's Tau	-0.2444	-0.0667	-0.3778	-0.1111
Ireland	p-value	3.25E-01	7.88E-01	1.28E-01	6.55E-01
	Kendall's Tau	0.1556	0.0222	-0.3778	0.3333
Italy	p-value	5.31E-01	9.29E-01	1.28E-01	1.80E-01
	Kendall's Tau	0.3333	-0.0222	0.1111	0.2000
Luxembourg	p-value	1.80E-01	9.29E-01	6.55E-01	4.21E-01
Netherlands	Kendall's Tau	0.2000	0.2444	-0.2000	0.3778

		SD^{UE} (total)	SD^{UE} (social)	SD^{UE} (economic)	SD^{UE} (environmental)
	p-value	4.21E-01	3.25E-01	4.21E-01	1.28E-01
	Kendall's Tau	0.2889	0.4667	0.3333	0.0222
Portugal	p-value	2.45E-01	6.03E-02	1.80E-01	9.29E-01
	Kendall's Tau	0.6444	0.1111	-0.0667	0.6000
Spain	p-value	9.49E-03	6.55E-01	7.88E-01	1.57E-02
	Kendall's Tau	-0.0222	-0.2444	0.2000	0.1111
Sweden	p-value	9.29E-01	3.25E-01	4.21E-01	6.55E-01

Source: *own research.*

Among the "new" EU countries (category B), Malta stands out in this respect, as the development of the creative class depended not only on the level of sustainable development in total (τ= 0.64, p-value=9.49E-03) but also on the environmental (τ= 0.46, p-value=6.03E-02), economic and social factors (τ= 0.21, p-value=3.97E-02). Economic and social factors also significantly influenced the development of the creative class in the discussed period in the case of Romania (τ= 0.47, p-value=6.03E-02) and Slovenia (corresponding τ=0.51 and p-value=3 .97E-02 and τ= 0.78, p-value=1.75E-03).

Table 6. Study of the relationship between CC^{UE} and SD^{UE} (new EU - category B included)

		SD^{UE} (total)	SD^{UE} (social)	SD^{UE} (economic)	SD^{UE} (environmental)
	Kendall's Tau	0.4222	-0.0222	0.3333	0.0222
Bulgaria	p-value	7.88E-01	9.29E-01	4.21E-01	6.55E-01
	Kendall's Tau	0.4222	0.3778	0.3778	-0.0222
Croatia	p-value	8.92E-02	1.28E-01	1.28E-01	9.29E-01
	Kendall's Tau	0.3778	0.1556	0.3333	0.3333
Cyprus	p-value	1.28E-01	5.31E-01	1.80E-01	1.80E-01
	Kendall's Tau	-0.2889	-0.0222	-0.2444	-0.3778
Czechia	p-value	2.45E-01	9.29E-01	3.25E-01	1.28E-01
	Kendall's Tau	-0.2889	0.1111	-0.0667	-0.1111
Estonia	p-value	2.45E-01	6.55E-01	7.88E-01	6.55E-01
	Kendall's Tau	0.2444	0.4667	-0.3333	0.7333
Hungary	p-value	3.25E-01	6.03E-02	1.80E-01	3.16E-03
	Kendall's Tau	0.3778	0.0667	0.2444	0.3333
Latvia	p-value	1.28E-01	7.88E-01	3.25E-01	1.80E-01
	Kendall's Tau	-0.1111	0.0667	0.0667	-0.0667
Lithuania	p-value	6.55E-01	7.88E-01	7.88E-01	7.88E-01
	Kendall's Tau	0.6444	0.5111	0.5111	0.4667
Malta	p-value	9.49E-03	3.97E-02	3.97E-02	6.03E-02
	Kendall's Tau	0.3333	0.4222	-0.0222	0.4222
Poland	p-value	1.80E-01	8.92E-02	9.29E-01	8.92E-02
	Kendall's Tau	0.3333	0.4667	0.4667	0.2889
Romania	p-value	1.80E-01	6.03E-02	6.03E-02	2.45E-01
	Kendall's Tau	-0.1556	-0.0667	-0.5111	0.0222
Slovakia	p-value	5.31E-01	7.88E-01	3.97E-02	9.29E-01
	Kendall's Tau	0.2889	0.5111	0.7778	-0.2000
Slovenia	p-value	2.45E-01	3.97E-02	1.75E-03	4.21E-01

Source: *own research.*

5. DISCUSSION

An essential process in the modern economy is a strong tendency to concentrate human capital, including the creative class. There is talk of a trend of accumulation of this capital in selected global metropolises. At the same time, in the literature on the subject, there are attempts to explain why only selected areas are centers of accumulation, not of human capital, but of the creative class (Klasik, 2018). This trend will intensify with the development of artificial intelligence, which provides a wide range of tools previously unused by the creative class for innovation. At the same time, artificial intelligence poses and will pose new challenges for the creative class. To meet the need for further research, the article proposes the development of a creative class (CC^{UE}) indicator, which was presented as a result of comparative research of a group of European Union countries. The index was constructed based on data availability for all EU countries surveyed in Eurostat. The analysis of the development of the creative class showed that in 2013, its best condition, based on selected indicators, was observed in countries such as Ireland, Slovakia, Romania, Lithuania, and Malta. It can be said that positive trends were observed in the countries that joined the European Union after 2004 (category B). It seems very interesting to conduct systematic research on artificial intelligence and its impact on the development of the creative class. The latest reports and decisions of the US government have indicated wider access to the development of artificial intelligence in the countries of the Old European Union (Marszycki, 2024; Brokking, 2025). *One can ask whether this trend will be maintained or completely reversed.* Comparing the surveyed countries in terms of CC^{UE}, in 2022, after 10 years, there were minor changes: Malta was in third position in the surveyed group of countries, while Romania moved from third position to seventh. The analysis showed that the level of variability among the leaders (the first five countries in the ranking) is small. It can therefore be concluded that the trend is constant and the direction of development is also significantly unchanged. The countries of the old European Union (category A) did not rank high in this respect. It can be concluded that the results obtained in the study do not confirm the direct impact of the creative class on the country's innovativeness. The article makes rather general implications due to the lack of much data regarding the impact of artificial intelligence on the development of creative capital. However, in an attempt to address these issues, one can, for example, cite the research conducted by B. Brey and E. Marel (2024), which showed a relationship between human capital and the implementation of artificial intelligence in various industries and countries. Their research showed that higher levels of human capital are associated with higher shares of artificial intelligence implementation by companies. Although the analysis concerns human capital, creative capital is part of it. Hence, it can be concluded that the same relationship may appear in the case of analyses conducted using the creative capital indicator. In 2017, the European Commission indicated that, for example, Sweden again became the innovation leader of the European Union, followed by Denmark, Finland, the Netherlands, and Great Britain (*EU innovation ranking. Poland was in fourth place in 2017*. Denmark is the new leading innovator with the best results in the EU, overtaking Sweden after several years in the leading position. Other innovation leaders include Sweden, Finland, the Netherlands, and Belgium (European Innovation Scoreboard, 2023). Therefore, the so-called countries were at the forefront. old European Union (category A). Therefore, the presented research shows that the role of the creative class in European economies does not play such an important role in the level of innovation in EU countries. As can be seen, in countries where innovation is developing, the level of development of the creative class included in the ranking of countries does not achieve leading positions. For example, in terms of the development of the creative class in 2013, Denmark was in 23rd position in the ranking of 27 countries (in 2022 - 25th position), Sweden in 26th position (in 2022 - 23rd position), Finland in 16th position (in 2022 - 27th position) and the Netherlands and Belgium were 24th and 13th respectively, and in 2022 it was the same position in the ranking (see chart 1 and 2). Indeed, the countries that joined the European Union after 2004 (category B) are countries that, thanks to the transformation process that has been taking place over the years, are developing better and better and occupy higher and higher positions in such rankings. However, the leading economies in this dimension are still the countries of the old European Union (*Real GDP growth rate - volume*, Eurostat, 2024). The results of the research presented in the article in this area are confirmed by Glaeser's (2004) research. The cited second author admits that the preferences of the most creative

people do not differ from those of other employees. Glaeser, performing his calculations, finds no confirmation that Florida's Bohemian Index plays a role in economic development. It can also be pointed out that another researcher, Malanga (2004), goes a step further and claims that Florida's creative centers are not the regions that have experienced the greatest employment growth. According to him, growth occurred in cities with low corporate tax burdens and generally pro-business environments focused on achieving success in population and employment growth and creating modern jobs. Additionally, justification can be sought in many conditions for the development of the creative class, which negatively affects their development. It should be concluded that for the creative class to develop and generate added value, it is necessary to create favorable socio-economic conditions in the studied countries, as mentioned in the article's theoretical part. According to the article's authors, these conditions should be created in urban and rural areas. A lot depends on these conditions, which may stimulate or inhibit the development of entities from the discussed industry. It should also be noted that assessing the effectiveness of these research categories is very difficult because they are complex phenomena. They reflect the features of society as a nation, its characteristics, and the requirements placed on these entities as generators of novelty. Moreover, our research results have shown that the concentration of high-income countries (*World Economic Outlook Database*, October 2019, 2020) in our ranking presented in tables 2 and 3 of the article indicates a negative relationship between the development of the creative class (CC^{UE}) and the socio-economic development economic situation of the surveyed EU countries. In 2012, the overall sustainable development (SD^{UE}) index was highest in countries such as Sweden, Denmark, Luxembourg, the Netherlands, and Finland. In 2021, the following changes occurred in the ranking: Luxembourg moved from third place to eighth, Germany took third place, the Netherlands moved to seventh, Finland moved to fourth, and Austria moved to fifth. The paper entitled European Elections, Europe's Future and the Sustainable Development Goals presented very similar and comparable results to those presented in this article regarding the development of SDUE, but covering the years 2023 and 2024. *Europe Sustainable Development Report 2023/2024*. From 2024, here are the first five countries in the ranking: Finland, Sweden, Denmark, Austria, and Norway.

According to the research presented in the article, individual SD^{UE} sub-indices were as follows in 2012: SD^{UE} social: Sweden, Luxembourg, Denmark, Finland, and Belgium; Economic SD^{UE} in 2012: Denmark, Austria, Sweden, Ireland, and Finland; Environmental SD in 2012: Sweden, Germany, Luxembourg, the Netherlands, and Denmark. When making a comparative analysis of the years 2012 to 2022, it is worth pointing out that there have been minor changes in the ranking of countries in the social area. Thus, Ireland, which has become the leader, takes first place, and Sweden is in eighth place. Luxembourg is also outside the top five and is in sixth place, followed by Denmark and Belgium, which took third place. The Netherlands took fifth place. Similarly, analyzing the SD^{UE} economic area and the changes made in it, it can be said that: Sweden moved from third position to first position, Denmark, which was the leader, moved to second position, Finland advanced to third position, Ireland dropped to fifth position and Austria moved to in fourth place from the other. There were also changes in the environmental area: Germany moved to second place, Sweden became the leader, Denmark advanced to third position, Belgium to fourth position, and the Netherlands to fifth position. Luxembourg was outside the top five, ranking sixth in 2022. The comparative analysis showed that changes are minor within the first five countries that are leaders in the development of SDUE in general and its components. They involve countries moving up one, two, or three positions in the ranking. Therefore, a constant socio-economic policy has been maintained over the last 10 years, which determines the development of sustainable (SD^{UE}) countries in the study. The research undertaken in the article regarding the assessment of the level of sustainable development of member countries, divided into old European Union countries (category A) and those that joined after 2004 (category B), does not exhaust multidimensional issues but constitutes an important supplement to the analyses undertaken in the literature. In general, it should be stated that the new EU countries are among those approaching the member states' average level of sustainable development (SDUE). Based on the empirical research reported above, it is possible to formulate a set of conclusions regarding the development of the creative class (CC^{UE}) and sustainable development (SD^{UE}), which will be presented at the end of the article. Initiated research on the impact of the creative class (CC^{UE}) and sustainable development (SD^{UE}) argues that they have a specific interdependence. Not all components of SD^{UE} are directly translated and

supported by research by other authors of thematic works. However, the authors hope their experimental study sheds new light and allows more detailed analyses showing a broader context of the issues considered here.

Considering the above remarks, the following conclusions come to mind when analyzing the research results in the field of the relationship between the creative class (CCUE) and sustainable development (SDUE) and its sub-indices. The first is that there is no significant positive impact of the creative class expressed by the aggregate CC^{UE} index on total sustainable development (SD^{UE}) in 2012 in the case of the old European Union countries (category A). The greater strength of the positive relationship was demonstrated in the case of models describing the impact of the creative class index in general on the dimension of sustainable development in general in the case of the new European Union. In the case of new European Union countries (category B), sustainable development (SDUE), had a significant overall impact on the level of the creative class (CC^{UE}). In other words, countries with higher values of the creative class (CC^{UE}) index tended also to experience higher levels of the sustainable development (SD^{UE}) index, and both indices increased/decreased relatively proportionately and simultaneously. This aspect is extremely positive because it is visible that the tested components interact and are interdependent. Therefore, supporting one directly impacts the other, and thus it should translate into a better socio-economic life. It has been proven (despite critical voices - for example, Kagan and Hahn, 2010) that areas with a much better standard of living generate employees with higher creative predispositions, which then influences a higher level of development of cultural industries (Bayliss, 2007). Shortly, it is worth considering whether these trends will be maintained or whether the impact of artificial intelligence will result in a completely different arrangement of regions concerning the development under study. It is worth noting that in 2022, in the countries of the old European Union (category A), the development of the creative class showed a positive relationship not only to the total SD^{UE} but also to its sub-indices, including the environment, describing this development and the economic area. In the case of the new European Union countries (category B), sustainable development had a significant overall impact on the level of the creative class. Therefore, the areas of sustainable development include the so-called environment and economics, which are the driving forces behind the development of the creative class and vice versa.

6. CONCLUSION

The creative class (CC^{UE}) and sustainable development (SD^{UE}) are separate research categories popular among researchers interested in the presented scientific trends. It should be noted, however, that in the case of the creative class, its development preferences are most often studied in the context of cities. The limited amount of research on countries and conditions creating both urban and rural areas for developing the creative class causes a gap in this research area. Also, many studies on sustainability analyze various aspects but rarely relate them to the development of the creative class. This inspires researchers to explore further topic areas and contribute to developing this topic. Comparative research is an important tool in implementing the idea of a creative class (CC^{UE}) and its possible relationships with sustainable development (SD^{UE}). Monitoring the spatial diversification of the development of Member States in this presented area is a source of valuable information allowing the determination of strategic actions and the identification of future trends. Determining the position of the studied countries relative to each other allows for observations to be made over time and thus to assess the changes taking place.

To be able to perform such an analysis, the authors of the article proposed indicators used in the study based on a theoretical review. However, it should be noted that, like any study, this one also has some limitations. One of the limitations is the subjective selection of the indicators used (describing the creative class (CC^{UE}) and sustainable development (SD^{UE}). However, it was carried out carefully, based on available analyses, theories, and reports. Another limitation that requires further research is the lack of detailed data on using the creative class to achieve sustainable development. After completing the study, it is suggested that the development of Eurostat databases containing information on the variables determining the development of the creative class be emphasized. Panel data analysis, cyclicality, and reproducibility of studies would enable broader conclusions and more robust results regarding the

influence of the creative class on SD^{UE} and vice versa, as well as overcoming the limitations of the current study.

The conclusions drawn from the study justify the thesis that the creative class (CC^{UE}) and its development do have an impact on sustainable development (SD^{UE}) in certain areas in the analyzed countries of the old (category A) and new European Union (category B) (for example Lozano, 2011; Lim, 2016; Shu et al., 2020). The data obtained essentially confirms the long-term contribution of various authors to these research aspects. Considering the development of countries, the authorities of the European Union and regions should pay special attention to the discussed aspects, as they determine the increase in potential towards sustainable development. Our research has shown that in 2022, special relationships exist between the creative class in the area of sustainable development in general and in the economic and environmental areas in particular. This dependence was particularly visible in the countries of the old European Union. This means that the conditions for the above-mentioned dependencies are certain socio-economic development conditions, such as long-term economic growth, including innovative growth. In the context of sustainable regions and the creative class, the impact of artificial intelligence will be crucial, among other things:

- automation of creative processes, which may condition the performance of more creative tasks and increase the number of generated ideas;
- creation of new, previously unknown tools for creators;
- implementation of AI in the education process may affect the development of new competencies of representatives of the creative class;
- changing trends in the labour market, including areas related to creativity and innovation processes.

Attention to the development of these key aspects leads not only to the economic development of countries but also to improving the standard of living of the inhabitants of a given territorial area. Such guidelines and conducted research allow for identifying areas whose functional improvement could allow for more effective development, not only in the article's scope but also to meet global competitiveness requirements.

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Annex:

Table 7. Values of weights for individual variables describing CC in 2013 depending on the group of countries

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
EU27	0.0955	0.1163	0.0744	0.0818	0.0634	0.0771	0.0907	0.0831	0.0711	0.1131	0.0601	0.0732

A	0.1163	0.0902	0.0857	0.0813	0.0645	0.0770	0.0996	0.0773	0.0645	0.1052	0.0625	0.0759
B	0.0870	0.1104	0.0695	0.0897	0.0744	0.0787	0.0909	0.0858	0.0733	0.0809	0.0816	0.0777

Source: *own research.*

Table 8. Values of weights for individual variables describing CC in 2022 depending on the group of countries

	X1	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**X9**	**X10**	**X11**	**X12**
EU27	0.1094	0.1068	0.0721	0.0800	0.0712	0.0731	0.0702	0.0753	0.0733	0.1034	0.0812	0.0840
A	0.1111	0.0778	0.0754	0.0855	0.0735	0.0711	0.0922	0.0714	0.0808	0.0985	0.0740	0.0888
B	0.0812	0.1051	0.0920	0.0869	0.0703	0.0783	0.0716	0.0835	0.0689	0.0877	0.0909	0.0836

Source: *own research.*

Table 9. Descriptive statistics for variables characterizing CC in 2013

		Mean	**Median**	**Minimum**	**Maximum**	**Lower**	**Upper**	**Deviation**
X1	EU27	18.8185	18.50	12.20	28.30	16.60	21.10	3.6589
	A	18.7357	19.25	12.20	25.00	14.50	22.00	4.0778
	B	18.9077	18.40	15.80	28.30	16.70	20.00	3.3130
X2	EU27	32.3741	33.40	18.30	47.80	24.50	40.90	8.4886
	A	34.5286	35.60	19.80	47.80	29.50	41.20	8.8235
	B	30.0538	30.20	18.30	43.20	24.50	35.20	7.7802
X3	EU27	88.1037	89.20	73.10	98.60	83.50	92.90	6.4936
	A	86.2071	86.75	76.90	92.90	83.10	90.80	5.2188
	B	90.1462	92.40	73.10	98.60	85.50	95.60	7.2897
X4	EU27	14.6704	13.70	8.40	32.10	10.70	16.90	5.2990
	A	15.2429	13.60	8.40	32.10	10.70	17.20	6.5795
	B	14.0538	13.70	8.90	21.00	10.90	16.50	3.6257
X5	EU27	84.2630	85.70	49.40	97.30	75.70	91.90	10.2136
	A	77.5429	78.25	49.40	91.50	73.80	84.20	9.8961
	B	91.5000	91.90	85.10	97.30	89.80	93.40	3.2406
X6	EU27	96.0111	95.90	91.10	99.50	94.70	97.80	2.2342
	A	95.4286	95.70	91.10	98.70	94.50	97.50	2.3818
	B	96.6385	97.20	93.20	99.50	95.40	98.00	1.9615
X7	EU27	18.4074	17.60	10.10	30.30	14.30	21.90	5.3922
	A	16.1857	16.60	11.10	21.90	13.20	18.00	3.0475
	B	20.8000	20.20	10.10	30.30	15.10	26.20	6.4013
X8	EU27	70.4037	69.80	41.90	93.60	59.80	81.40	12.4833
	A	67.0000	65.05	52.60	93.60	57.80	73.10	11.2313
	B	74.0692	79.20	41.90	89.50	69.30	81.50	13.1496
X9	EU27	82.1407	83.40	51.60	99.20	72.20	91.90	12.5474
	A	76.2643	79.45	51.60	91.90	69.00	83.40	10.6089
	B	88.4692	91.90	61.90	99.20	87.00	95.90	11.6409
X10	EU27	37.6519	36.90	13.20	64.00	28.30	43.20	13.5290
	A	40.8929	38.95	13.20	64.00	31.20	55.00	14.8783
	B	34.1615	36.70	15.80	57.80	23.30	39.50	11.4590
X11	EU27	76.3000	76.80	42.40	93.70	69.80	83.80	10.6491
	A	71.4571	71.65	42.40	84.40	68.90	77.20	10.3606

		Mean	Median	Minimum	Maximum	Lower	Upper	Deviation
	B	81.5154	79.60	66.70	93.70	76.80	88.80	8.5200
	EU27	91.3815	92.80	78.60	99.40	86.90	96.20	5.4931
X12	A	89.9500	90.70	78.60	97.60	85.30	96.20	6.1360
	B	92.9231	93.20	85.10	99.40	90.00	96.00	4.4300

Source: *own research.*

Table 10. Descriptive statistics for variables characterizing CC in 2022

		Mean	Median	Minimum	Maximum	Lower	Upper	Deviation
	EU27	17.3407	15.90	11.70	27.10	14.20	20.20	3.9294
X1	A	18.8929	19.35	12.80	27.10	14.30	21.30	4.1878
	B	15.6692	14.50	11.70	22.80	14.20	15.90	2.9355
	EU27	39.5704	39.90	24.10	55.70	32.70	46.40	8.7933
X2	A	42.3429	42.15	24.30	55.70	37.70	47.40	8.5779
	B	36.5846	33.90	24.10	50.00	31.60	42.80	8.3182
	EU27	89.2185	89.90	72.20	98.10	84.10	94.50	6.3002
X3	A	85.8000	85.85	72.20	92.60	83.50	90.20	5.6456
	B	92.9000	94.50	84.50	98.10	88.60	96.90	4.8121
	EU27	13.3889	12.70	8.30	27.30	10.60	15.00	4.0200
X4	A	13.8000	12.95	8.30	27.30	10.00	15.00	5.1326
	B	12.9462	12.30	10.20	18.80	11.70	14.90	2.4629
	EU27	85.3296	87.70	56.60	98.20	78.70	93.10	10.0602
X5	A	78.5357	79.75	56.60	92.20	74.60	82.70	9.2827
	B	92.6462	93.10	84.70	98.20	90.50	94.70	3.7536
	EU27	95.9481	95.80	89.80	99.60	94.70	98.40	2.4170
X6	A	95.0714	95.20	89.80	98.80	93.90	96.50	2.4721
	B	96.8923	97.10	93.10	99.60	95.50	98.60	2.0431
	EU27	16.9037	16.60	8.50	31.70	12.70	18.90	4.9541
X7	A	16.4071	17.30	10.90	19.80	15.70	18.10	2.7692
	B	17.4385	15.50	8.50	31.70	12.70	21.20	6.6536
	EU27	76.1074	78.20	54.70	92.10	71.90	80.40	8.0697
X8	A	74.7571	74.50	54.70	92.10	69.10	82.10	9.1052
	B	77.5615	79.30	61.70	86.60	77.40	80.30	6.8457
	EU27	83.6148	85.00	52.90	100.00	74.40	92.90	11.6760
X9	A	75.5500	76.55	52.90	86.60	69.70	83.60	9.3254
	B	92.3000	92.90	74.40	100.00	89.90	97.20	6.6006
	EU27	42.9000	43.90	17.10	66.10	32.70	51.90	12.3563
X10	A	44.8000	44.10	17.10	66.10	39.70	54.10	12.5607
	B	40.8538	40.80	20.20	60.30	32.50	49.70	12.2938
	EU27	77.1000	74.30	58.70	95.10	70.50	83.80	9.8236
X11	A	71.3571	71.80	58.70	83.80	67.60	74.10	7.0084
	B	83.2846	83.70	69.90	95.10	75.90	92.10	8.7159
	EU27	90.7074	90.90	80.40	100.00	85.80	94.10	5.3827
X12	A	88.7429	89.40	83.80	94.70	85.20	91.50	3.5785
	B	92.8231	93.90	80.40	100.00	90.40	97.50	6.2889

Source: *own research.*

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ENHANCING SUSTAINABILITY IN FACILITY MANAGEMENT: DATA-DRIVEN DECISION MAKING THROUGH INTELLIGENT ENERGY MONITORING

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ABSTRACT

Purpose: *This article explores the role of intelligent energy monitoring in enhancing sustainability within facility management, highlighting the potential of dedicated IT system implementations to support this goal. The following research questions are considered:*
Q1: How does intelligent energy monitoring contribute to achieving higher sustainability in buildings?
Q2: How can integrating various data from intelligent meters, sensors, IT systems, and advanced data analytics support decisions to optimize energy consumption?
Q3: What are the quantifiable benefits of adopting intelligent energy monitoring solutions in buildings?

Need for the study: *As one of the largest energy consumers, the construction sector needs advanced IT solutions to track, analyze, and optimize energy use and plan more effective energy strategies in line with environmental regulations and Sustainable Development Goals (SDGs).*

Methodology: *The research adopts a case study methodology, focusing on implementing imperiusFM across four City Office buildings. Three main phases were conducted during the study: data collection, system performance analysis, and evaluation in a sustainability context.*

Findings: *Empirical results of imperiusFM implementations in four city facilities highlighted the platform's operational efficiency. Real-time, intelligent energy monitoring, fault detection, and advanced analytics reduced energy consumption by 18.6% and CO2 emissions by over 68,3 tons per season.*

Practical Implications: *The research provides valuable insights for facility managers and decision-makers, demonstrating the role of intelligent energy monitoring in optimizing energy strategies. The imperiusFM platform enables cost-effective and environmentally responsible facility management to align more effectively with global sustainability targets.*

Keywords: sustainability, sustainable development, energy monitoring, energy efficiency, facility management

Jel codes: Q55; Q01; Q41

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1. INTRODUCTION

The concept of sustainable development is becoming a fundamental paradigm guiding transformations across various sectors of the economy and industry, as well as shaping the daily lives and citizens' actions. The implementation of sustainable development principles necessitates a comprehensive range of initiatives on political, economic, social, or technological grounds so that, in effect, meets the principle that says that our actions today should not limit the range of economic, social, and environmental options of future generations (Golden & Devi, 2022).

Energy efficiency is a key consideration in various sectors, including industry, construction, transport, modern technologies development, and digitalization. In particular, the construction sector plays a vital role in maintaining a balance between growing energy demands and the need for consumption reduction, as buildings account for 40% of the EU's final energy consumption and 36% of greenhouse gas emissions (European Parliament,& Council of the European Union, 2024).

On one hand, energy needs cause the increase in energy consumption, on the other hand, they create space for action and the implementation of many initiatives and solutions concerning buildings. These efforts respond to the demands of the Sustainable Development Goals (SDGs), which express their practical implications in EU directives, regulations, and national programs. In the case of Poland, this is exemplified by the Energy Policy of Poland until 2040 (Ministerstwo Klimatu i Środowiska, 2021).

Optimizing energy use in buildings involves not only technological advancements in materials but also intelligent energy monitoring and management systems that allow the creation of innovative energy strategies. In the article, the applicability of one existing system is considered for increasing energy efficiency and reducing CO2 emissions. The system's role is underlined as an important link in integrating existing building subsystems, equipment, and installations to provide a coherent and comprehensive environment for optimizing energy consumption.

Although intelligent energy monitoring is widely discussed in the context of climate changes, energy efficiency in buildings, and the application of modern and intelligent solutions for building performance optimization (Sivasankari & Rathika, 2025; Hsieh et al., 2024; Mostafa et al., 2024; Sharma & Alshatshati, 2024; Vandenbogaerde et al., 2023), empirical validation in real-world public sector facility management remains limited. Based on the exploration of imperiusFM (imperiusFM, 2024) functionalities and implementations, the advantages of the system application were explored in the context of cost savings and CO2 reduction. The study enhances existing knowledge by providing new empirical evidence emphasizing the system-level integration analysis and practical insights for sustainable facility management.

The following research questions are considered: Q1: How does intelligent energy monitoring contribute to achieving higher sustainability in buildings?; Q2: How can integrating various data from intelligent meters, sensors, IT systems, and advanced data analytics support decisions to optimize energy consumption?; Q3: What are the quantifiable benefits of adopting intelligent energy monitoring solutions in buildings?

The research questions respond to challenges in recent literature concerning building sustainability, energy efficiency, and IT-based facility management (e.g., Ali et al., 2024; Hsieh et al., 2024; Akram et al., 2022). They align with current policy frameworks such as the EPBD Directive (2024) and Sustainable Development Goals requirements (United Nations, 2024; European Parliament & Council of the European Union, 2024). By focusing on both technological integration and measurable outcomes, the study addresses the gap between conceptual discussions and operational realities in energy management.

Based on data collection analysis, in-depth analysis of system functionalities, and evaluation of the system applications concerning sustainability aspects, the significant role of such IT systems in achieving better energy efficiency was proved. Energy monitoring and advanced analytics have led to reduced energy consumption and a corresponding decrease in CO2 emissions. The presented savings confirmed that the implementation of the imperiusFM system outperforms traditional energy management methods and highly supports the requirements of the Sustainable Development Goals (SDGs) and related to EU directives, in particular the Energy Performance of Buildings Directives (EPBD). From a practical perspective, the key value of this research is emphasized in the potential of specialized IT system implementations to enhance energy efficiency. This provides valuable insights for facility managers and decision-makers, helping them better understand the role of IT systems in

minimizing environmental impact, decreasing energy expenses, and enhancing alignment with global sustainability objectives through data-driven energy monitoring and management.

2. LITERATURE REVIEW

2.1. Sustainability impact on energy efficiency: SDGs and building directives

The term sustainability was formally adopted in 1992 during the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro (known as "Earth Summit") (Misztal, 2018). It was a consequence of the Brundtland Report publication, developed by the United Nations World Commission on Environment and Development, in which the definition of sustainable development was formulated as "such development in which the needs of the present generation can be met without diminishing the chances of future generations to meet them" (Mensah, 2019; Płachciak, 2012; Pavis et al., 2019).

At the Rio Earth Summit, sustainable development was recognized as "a strategy of ecological, social, technical-technological and organizational transformation aimed at achieving a rational and sustained level of social well-being that makes it possible to pass it on to future generations without fear of threatening the destruction of natural resources and ecosystems" (Płachciak, 2012; Wolczek, 2014).

The adoption of Agenda 21 as a comprehensive action plan for sustainable development was intended for environmental protection, on the one hand, and social development, on the other, as crucial for developing countries. Nevertheless, the lack of measurable indicators for implementing Agenda 21 and mechanisms for monitoring and enforcing actions limited its effectiveness. It became the reason for adopting the Millennium Declaration at the UN Summit in 2000, which introduced the adoption of 8 Millennium Development Goals (MDGs). The formulation of MDGs enabled the establishment of concrete, measurable objectives with a clear deadline for their realization in 2015. The implementation of the 8 Millennium Goals, as well as the success in achieving the set results, led to the foundation for the adoption of the Agenda 2030 by 2015 and the formulation of 17 Sustainable Development Goals (SDGs), encompassing the three dimensions of sustainable development (economic, social and environment) (Kuhlman & Farrington, 2010).

The SDGs consist of 17 sustainable development goals and 169 associated targets to be achieved globally by 2030 (Sustainable Development Goals, 2024). These goals include a broad spectrum of global challenges. On the one hand, they aim to fight poverty and hunger, ensure universal access to education and healthcare, and uphold principles respecting equality, promoting the rule of law, human rights, and international cooperation and partnership. On the other hand, they emphasize the need to support economic development, implement measures to protect the climate, promote the efficient use of resources, and encourage responsible consumption and production. Within this framework, energy efficiency has emerged as one of the key elements in combating climate change and excessive consumption of natural resources (Maryanti et al., 2022; Mishra et al., 2023; Yakovleva et al., 2019; Zimon, 2019).

Energy efficiency is crucial in supporting sustainable economic growth by enhancing energy security and contributing to a stable and resilient economy. Its positive impact on economic development becomes particularly significant over the long run. Increased energy efficiency serves as a catalyst for stimulating economic development by reducing costs, improving productivity, and minimizing dependence on energy imports. Therefore, formulating and implementing supportive policies and incentive mechanisms to optimize energy consumption is essential (Udemba et al., 2025). The inefficient energy use hampers economic development, limiting growth potential and increasing resource consumption (Sydykova et al., 2024).

Considering the context of the SDGs related to energy efficiency in facility management, the following goals can be considered as those addressing the reduction of energy consumption and greenhouse gas emissions, increasing access to clean energy, and fostering a sense of shared responsibility for advancing energy efficiency (SDG, 2025):

- Goal 7 – Affordable and clean energy – focuses on modernization of buildings, promoting passive and energy-efficient construction and the use of renewable energy sources, increasing investment in technologies ensuring clean energy and the share of renewable energy sources in the energy mix, using modern and intelligent solutions (IoT devices, sensors, energy

storages, heat pumps, etc.) and advanced IT systems for monitoring energy consumption and optimizing energy use.

- Goal 9 – Industry, innovation, and infrastructure – focuses on modernizing industry and industrial buildings, developing energy-saving technologies and intelligent energy management and energy-consumption control systems, designing and constructing smart buildings, and supporting innovations that increase energy efficiency in industrial processes while reducing resource consumption.
- Goal 11 – Sustainable cities and communities – focuses on reducing cities' negative environmental impact by improving air quality and building energy efficiency, and promoting the development and implementation of green building practices.
- Goal 12 – Responsible Consumption and Production – focuses on promoting the sustainable use of resources, including energy saving, recycling, and the reuse of materials in construction, efficient resource management, the integration of renewable energy sources, and the adoption of technologies that reduce water and energy consumption in buildings.
- Goal 13 – Climate Action – focuses on incorporating the energy efficiency postulates of buildings as part of the implementation of climate policy in national strategies, creating standards for energy-efficient construction (zero emission buildings standards), decarbonizing the construction sector by reducing energy consumption, and switching to renewable energy sources and modernizing public and private buildings, creating favorable incentives and financial programs to accelerate support the energy transformation of buildings.

Implementing the Sustainable Development Goals has become the foundation for developing a range of directives and regulations at the EU level, as well as formulating national energy policies. Key legislative instruments in the construction sector are the Energy Performance of Buildings Directives (EPBD), which aim to drive the energy transition in the construction sector and reduce greenhouse gas emissions. The currently applicable 4th EPBD, Directive (EU) 2024/1275 of the European Parliament and of the Council on the energy performance of buildings, strongly supports the development and use of intelligent energy management systems and the implementation of smart meters, and the automation and digitization of building sector (European Parliament & Council of the European Union, 2024). Its provisions continue the provisions of the previous EPBD directive (Directive (EU) 2018/844), which promoted the implementation of energy management systems and smart meters and introduced the Smart Readiness Indicator (SRI), a measure assessing of buildings' capacity for efficient energy management, automation, and the ability to monitor energy supply and consumption in accordance with users' needs (European Parliament & Council of the European Union, 2018).

2.2. IT support in building operation and management

In response to growing sustainability demands and evolving policy frameworks, the integration of IT systems into building operations, aimed at optimizing energy consumption and managing facilities, has emerged as a pillar of modern facility management (Hsieh et al., 2024; Matarneh, 2022; Mostafa et al., 2024; Ogundiran et al., 2024; Zhang et al., 2025).

The scope of support provided by building systems depends on their level of advancement - ranging from systems that control individual installations (BCS – Building Control System) to systems that automate the operation of building systems (BAS – Building Automation System) and further to systems that manage buildings (BMS – Building Management System) enriched with analytical and predictive capabilities or Facility Management Systems (FMS) that monitor, control, and optimize various aspects of building operations, including maintenance, servicing, security, energy, environmental performance, and operational costs.

Today the distinction is most commonly made between BMS and FMS as the leading system classes (Hsieh et al., 2024), (Moskwa & Dechnik, 2020), (Mostafa et al., 2024) (Ogolla, 2021), (Ali et al., 2010), (Sharma & Alshatshati, 2024), (Lowery & Sorenson, 2021), (Kastner et.al, 2005), Wang &Xu, 2012), (Remote Fill System, 2025). While a Building Management System (BMS) primarily focuses on the technical aspects of building operation, a Facility Management System (FMS), when integrated with the BMS, creates an environment for multidimensional analysis using AI-driven algorithms and machine learning. This integration enables strategic facility management, particularly in the context of improving energy efficiency. Implementing such solutions appears to be an inevitable consequence of the ongoing

automation of buildings and the digitalization of management processes in this domain. In light of the challenges posed by the Sustainable Development Goals, these systems are essential for the continuous optimization of energy consumption and for fostering a more energy-efficient environment.

2.3. Implementation of smart technologies in advancing building energy efficiency

Reduction of final energy consumption of buildings in the EU by 11.7% by 2030 (compared to 2020 levels) primarily requires large-scale thermal modernization of buildings and substantial technological expansion to enable intelligent energy management (Akram et al., 2022; EUR-Lex, 2024; Karki et al., 2023). Implementing advanced technologies based on artificial intelligence (AI), the Internet of Things (IoT) solutions, intelligent monitoring and energy management systems, in light of these requirements, is becoming a significant challenge to be met by building owners and managers (Ali et al., 2024; Sivasankari & Rathika, 2025; Ogundiran et al., 2024).

Practical applications of AI and IoT in energy-efficient buildings enable predictive diagnostics of building technical systems, real-time energy consumption monitoring, and automated adjustment of HVAC and lighting systems based on occupancy and environmental data (Ali et al., 2024; Sivasankari & Rathika, 2025; Shah et al., 2022; Wang & Gadi, 2024). AI algorithms can detect anomalies and energy consumption patterns, forecast demand, and optimize building performance without human intervention. IoT devices, such as smart thermostats, occupancy sensors, and connected meters, provide granular data that enable system learning and continuous performance improvement (Ali et al., 2024; Ogundiran et al., 2024; Shah et al., 2022; Wang et al., 2022). When integrated into a centralized facility management system, these technologies significantly enhance responsiveness, operational transparency, and user comfort, reducing energy waste and emissions (Al-Ghaili et al., 2021; Hsieh et al., 2024; Sivasankari & Rathika, 2025; van Roosmale et al., 2024).

Nevertheless, several crucial barriers may hinder the implementation of advanced technologies in buildings. These include high initial investment costs, a lack of awareness and technical competencies among facility managers and end-users, and skepticism about the benefits of smart building solutions, which causes resistance to replacing traditional infrastructure. Additional obstacles involve industry resistance to change, concerns over complexity and difficulties with the incorporation of smart technologies into existing building infrastructure, and a lack of financial incentives and governmental support to encourage the adoption of smart technologies (Carlander & Thollander, 2023; Honold & Lützkendorf, 2019; Tabaku et al., 2025). The challenge is also the integration of various technologies and systems for efficient energy management. The deployment of multiple devices and advanced systems, which are implemented within the building, often results in gathering heterogeneous building-related data in different formats with different detail levels and different presentation modes (Kozlovska et al., 2023; Shah et al., 2022).

Overcoming the barriers associated with implementing energy efficiency-oriented technologies in buildings requires a multifaceted approach. This includes awareness-raising initiatives concerning the benefits and application of modern technologies, as well as the development of targeted support programs to facilitate retrofitting and the adoption of innovative solutions (Bagaini, 2020). It is also essential to implement solutions that integrate and enable data processing from various sources while offering the capability to conduct multidimensional analyses to support comprehensive building management.

3. METHODOLOGY

The article is focused on a case study analysis of imperiusFM system implementations, which constitutes the basis for evaluating the effectiveness of intelligent energy monitoring in enhancing sustainability within facility management. Three main phases were implemented during the research: data collection, system analysis, and evaluation of outcomes in a sustainability context. The data collection is based on gathering data directly from the system from real-life implementations to analyze the energy consumption, CO2 emission, and potential of offering efficient energy consumption strategies based on imperiusFM system support. Additionally, interviews with implementation and maintenance staff were conducted to ensure a comprehensive understanding of imperiusFM operation. In the system analysis phase, the analysis of the imperiusFM system modules was provided, and the role of system openness to integrate data coming from external solutions. The role of energy-related data collection and

integration possibilities was underlined for current energy monitoring and future energy consumption prediction. The evaluation phase allowed for assessing the system's effectiveness in enhancing sustainability. The savings, both financial and environmental, coming from system implementation in one of the City Offices in Poland compared to traditional energy management were highlighted.

Following the identified phases, the aim was to provide a comprehensive evaluation of the imperiusFM system capabilities and present actionable benefits for enhancing sustainability in facility management.

In the research, the City Office buildings were selected due to their early adoption of the imperiusFM system and the availability of historical energy consumption data. It was possible to analyze the applicability of different energy actions based on data analysis coming from the system (i.e., reduction of contracted capacity). Additionally, the buildings reflect common public-sector challenges in energy management, making the results broadly applicable to other municipalities.

The dataset included monthly readings of thermal energy consumption (in GJ), outdoor temperature data, and calculated contracted capacities for each building. All four facilities were monitored continuously for the studied period. Energy consumption was benchmarked against the energy consumption level before the system implementation.

To better understand the system operation, the role of thermal energy consumption indicators, and data processing algorithms applied in the imperiusFM platform, several informal interviews were conducted with system operators and maintenance staff involved in the implementation and daily use of imperiusFM. Although the interviews were not formally structured or recorded, they served as supplementary sources of insight that helped to understand the modules' integration advantages as well as interpret the quantitative findings and assess practical challenges encountered during deployment.

4. RESULTS

The research was conducted based on a case study of one of the existing Facility Management Systems, developed by Promar and called imperiusFM. This solution has been implemented in over 2,500 facilities in Poland and abroad, enabling significant energy savings through the platform's advanced analytical capabilities and comprehensive monitoring of various building operation parameters. The system's modular architecture, along with its integration with other systems used in buildings - as well as with IoT solutions, meters, sensors, and external data sources (e.g., weather forecasts) - enhances the overall efficiency of building management. It facilitates the reduction of energy consumption and CO2 emissions while simultaneously improving safety and optimizing the operation of installations and utility networks.

The five modules of the system serve as a source of operational data, enabling multidimensional and multifaceted analysis.

The AIM (Asset Information Model) module integrates data related to the building and its technical installations. Source data are primarily imported from a Building Information Modeling (BIM) model, allowing for the visualization and tracking of both structural elements of the building and the spatial layout, such as division of interior space and placement of technical systems and installations within the facility.

The CMMS (Computerized Maintenance Management System) module functions as a comprehensive equipment database, supporting maintenance planning and ensuring the operational durability of technical assets. It stores detailed information including equipment names and types, manufacturers, year of production, installation dates, maintenance schedules, warranty periods, and repair histories. Based on this data, the module facilitates monitoring of equipment performance in terms of failure rates and operational correctness, as well as planning and issuing maintenance and service orders. Through built-in analytics and alert systems, CMMS supports the optimization of maintenance strategies, monitors equipment longevity, and identifies trends in the operation of various components of the building's technical infrastructure.

Energy performance analysis is a fundamental function of the EMS (Energy Management System) module. This module integrates data collected from energy meters, sub-meters, and other technical systems working in the buildings. It offers a comprehensive set of performance indicators and analytical algorithms that enable real-time monitoring and optimization of energy consumption, as well as

forecasting future energy demand. EMS is equipped with an alert and notification system that facilitates the analysis of current device operation and the early detection of anomalies or inefficiencies. Additionally, it allows for trend analysis related to energy usage and demand over different periods. The module supports the adjustment and control of operational parameters for heating, lighting, ventilation, and air conditioning systems.

The CAFM (Computer Aided Facility Management) module is part of the imperiusFM system dedicated to supporting facility management processes. It enables in-depth analysis of building usage and space management. The module stores data on room occupancy, equipment inventory, and usage patterns over time. This functionality supports the dynamic adjustment of energy supply and consumption in specific areas of the building, improving both operational efficiency and energy performance.

The fifth module serves as the configuration environment for the imperiusFM platform. It allows for managing user access, visualization settings, and other technical parameters essential to the operation and customization of the platform.

The extensive functionality of the imperiusFM platform and the broad scope of data stored within the system enable users to perform comprehensive, multidimensional analyses. The system integrates data from various building subsystems, including those responsible for technical operations, as well as enterprise-level systems such as ERP (Enterprise Resource Planning), CRM (Customer Relationship Management), and external databases (e.g., weather or economic data). These integrations make imperiusFM a holistic solution for property management, enabling cost optimization, improved operational efficiency, and the automation of facility maintenance processes.

The platform also supports the integration of dedicated control and automation systems that operate within the building, including BCS (Building Control Systems), BAS (Building Automation Systems) or BMS (Building Management Systems) (Hsieh et al., 2024), (Moskwa & Dechnik, 2020), (Mostafa et al., 2024) (Ogolla, 2021), (Ali et al., 2010), (Sharma, & Alshatshati, 2024), (Lowery & Sorenson, 2021), (Kastner et.al, 2005), Wang & Xu, 2012), (Remote Fill System, 2025).

Building Control Systems (BCS) are designed to manage individual subsystems within a facility, which are responsible for heating, ventilation, air conditioning, access control, etc. These subsystems are monitored and controlled to ensure proper operation within defined parameters and timeframes, which in consequence contribute to the reduction of energy and maintenance costs. However, BCS alone is insufficient for managing the building's overall energy performance effectively. In response to this need, Building Automation Systems (BAS) and Building Management Systems (BMS), followed by Facility Management Systems (FMS), have emerged as more advanced solutions.

BAS platforms integrate and automate the operation of selected building subsystems, enabling the analysis of interdependencies and coordinated control of HVAC, lighting, green energy sources, and energy storage systems. This integration enhances infrastructure oversight and leads to reduced operational costs without compromising service quality or occupant comfort.

While BAS is focused primarily on controlling the technical aspects of a building, automating operations, and optimizing energy consumption, a Building Management System (BMS) extends the functionalities of BAS by integrating all technical subsystems within a building and adding advanced analytical capabilities. BMS platforms centralize control of building systems through a unified interface, enabling comprehensive energy monitoring across the entire facility and generating alerts in case of faults or irregularities, which supports the identification of areas for optimization. BMS manages the technical building systems, optimizing their functioning by assuming control functions over their operation. Although it does not directly handle heating, lighting, heat delivery, or temperature regulation itself, it processes and analyzes data from these systems to offer predictive insights and informed decision-making. Thus, through those capabilities, BMS contributes to both technical and energy optimization of the building based on centralized and continuously updated data.

A Facility Management System (FMS) is designed to enable comprehensive property management.

By integrating data from the building's technical subsystems, FMS functions as a superior, overarching system that not only continuously monitors and supervises subsystem operations, but also supports strategic planning aimed at maintaining infrastructure performance, optimizing space utilization, and managing available resources, including human resources (e.g., maintenance teams). This comprehensive approach allows for effective facility management across multiple operational dimensions, including the control of maintenance-related costs. Although an FMS does not directly

control the operation of building devices and installations, it analyzes all collected data across various contexts to ensure optimal resource and space utilization, while minimizing waste and utility consumption. As illustrated in Figure 1, FMS leverages systems such as BCS (Building Control System), BAS (Building Automation System), and BMS (Building Management System) as sources of information, which it uses to generate advanced analyses and reports for facility managers.

FMS is capable of assessing the operational costs of specific subsystems, devices, and installations. It can recommend adjustments to technical parameters, forecast potential failures, and plan preventive maintenance activities to ensure continuous and efficient operation. Through advanced analytical tools, the system enhances operational efficiency by maximizing subsystem performance and reducing resource usage. By integrating with BCS, BAS, and BMS systems, FMS enables holistic building management, covering both operational and automation aspects, which plays a fundamental role in improving the energy efficiency of the facility.

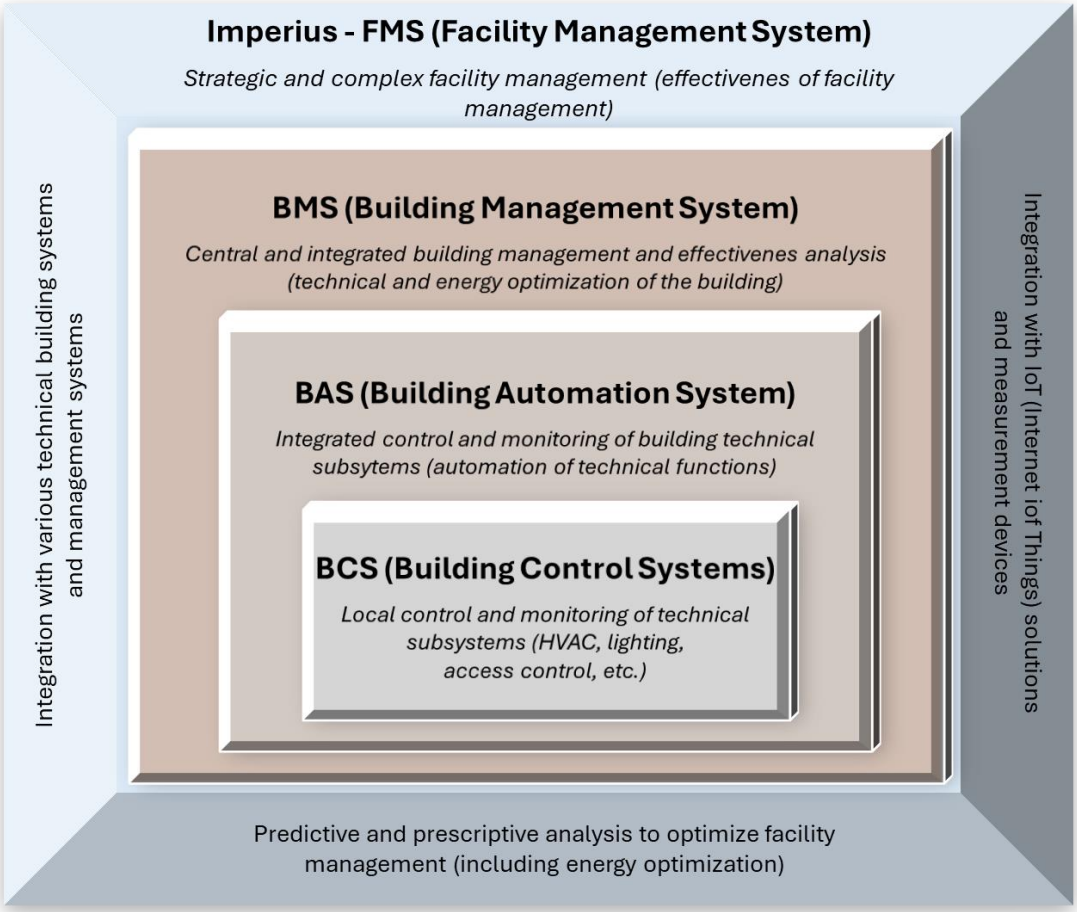


Figure 1. FMS as a comprehensive platform that aggregates data from BCS, BAS, and BMS to optimize building performance and resource use
Source: own elaboration.

Fulfilling tasks related to energy consumption optimization and the performance of building technical systems, imperiusFM utilizes a wide range of data concerning the facility. This includes information such as the building's floor area, volume, number of occupants, technical specifications of installed devices, HVACR (heating, ventilation, air conditioning, and refrigeration) systems, and components, as well as environmental parameters within rooms (e.g., temperature, humidity, air quality), data on renewable energy production and consumption and energy storage.

Data stored in the system feeds individual system modules and is processed in the imperiusFM environment according to user needs. The AIM (Asset Information Model) module leverages BIM (Building Information Modeling) models, which digitally represent the building and its components.

The CMMS module stores technical data about the equipment, including certifications, specifications, and maintenance records. Meanwhile, the CAFM module provides information on room utilization and the organizational structure of building users. Thanks to its support for various integration protocols, the EMS (Energy Management System) module within imperiusFM unifies data collected from diverse sources, including building automation systems, energy meters, environmental sensors, and other monitoring devices. This allows for detailed energy use tracking across different building zones and subsystems.

Table 1 presents a set of core capabilities of the imperiusFM platform that form the basis for comprehensive energy analysis, energy balancing, and real-time comparisons of energy production and consumption. The integration of external data sources - including historical records, manual measurements, and billing data - combined with the application of machine learning and artificial intelligence algorithms, enables both predictive and prescriptive analytics, which support dynamic energy management across various sources, detection of real-time anomalies, identification of unexpected patterns or deviations in system performance (e.g., equipment failures, overloads), and generation of recommendations for operational adjustments and potential technical systems' modernizations.

Table 1. The applicability of the imperiusFM platform for data-driven optimization of building energy efficiency

Dimensions of imperiusFM platform capability	**Main functionalities developed within the imperiusFM framework to optimize energy efficiency in buildings**
Integration	Integration with building control systems responsible for HVACR (heating, ventilation, air conditioning, and refrigeration), lighting, access control, and more, as well as with Building Control Systems (BCS), Building Automation Systems (BAS), and Building Management Systems (BMS). Integration with BIM (Building Information Modeling) software enabling the import and use of digital building models. Integration with renewable energy systems, energy storage units, electric vehicle charging stations, and micromobility charging infrastructure such as bike and scooter stations. Integration with enterprise-level management systems, including ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) platforms. Integration with external data sources, such as weather systems and market information services, enables real-time adaptation to external factors that may affect energy consumption and operational performance. Support for integration protocols: Modbus / Modbus TCP/IP, OCPP (Open Charge Point Protocol), MQTT (Message Queuing Telemetry Transport), BACnet (Building Automation and Control Networks), KNX (Konnex), LonWorks (Local Operating Network), DALI (Digital Addressable Lighting Interface), Zigbee i Z-Wave, M-Bus (Meter-Bus), OPC UA (Open Platform Communications Unified Architecture).
Data processing	Data processing based on advanced analytical tools capable of identifying patterns, predicting trends, and indicating areas for improving energy efficiency. Forecasting of energy demand over various time scales, from hours to years. The use of artificial intelligence (AI) and machine learning (ML) technologies enables advanced capabilities in energy prediction, including the forecasting of energy consumption, renewable energy production (e.g., from solar panels or wind turbines), the utilization of energy storage systems, as well as supporting anomaly detection and benchmarking. The implementation of ML and AI algorithms allows for the automatic analysis of large datasets and the identification of unexpected energy usage patterns. They help detect technical faults and failures in specific devices and installations, flag unauthorized energy use, and automatically identify inefficiencies. Predictive and forecasting algorithms make it possible to anticipate future energy demand and assess

Dimensions of imperiusFM platform capability	Main functionalities developed within the imperiusFM framework to optimize energy efficiency in buildings
	the potential impact of external variables such as weather changes, energy prices, and other influencing factors. These algorithms can generate energy demand forecasts across multiple time scales (hours, weeks, months, years, etc.), thus enabling more strategic and dynamic energy management. Access to resource management functions enables tracking of the location, condition, and service history of each device, which is crucial for effective planning and budget management. Each device (e.g., sensor, meter, component, and control system) can be precisely located and identified using a unique device ID, including details such as address, facility name, and exact placement within the building). Ability to customize analytical tools to specific user needs, enabling more detailed data analysis based on specific operational or regulatory requirements. Interactive dashboards allow users to continuously monitor key performance indicators (KPIs) and analyze data in real-time, providing actionable insights for informed decision-making. Possibility to aggregate and analyze data based on a variety of parameters, such as building type, size, construction technologies used, window class, or building management systems (BMS), etc. Implementation of extended calendars' functionalities, which goes beyond recognizing public holidays and non-working days, and takes into account the schedules of additional activities or other events taking place in a given building or zone. The calendar allows to add and manage the events' schedule across facilities, enabling the optimization of building subsystems' settings, such as lighting, heating, or air conditioning, based on the actual occupancy and demand for specific spaces during particular hours.
Energy monitoring and control	Continuous monitoring of technical energy parameters includes both total energy consumption and detailed usage by individual systems or building zones, as well as indoor and outdoor temperatures, renewable energy production, energy storage utilization, and HVACR system performance. Data monitoring is carried out in real time and sourced from a variety of inputs, including energy meters, sensors, HVACR systems, and other energy-consuming devices. Ongoing assessment of energy consumption and rapid response to anomalies or irregularities are enabled by a system of notifications and alerts. Automated alerts notify users of threshold exceedances, potential failures, or other critical events, providing timely information about any significant changes that may affect energy management. These notifications can also be delivered via email or SMS for immediate action. Benchmarking of current energy consumption is supported through comparisons with similar buildings or historical performance data, allowing for the evaluation of operational efficiency and the identification of areas for improvement. Implementation of advanced energy management strategies, such as demand response and peak load management. The system applies a dual-track approach: – Demand response is supported through alerting mechanisms that notify users of low-cost and high-cost energy periods, based, for example, on Day-Ahead Market (DAM) pricing forecasts. – Peak load management is realized by generating alerts when there is a risk of exceeding the contracted capacity for gas or electricity supply.
Energy reports and data visualization	A comprehensive suite of tools for generating reports, charts, and dashboards provides in-depth analyses of energy performance, historical comparisons, and progress assessments toward energy-related goals.

Dimensions of imperiusFM platform capability	Main functionalities developed within the imperiusFM framework to optimize energy efficiency in buildings
	Possibility to customize analytical tools to meet specific user needs, which enables more detailed data analysis tailored to particular operational or regulatory requirements. Visualization capabilities allow users to filter and adjust data views according to individual preferences. Data can be filtered based on defined parameters such as date, type of installation, or specific zones within the building. Time selectors support browsing of historical data or real-time monitoring of current consumption across multiple time scales (hours, years, etc).
	Possibility to schedule automated report generation, which can be delivered via email or made available for download through a web interface.
	Possibility to support energy consumption analysis and reporting about occupancy schedules, room usage, public holidays, and seasonal breaks to evaluate energy strategies and identify areas for further optimization.
	Access to an advanced tool for generating comprehensive energy balance reports and analyzing the performance of individual devices. These reports are essential for both operational and strategic decision-making.
	Possibility to export data in multiple formats, such as CSV, Excel (XLSX), JSON, or PDF, ensuring compatibility with other systems and facilitating integration into external workflows.

Source: own elaboration.

For the purpose of energy monitoring, the imperiusFM platform integrates three interrelated functions: monitoring, control, and fault response. Continuous recording of parameter values serves as a primary data source, which is then used to rationalize energy consumption and optimize operational costs. By reducing energy use, the platform also contributes to lowering CO2 emissions, thereby supporting the achievement of the Sustainable Development Goals (SDGs).

The effectiveness of energy savings is confirmed by results from various imperiusFM implementations. Below is a case study of the system's implementation across four facilities administered by one of the City Offices in Poland. The analysis focuses on energy consumption - specifically thermal energy - with particular emphasis on the most recently completed heating season, spanning from October 2023 to April 2024, for one of the four monitored properties.

The implementation of the imperiusFM system in municipal buildings has delivered measurable economic benefits and contributed to improved energy efficiency in the analyzed facilities. By adjusting heating system parameters in response to outdoor temperatures, correcting disruptions in boiler room operation, and modifying setpoints within specific time intervals, the demand for gas was reduced, leading to lower variable and fixed costs associated with energy use.

Table 2 presents the exploitation savings of variable costs for four facilities administered by one of the City Offices in Poland. The analysis covers three completed heating seasons: 2021/2022, 2022/2023, and 2023/2024. The savings achieved result from comparing actual heat consumption to calculated heat demand based on the actual average monthly outdoor temperature.

Table 2. Exploitation savings of variable costs for 4 facilities administered by one of the City Offices in Poland for three heating seasons 2023/2024, 2022/2023, 2021/2022

	Exploitation savings of variable costs for 3 selected heating seasons		
Facility	**Heating season 2023/2024 Savings on variable costs [net]**	**Heating season 2022/2023 Savings on variable Costs [net]**	**Heating season 2021/2022 Savings on variable costs [net]**
O1	189 380,34 zł	398 507,30 zł	144 433,66 zł

Exploitation savings of variable costs for 3 selected heating seasons			
Facility	**Heating season 2023/2024 Savings on variable costs [net]**	**Heating season 2022/2023 Savings on variable Costs [net]**	**Heating season 2021/2022 Savings on variable costs [net]**
O2	41 859,69 zł	57 364,21 zł	22 653,43 zł
O3	17 259,80 zł	11 975,52 zł	3 257,66 zł
O4	21 867,77 zł	22 987,88 zł	9 978,35 zł
Savings in Total [net]	**270 367,60 zł**	**490 834,91 zł**	**180 323,10 zł**
Savings in Total [gross]	**332 552,15 zł**	**603 726,94 zł**	**221 797,41 zł**

Source: own elaboration.

Each of the three heating seasons resulted in measurable energy savings across all monitored facilities. The magnitude of savings varied depending on the building's size, volume, technical condition, and the type of installed systems and equipment. Nevertheless, savings often exceeded 20% compared to the baseline year before the implementation of the imperiusFM system.

The total net savings across the three analyzed seasons amounted to PLN 941,525.61 (around 22 500$), which translates to PLN 1,158,076.50 (around 275 000$) gross.

Considering the cumulative net savings achieved from the beginning of energy monitoring implementation up to the most recently completed heating season (2023/2024), the total reached PLN 2,509,711.02 (around 600 000$), as shown in Table 3.

It is particularly noteworthy that a significant portion of the savings—PLN 507,649.57 (around $ 120,000)—resulted from reduced fixed energy charges. This outcome is directly linked to the reduction of contracted capacity in the monitored facilities. This parameter is continuously monitored for each building, and according to system data, further reductions in contracted capacity are recommended for buildings O2 and O4.

Table 3. Total exploitation savings of variable and fixed costs for four facilities administered by one of the City Offices in Poland from the beginning of energy monitoring service by the 2023/2024 heating season

Total exploitation savings of variable and fixed costs by the 2023/2024 heating season		
Facility	**Variable costs savings**	**Fixed costs savings**
	[net]	**[net]**
O1	1 473 751,96 zł	161 463,79 zł
O2	223 829,93 zł	25 408,88 zł
O3	179 285,10 zł	320 776,90 zł
O4	125 194,46 zł	-
Total	2 002 061,45 zł	507 649,57 zł
TOTAL SAVINGS [net] (from the beginning of Promar service)	**2 509 711,02 zł**	
TOTAL SAVINGS [gros] (from the beginning of Promar service)	**3 086 944,56 zł**	

Source: own elaboration.

The savings resulting from reduced gas consumption also contribute to a decrease in CO2 emissions. Changes in this area are discussed using the example of one of the analyzed buildings - facility O1. The basic characteristics of this building are presented in Table 4.

This administrative facility covers a total area of 15,264 m², and its heat supply is provided by a gas boiler plant with a contracted capacity of 720 kWh/h. At present, it is recommended to maintain the current contracted capacity, which was adjusted in June 2020, when it was reduced from 823 kWh/h to 720 kWh/h.

Table 4. Description of O1 facility parameters

O1 facility parameters	
Type of facility:	Public administration building
Total area [m^2]:	15 264
Facility volume [m^3]:	91 800
Heat source:	Gas boiler room
Conventional power [kWh/h]:	720
Tariff group:	BW-6 / W-6.1

Source: own elaboration.

The analyzed facility and associated gas consumption cover the heating season of 2023/2024.

Table 5 presents the energy savings resulting from real-time thermal energy monitoring and the regulation of installations' operation within the building. In contrast, Table 6 outlines the level of CO2 reduction achieved through decreased consumption.

The forecasted heat consumption for the current heating period was estimated using the following formula:

$$Qb = Qr \times (20 - Tb) / (20 - Tr)$$

where:
Qb – calculated heat consumption for the current period (GJ, kWh, MJ)
Qr – actual heat consumption in the same month of the reference year (GJ, kWh, MJ)
Tb s– average outdoor temperature in the current period (°C)
Tr – average outdoor temperature in the reference period (°C)
"20" represents the assumed standard indoor temperature (in °C).

CO2 emissions from natural gas combustion were calculated using the fuel's emission factor, which defines the amount of CO2 emitted per gigajoule (GJ) of consumed energy (Krajowy Ośrodek Bilansowania i Zarządzania Emisjami, 2024). The formula is as follows:

$$\text{CO2 Emission} = \text{Energy Consumption (GJ)} \times \text{CO2 Emission Factor (kg } CO_2\text{/GJ)}$$

where:
CO2 Emission Factor for natural gas: 56 kg CO_2/GJ

To convert CO2 emissions from kilograms to metric tons, the following formula was applied:

$$\text{CO2 Emissions (tony)} = \text{CO2 Emissions (kg)}/1000$$

Table 5. Variable cost savings of O1 building in the heat season 2023/2024

Heat season 2023/2024									
O1	**Year**	**Month**	**Heat consumption**	**Average monthly outdoor temperature**	**Calculated heat consumption for a given average monthly outside temperature**	**The difference between the calculated and real heat consumption**	**Percentage change in heat consumption after using imperiusFM**	**Calculated value of 1 GJ**	**Profit/Loss (-) at current tariff**
			[GJ]	**[ºC]**	**[GJ]**	**[GJ]**	**[%]**	**[net]**	**[net]**
Without monitoring	2008	October	836,7	9,2					
imperiusFM	2023	October	**530,1**	11,1	**689,5**	159,4	-23,1%	233,51zł	37 213,37zł
Without monitoring	2008	November	941,9	5,3					

Heat season 2023/2024									
O1	**Year**	**Month**	**Heat consumption**	**Average monthly outdoor temperature**	**Calculated heat consumption for a given average monthly outside temperature**	**The difference between the calculated and real heat consumption**	**Percentage change in heat consumption after using imperiusFM**	**Calculated value of 1 GJ**	**Profit/Loss (-) at current tariff**
			[GJ]	**[ºC]**	**[GJ]**	**[GJ]**	**[%]**	**[net]**	**[net]**
imperiusFM	2023	November	**800,4**	4,7	**983,5**	183,1	-18,6%	259,45zł	47 514,93zł
Without monitoring	2008	December	1187,0	1,2					
imperiusFM	2023	December	**994,1**	2,7	**1091,6**	97,6	-8,9%	259,45zł	25 315,52zł
Without monitoring	2009	January	1404,1	-2,8					
imperiusFM	2024	January	**1087,5**	0,5	**1203,9**	116,4	-9,7%	101,82zł	11 850,60zł
Without monitoring	2009	February	1300,6	-0,6					
imperiusFM	2024	February	**740,2**	6,3	**862,4**	122,3	-14,2%	101,81zł	12 448,29zł
Without monitoring	2009	March	1113,3	3,5					
imperiusFM	2024	March	**712,8**	7,8	**825,2**	112,5	-13,6%	101,81zł	11 450,30zł
Without monitoring	2009	April	836,5	12,0					
imperiusFM	2024	April	**483,6**	11,3	**911,8**	428,1	-47,0%	101,81zł	43 587,33zł
TOTAL									
Without monitoring			**7620,0**	**4,0**					
After the implementation of the imperiusFM platform by PROMAR Sp. z o.o.			**5348,7**	**6,3**	**6568,0**	**1219,3**	**-18,6%**		**189 380,34 zł**

Source: own elaboration.

The results confirm that, with an average outdoor temperature of 6.3°C during the 2023/2024 heating season, energy savings amounting to PLN 189 380, 34 (around 45 000$) were achieved, corresponding to an 18.6% reduction in heat consumption. The 18,6% percentage change in heat consumption after using imperiusFM" is calculated using the formula: (Actual heat consumption / Predicted heat consumption for the given average outdoor temperature) – 1. This formula compares the actual post-implementation consumption with a baseline value that reflects expected usage under identical climatic conditions. By incorporating temperature normalization, it ensures comparability across different months and heating seasons.

The savings achieved based on available imperiusFM platform data analysis were possible through optimizing boiler operations, lowering indoor temperatures during non-working days, and prompt detection of a malfunction in Boiler 1.

During the 2023/2024 heating season, total heat consumption reached 5 348,7 GJ, which is 2271,3 GJ lower compared to the reference period before the implementation of the energy monitoring system.

Table 6. The level of CO2 reduction for facility O1 during the 2023/2024

Heat season 2023/2024									
O1	**Year**	**Month**	**Heat consumption**	**CO2 emission of heat consumption**	**Calculated heat consumption for a given average monthly outside temperature**	**CO2 emission of calculated heat emission**	**The difference between the calculated and real heat consumption**	**Savings in CO2 emission between calculated and real heat emission**	**Percentage change in heat consumption after using imperiusFM**
			[GJ]	**[t]**	**[GJ]**	**[t]**	**[GJ]**	**[t]**	**[%]**
Without monitoring	2008	October	836,7	46,86					
imperiusFM	2023	October	**530,1**	**29,69**	**689,5**	**38,61**	**159,37**	**8,93**	-23,1%
Without monitoring	2008	November	941,9	52,75					
imperiusFM	2023	November	**800,4**	44,82	**983,5**	**55,08**	183,13	10,25	-18,6%
Without monitoring	2008	December	1187,0	66,47					
imperiusFM	2023	December	**994,1**	55,67	**1091,6**	**61,13**	97,57	5,47	-8,9%
Without monitoring	2009	January	1404,1	78,63					

Heat season 2023/2024									
O1	**Year**	**Month**	**Heat consumption**	**CO2 emission of heat consumption**	**Calculated heat consumption for a given average monthly outside temperature**	**CO2 emission of calculated heat emission**	**The difference between the calculated and real heat consumption**	**Savings in CO2 emission between calculated and real heat emission**	**Percentage change in heat consumption after using imperiusFM**
			[GJ]	**[t]**	**[GJ]**	**[t]**	**[GJ]**	**[t]**	**[%]**
imperiusFM	2024	January	**1087,5**	60,90	**1203,9**	**67,42**	116,39	6,52	-9,7%
Without monitoring	2009	February	1300,6	72,83					
imperiusFM	2024	February	**740,2**	41,45	**862,4**	**48,29**	122,26	6,85	-14,2%
Without monitoring	2009	March	1113,3	62,34					
imperiusFM	2024	March	**712,8**	39,92	**825,2**	**46,21**	112,46	6,30	-13,6%
Without monitoring	2009	April	836,5	46,84					
imperiusFM	2024	April	**483,6**	27,08	**911,8**	**51,06**	428,10	23,97	-47,0%
TOTAL									
Without monitoring			**7620,0**	**426,7**					
After implementation of imperiusFM platform by PROMAR Sp. z o.o.			**5348,7**	**299,5**	**6568,0**	**367,8**	**1219,3**	**68,3**	**-18,6%**

Source: own elaboration.

An over 18% reduction in heat consumption also contributed to a significant decrease in CO2 emissions.

For facility O1, the savings in CO2 emissions between the calculated and actual heat-related emissions amounted to 68.3 [t] CO2 over the entire 2023/2024 heating season. The actual CO2 emissions totaled 299,5 tons, which represents a reduction of 127,2 tons of CO2 compared to the period before the implementation of the energy monitoring platform.

The achieved results, an 18.6% reduction in energy use and over 68 tons of CO2 emissions avoided, are consistent with savings reported in other studies, which highlight the role of application of technical building systems control, AI and IoT devices, applied analysis and algorithms, occupants behaviors and collaboration, anomaly detection, thermal comfort optimization, and indoor air quality (Hwang et al., 2025; Liang & Wang, 2024; Ogundiran et al., 2024; Rocha et al., 2015; Wang et al., 2022; Wang & Gadi, 2024; Vandenbogaerde et al., 2023). The range of savings may differ due to the type of buildings, level of automation and systems integration, applied optimization algorithms, or user engagement, but as the imperiusFM example represents a substantial achievement that aligns directly with the goals of the revised EPBD Directive, supporting the EU's broader strategy for sustainable building stock and energy efficiency improvement by 2030 (European Parliament & Council of the European Union, 2018).

5. DISCUSSION

The article aimed to explore the role of intelligent energy monitoring in advancing sustainability within facility management. This objective was supported by a practical case study of the imperiusFM platform based on the analysis of platform functionalities and implementation in the buildings, to underline the possible advantages related to energy consumption costs saving and reduction of negative impact on the environment, without changing the comfort of building utilization for its user.

The platform's modular architecture, comprised of components such as AIM (Asset Information Model), EMS (Energy Management System), CMMS (Computerized Maintenance Management System), and CAFM (Computer-Aided Facility Management), allowed to present the applicability of its functionalities to meet the specific needs of various building types and organizations. These modules collect and process a wide range of operational and environmental data to support energy consumption tracking, device performance analysis, identification of the location of detected irregularities in the operation of systems and installations, adaptation of temperature settings, space usage monitoring, and maintenance, and modernization planning.

The study's findings confirm that the application of automated and intelligent energy monitoring within advanced IT systems, such as imperiusFM, plays a significant role in enhancing energy efficiency

in buildings. Through the integration of external devices and IT systems, it becomes possible to utilize various-origins data, gathered in real time and unified for the purpose of providing multidimensional analyses and delivering measurable, sustainable outcomes.

As demonstrated by data, the achieved energy savings averaged around 20 percent annually compared to the baseline period before system implementation. The savings affected both variable and fixed costs. Notably, the analysis reveals that these savings were achieved through various strategic approaches, including reduced thermal energy demand and renegotiation of energy supply contracts, fast identification of issues related to the operation of the heating system in the facilities, or adjustment and regulation of the temperature to the building utilization and occupancy. Although this was not demonstrated in the selected example, experiences from other implementations of the imperiusFM platform, not yet publicly presented, suggest that energy savings from optimization efforts can significantly exceed 50%, particularly in the first year following system deployment, especially in facilities that were previously unmanaged in terms of energy use or had limited monitoring capabilities.

Empirical evidence from the case study also confirms that improving energy efficiency has a tangible impact on reducing greenhouse gas emissions. During the analyzed heating season, the reduction of heat demand in facility O1 led to a decrease of over 120 tons of CO2 emissions, contributing directly to national climate goals and fulfilling the requirements set forth by the EPBD Directive. This result is particularly relevant in current EU statistics, where buildings are responsible for 40% of final energy consumption and 36% of energy-related greenhouse gas emissions. In comparison, 75% of Union buildings remain energy-inefficient (European Parliament & Council of the European Union, 2024). Each ton of CO2 avoided through digital energy management holds significant environmental value.

In addition to environmental benefits, the observed reduction in energy use translated into notable financial savings for the city budget, freeing resources for other public services. Total exploitation savings of variable and fixed costs for four facilities administered by one of the City Offices in Poland from the beginning of energy monitoring service (2012) by the 2023/2024 heating season amounted to 3 086 944,56 PLN gross, which gives an average annual savings more than 250 000 PLN gross (~65 000 $ gross). In the context of rising energy prices and fiscal pressures on local governments, such savings may help sustain other public services and create stable foundations to extend monitoring to other city buildings directly dependent on public money and managed by the city government.

The achieved energy savings contributed not only to enhancing the economic efficiency of building operations but also to the stabilization of the heating system's performance. Maintaining optimal indoor thermal conditions ensured a work environment conducive to user thermal comfort, directly impacting occupants' well-being and productivity. The implemented optimization measures, including the reduction of contracted power, early detection of malfunctions in the heating system, and temperature reduction during periods of low occupancy (e.g., weekends and public holidays), enabled a dynamic adaptation of the system to actual energy demand. As a result, the stabilization of the heating system facilitated not only rationalized energy consumption but also ensured continuous indoor comfort, which is a crucial component of sustainable public facility management.

Although the findings confirm the system's contribution to sustainability targets, better energy efficiency, and in consequence money savings, they are based on a limited number of facilities. Therefore, future research should investigate the scalability of the approach and its applicability to other building types, such as educational institutions and residential or commercial buildings, where occupancy patterns and technical infrastructures may differ significantly.

In light of these findings, future research could further explore the capacity of facility management systems to support long-term adaptation strategies to climate change. Comparative studies assessing the effectiveness of various energy management strategies in different building types or buildings with similar characteristics, usage profiles, and organizational contexts would also offer valuable insights.

6. CONCLUSION

Sustainability influences the scope and direction of activities across all sectors of the economy. As one of the sectors with the highest greenhouse gas emissions, the construction industry is undergoing a significant transformation in energy efficiency.

Increasing the energy efficiency of buildings while meeting sustainability and regulatory goals has become essential. A key approach - alongside modernization efforts and the design of zero-emission buildings - is using advanced technologies and systems to monitor energy consumption and dynamically adjust the parameters of building technical systems. By integrating data from various meters, sensors, IoT devices, and IT systems, advanced data analytics enable real-time performance tracking of building installations, early anomaly detection, and data-driven decision-making for better planning energy consumption strategy in buildings.

The article explores the role of facility management systems in driving energy optimization. It is based on a case study analysis of the imperiusFM platform, whose implementations confirmed that the integration of intelligent monitoring and advanced analytics resulted in measurable reductions in energy consumption and a significant decrease in CO2 emissions.

The results of system deployment in a group of buildings managed by one of the City Offices in Poland are presented to demonstrate the scope of savings achieved through using the imperiusFM platform. Additionally, a detailed analysis of system functionalities was conducted to better understand the level of data integration and the role of specific modules in building effective energy strategies.

The findings highlight the value of digital tools for facility managers and decision-makers striving to reduce operational costs, minimize environmental impact, and align with the SDGs. The presented data demonstrates that achieving a high level of building sustainability is no longer possible without intelligent technologies and integrated systems.

The results provide strong evidence, especially for policymakers aiming to reduce emissions and improve energy performance in the public building sector. Integrating intelligent monitoring facilities in systems like imperiusFM could significantly contribute to meeting EU-level climate and energy targets. To better prove the value of such systems, future research should compare implementation across other cities, regions, and types of buildings. It would also be beneficial to explore how user engagement and institutional factors influence system effectiveness in the long run.

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INTELLIGENT SMART CITIES COMMUNICATION MANAGEMENT FOR SUSTAINABLE DEVELOPMENT

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ABSTRACT

Purpose: *The aim of the study is to assess the effectiveness of communication strategies employed by municipal offices in smart cities in Poland between 2020 and 2022. Particular attention was given to the use of social media in engaging residents.*

Need for the Study: *Effective communication between cities and citizens is crucial for implementing the smart city concept. Given the increasing role of digital communication tools, it is necessary to identify best practices for interacting with residents and measuring the effectiveness of communication strategies.*

Methodology: *The study is based on a taxonomic analysis using the zero-unitarization method. Social media data from cities in Poland were evaluated, classifying their communication strategies based on four categories of posts: e-services, ex-ante information, ex-post information, and promotional photo content. The implementation of city-resident communication strategies was assessed using constructed synthetic measures.*

Findings: *The analysis revealed significant differences in communication effectiveness among cities. Wrocław, Poznań, and Zielona Góra achieved the highest levels of resident engagement, while Szczecin lagged behind due to improper branding of the municipal office's page and irregular postings.*

Practical Implications: *The results highlight the need for active and interactive communication, promoting two-way dialogue, and utilizing advanced AI tools to analyze residents' preferences. The findings can serve as a basis for further research on the application of AI in urban communication.*

Keywords: Smart City, Effectiveness, AI, Classifications of cities, Zero-unitarization method, Communication, Public e-service, Social-media.

JEL classifications: C02, O3, O4, M39.

1. INTRODUCTION

There exists extensive literature analyzing the concept of smart cities from technological, social, and economic perspectives. Various studies and analyses discuss the smart city concept from the perspective of specific technology applications, such as ICT, IoT, and AI. This article addresses

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the smart city concept from a social perspective, with particular emphasis on management processes and citizen activation in urban development. While the implementation of cutting-edge information technologies is clearly an essential component of this concept, our work focuses on utilizing modern technologies and their role in building effective communication channels and activating residents for efficient urban management. Currently, in the concept of building smart cities, effective communication and cooperation among stakeholders presents the greatest challenge.

This article contributes to the development of the concept of activation and effective communication between municipal offices and citizens. The study focuses on assessing the effectiveness of city-to-citizen communication through social media platforms between 2020 and 2022. This research builds upon the findings presented by Guzowska and Kotnis (2024).

Due to the limitations of the DEA method used in Guzowska and Kotnis (2024), a model that simultaneously analyzed all four categories of input data was not examined. In this article, the empirical section is based on taxonomic research using the zero-unitarization method. The application of a multidimensional, two-stage indicator analysis enabled a detailed evaluation of effective communication between municipal offices and citizens, examining both the overall nature of changes and allowing for city benchmarking in terms of their adopted communication strategies.

This article is structured as follows: a review of the literature on smart city communication and the methods used to measure it, a presentation of the research methodology used, an analysis and discussion of the results obtained, together with practical recommendations.

2. LITERATURE REVIEW

The smart city concept integrates advanced information technologies to improve citizens' lives while promoting sustainable development. According to Trindade et al. (2017), "the smart city concept is perceived as a vision, manifesto, or promise aimed at creating a sustainable and ideal form of the twenty-first century city." Vanolo (2014) describes smart cities as efficient, technologically advanced, green, and socially integrated urban areas. Nam and Pardo (2011) distinguish three dimensions of building smart cities: the technological dimension (utilization of hardware infrastructure, software, and data); the human dimension (creativity, diversity, and education); and the institutional dimension (management of organizational resources and urban policy). According to Caragliu et al. (2011), the foundation of urban investment and political decisions should be investments in technology, citizen integration, and building organizational infrastructure to implement strategies based on the smart city concept, which generates sustainable development and improves population quality of life.

Consequently, the essence of all smart city initiatives is optimizing the effectiveness of public services in every sphere of activity (transportation, environmental, administrative, etc.). Contributing to innovation and better services for citizens through ICT utilization, as well as enhancing debates and political participation, intensifies cities' innovative potential. According to Dhingra and Chattopadhyay (2016), "intelligent and sustainable cities have goals that must be achieved in an adaptable, reliable, scalable, accessible, and resilient manner, such as:

- Improving residents' quality of life
- Ensuring economic growth with better employment opportunities
- Improving residents' welfare through access to social and communal services
- Establishing environmentally responsible and sustainable development approaches
- Providing effective delivery of basic services and infrastructure, such as public transport, water supply and sewage, telecommunications, and other public utilities
- Ability to cope with climate changes and environmental issues
- Providing effective regulatory mechanisms and local management ensuring fair policy".

Currently, the vision of smart cities is becoming increasingly realistic. Development directions and strategic actions of smart cities include utilizing information and communication technologies (ICT), artificial intelligence (AI), and Internet of Things (IoT) simultaneously to optimize urban infrastructure and services. In recent years, AI technologies have become an integral part of public administration, promoting intelligent city management and providing comprehensive solutions. Public administration,

through AI-based data processing, can optimize economic competitiveness and efficiency, bureaucratic procedures (Bibri et al., 2024), and mobility in sustainable smart cities. The implementation of IoT innovations in smart city management [Ortega-Fernández et al., 2020] can influence the design of innovative services and solutions for citizens. Additionally, IoT technologies and big data analytics can monitor decision-making regarding urban operations using AI-based design and planning functions, optimizing sustainable environmental development and citizens' quality of life in intelligent eco-cities (Yin, H.-T.; Wen, J.; Chang, 2023).

The efficiency of sustainable smart city development can be achieved through technological integration, effective management, active stakeholder participation, and developing intelligent models for optimal urban resource management. Technological integration involves utilizing artificial intelligence and robotic process automation (RPA) to streamline administrative workflows and improve public service delivery. According to Venigandla, Vemuri, Aneke (2024), "integration of AI and RPA technologies enables data-driven decision-making processes, streamlines administrative workflows, and improves service delivery." These technologies contribute to promoting city strategies based on smart city building. Additionally, the application of AI and RPA affects the effectiveness of promoting "sustainable development goals through optimization of resource utilization, improvement of environmental management practices, and increased climate resilience." Research also indicates a dependency between adopting comprehensive urban strategies and the necessity of building communication between stakeholders and citizens, as well as adopting an innovation culture.

Another dimension of smart cities is effective management using ICT, AI, and IoT technologies, along with active stakeholder participation (decision-makers/politicians and residents) in pro-development processes. Such effectiveness ensures transparency, accountability of decision-makers/politicians, and active engagement and communication among citizens. Matei, Cocoșatu (2024) indicate that these principles, strengthened by ICT, IoT, and AI, differentiate citizen interactions with e-administration and streamline urban mobility management. Intelligent urban management should effectively integrate Internet of Things (IoT), artificial intelligence of things (AI), intelligent decision-making algorithms based on big data technologies, and cloud processing. This is crucial as smart cities place particular emphasis on citizen engagement in decision-making processes and sustainable urban development.

Smart city construction also involves developing a model/roadmap for optimal management of urban resources. Developing sustainable smart city frameworks involves identifying key factors. Ahad, Paiva, Tripathi, Feroz (2020) point to the necessity of considering service importance and responding to developmental needs using local resources in smart city policies. Incorporating local hubs into smart city infrastructure improves awareness and operational control while optimizing the utilization of limited urban resources. According to Tanguay (2010), "the localization of resources and services using local hubs facilitates the possibility of capturing and disseminating information promptly so that the city can take steps before a crisis starts to intensify."

Effective communication management in smart cities is a key element of their sustainable development. Contemporary approaches to measuring the effectiveness of urban communication rely on productivity indicators, big data analysis, and mathematical models such as Data Envelopment Analysis (DEA) and the Malmquist Index. A crucial aspect of this evaluation is both administrative efficiency and the quality of interactions between cities and their residents.

One of the key approaches involves the use of productivity and efficiency indicators to assess the effectiveness of management within smart cities. Secinaro et al. (2021) developed a set of 71 indicators for evaluating smart cities, of which 5 focused on management efficiency, 18 related to urban governance, and 48 were dedicated to reporting and communication with residents. These studies suggest that communication effectiveness can be measured based on parameters such as the quality of access to information, municipal administration response time, and resident satisfaction levels.

Artificial intelligence (AI)- and machine learning-based management systems play a crucial role in city-resident interactions. Mahamuni et al. (2022) highlighted that AI algorithms can be used to analyze large datasets to assess how residents utilize digital urban services and how effective municipal communication is in real time. Specifically, predictive models are employed to forecast traffic congestion, transportation system efficiency, and air quality, all of which impact the quality of life in smart cities.

Brudnicka and Rybka (2019) emphasized that assessing smart city effectiveness requires developing appropriate measurement criteria that incorporate both technological dimensions and residents' social engagement. They pointed to the importance of using cloud technologies and integrated databases that enable the monitoring of citizen interactions with public services.

A new approach to measuring the effectiveness of the city's communication with citizens is the analysis of municipalities' activity on social media. Guzowska and Kotnis (2024) examined the effectiveness of communication on the Facebook pages of municipal offices in Poland between 2020 and 2022, applying DEA methods and the Malmquist Index across five thematic models. Their study found that cities vary in their ability to engage residents, with the most effective being those that actively fostered two-way dialogue and responded to citizens' needs.

In summary, the literature underscores the multifaceted nature of smart cities, where technological advancements—particularly in AI, ICT, and IoT—intersect with social participation and institutional governance. Effective communication is repeatedly emphasized as a critical enabler of sustainable urban development. The reviewed studies collectively highlight the growing importance of social media platforms and AI-driven tools in fostering active civic engagement, enhancing service delivery, and promoting transparent governance. These insights provide a robust foundation for the empirical investigation presented in the following sections.

3. RESEARCH METHODOLOGY

This study adopts a three-stage research scheme to assess the effectiveness of digital communication strategies in Polish cities between 2020 and 2022:

Stage I. Construction of communication effectiveness indicators.

Stage II. Application of the zero- unitarization method to normalise and compare communication strategies using a fixed benchmark over a three-year period.

Stage III. On the basis of the synthetic measure created in Stage II, rankings of cities were constructed, divided into four groups showing the effectiveness of city-resident communication.

In the first stage, based on the definition of productivity proposed by Caves et al. *(*1982), Charnes *et al.* (1978) and Charnes et al.(1995), indicators were developed according to the following formula:

$$U_q = \frac{\sum_{r=1}^{s} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} = \frac{\mu_1 y_{1j} + \mu_2 y_{2j} + \cdots + \mu_r y_{rj}}{v_1 x_{1j} + v_2 x_{2j} + \cdots + v_m x_{mj}} \quad (1)$$

where:
s – the number of outputs,
m – the number of inputs
y_r – output values,
x_i – input values,
μ_r – the weights of outputs,
v_i– the weights of inputs.

Subsequently, an analysis of changes in these indicators was conducted. At this stage, the taxonomic method of linear ordering proposed by Hellwig (1968) was applied, along with normalization based on a fixed reference point maintained throughout the entire analysis period (2020–2022). This fixed reference point defines the range of normalized variables in accordance with Equation (2) (see: Kukuła & Bogocz, 2014; Balcerzak, 2015).

$$R(X_{jt}) = \max_{it} x_{ijt} - \min_{it} ijt \quad (2)$$

In the third step, a comprehensive assessment of cities was conducted using a single synthetic measure based on four indicators proposed by the authors. Subsequently, the evaluation of cities was analyzed based on each of the four indicators individually. The applied method not only allowed for the ranking of cities and the assessment of progress in achieving key objectives related to city-to-citizen communication but also classified them into four levels of achievement: (a) very high, (b) high, (c) medium, and (d) low, in relation to the citizen communication strategy.

To construct the indicators, as generally described by equation (1), the study utilized four types of input variables and three types of output variables. The input variable group consisted of thematic categories of posts published by municipal offices on Facebook in September 2020, 2021, and 2022. Follow Guzowska and Kotnis (2024), the four thematic groups are as follows:

a) **E-services** (e.g., participatory budgeting, civic projects, public transport updates);
b) **Ex-ante information** (e.g., announcements about cultural and social events);
c) **Ex-post information** (e.g., reports on past events and citizen participation);
d) **Photos/Panoramas** (e.g., promotional content showcasing the city's attractions).

The output variables used to construct the diagnostic indicators include Likes, Shares, and Comments left by followers in each thematic category.

To enhance the precision of communication effectiveness assessment, a weighting system was introduced to assign different levels of significance to various user reactions. The following weights were applied: Like (weight =1), Share (weight=2) and Comment (weight=3). Assigning higher weights to comments and shares aligns with the principles of the smart city concept, which emphasizes community activation and citizen participation in building intelligent cities. Active communication and engagement play a crucial role in achieving this goal. Comments facilitate dialogue and social interaction, whereas shares increase the reach of public institutions, strengthening their impact. Consequently, municipal social media profiles that effectively encourage commenting and sharing demonstrate a higher level of communication efficiency.

Based on the above assumptions, the achievement of the objective related to communication between the city and the citizens was assessed through the following specific diagnostic indicators:

$$x_{1t} = \frac{(Likes{+}3\ Comments{+}2\ Sharings)\ in\ \text{"E - services"}\ per\ number\ of\ followers}{Total\ number\ of\ post\ "E-servives"}$$

$$x_{2t} = \frac{(Likes{+}3\ Comments{+}2\ Sharings)\ in\ "Ex{-}ante\ information"\ per\ number\ of\ followers}{Total\ number\ of\ post\ "Ex{-}ante\ information"} \quad (3)$$

$$x_{3t} = \frac{(Likes{+}3\ Comments{+}2\ Sharings)\ in\ "Ex{-}post\ coverage"\ per\ number\ of\ followers}{Total\ number\ of\ post\ "Ex{-}post\ coverage"}$$

$$x_{4t} = \frac{(Likes{+}3\ Comments{+}2\ Sharings)\ in\ \text{"Photo/panorama"}\ per\ number\ of\ followers}{Total\ number\ of\ post\ \text{"Photo/panorama"}}$$

All indicators used in the study were identified as stimulants, meaning they had a positive impact on the measure. To ensure comparability across variables, min-max normalization was applied (Kukuła, 1999). For the indicators classified as stimulants in this study, normalization was conducted using the following formula:

$$z_{ijt} = \frac{x_{ijt} - \min\limits_{it}\{x_{ijt}\}}{\max\limits_{it}\{x_{ijt}\} - \min\limits_{it}\{x_{ijt}\}} \quad (4)$$

$$(i = 1,2,\dots,n);\ (j = 1,2,\dots,m);(t = 1,2,\dots,l);z_{ij} \in [0,1]$$

where:
z_{ijt} is the normalized value of the *j*-th variable in the *i*-th city on year t,
x_{ijt} is the initial value of the *j*-th variable in the *i*-th city on year t.

Assessment of the variable that characterizes the objects – a synthetic measure SM_{it} – was obtained with the formula (4).

$$SM_{it} = \frac{1}{m}\sum_{j=1}^{m} z_{ijt} \quad (5)$$

$$(i = 1,2,\dots,n);\ (j = 1,2,\dots,m);(t = 1,2,\dots,l);z_{ij} \in [0,1];SM_i \in [0,1]$$

The synthetic measure enables to divide the set of cities into four groups:

1. Group I – the cities with very high level of synthetic measure of the **implementation of the city's communication strategy with residents**, where ($SM_{it} \geq \overline{SM_{it}} + S(SM_{it})$)

2. Group II - the cities with a high level of synthetic measure of the **implementation of the city's communication strategy with residents**, where ($\overline{SM_{it}} \leq SM_{it} < \overline{SM_{it}} + S(SM_{it})$),

3. Group III - the cities with an average level of synthetic measure of the **implementation of the city's communication strategy with residents**, where ($\overline{SM_{it}} - S(SM_{it}) \leq SM_{it} < \overline{SM_{it}}$),

4. Group III - the cities with a low level of synthetic measure of the **implementation of the city's communication strategy with residents** where ($SM_{it} < \overline{SM_{it}} - S(SM_{it})$),

where:

$\overline{SM_{it}}$- arithmetic mean of a synthetic measures SM_{it},

$S(SM_{it})$ - standard deviation of a synthetic measure SM_{it}.

4. RESEARCH RESULTS AND DISCUSSION

In the third stage of the study, the overall level of implementation of the cities' communication strategies with citizens between 2020 and 2022 was assessed. The assessment was made through a synthetic measure (SM) base on formula 5, with a fixed reference point over the period studied. The results of the analysis are presented in Table 1 and Figure 1.

Table 1. The result of multivariate analysis of **the implementation of the city's communication strategy with residents** in the years 2020, 2021 and 2022

2020			2021			2022		
No.	**Co.**	**SM**	**No.**	**Co.**	**SM**	**No.**	**Co.**	**SM**
I - Cities with very high level of synthetic measure of the implementation of the communication strategy								
1.	Kielce	0,6525025	1.	Łódź	0,4769669	1.	Zielona Góra	0,4458247
2.	Gorzów	0,5177172	2.	Zielona Góra	0,461955	2.	Wrocław	0,4454889
						3.	Kielce	0,4086795
						4.	Poznań	0,3924704
						5.	Gorzów	0,3779756
II - Cities with a high level synthetic measure of the implementation of the communication strategy								
3.	Olsztyn	0,2641034	3.	Gorzów	0,2971521	6.	Warszawa	0,3111264
4.	Lublin	0,2246891	4.	Kielce	0,2587215			
5.	Gdańsk	0,2160061	5.	Gdańsk	0,2088847			
6.	Łódź	0,2110856						
III - Cities with an average level synthetic measure of the implementation of the communication strategy								
7.	Białystok	0,1527726	6.	Warszawa	0,1875686	7.	Gdańsk	0,209059
8.	Toruń	0,1358353	7.	Toruń	0,1709839	8.	Bydgoszcz	0,192646
9.	Bydgoszcz	0,1331921	8.	Lublin	0,1704942	9.	Kraków	0,1596098
10.	Poznań	0,1189525	9.	Poznań	0,1572794	10.	Łódź	0,1535743
11.	Zielona Góra	0,1089662	10.	Olsztyn	0,1421787	11.	Toruń	0,1455361
12.	Warszawa	0,1068616	11.	Białystok	0,1345309	12.	Olsztyn	0,1428549
13.	Wrocław	0,0909639	12.	Bydgoszcz	0,132552	13.	Lublin	0,1427983
14.	Kraków	0,0465775	13.	Wrocław	0,1069189	14.	Białystok	0,1208622
15.	Katowice	0,0420685	14.	Kraków	0,1006745	15.	Katowice	0,1182322
			15.	Katowice	0,0864262			
IV - Cities with a low-level synthetic measure of the implementation of the communication strategy								
16.	Szczecin	0,0148285	16.	Szczecin	0,0477008	16.	Szczecin	0,1168602

Source: own elaboration.

The value of the synthetic indicator for the implementation of the city-to-citizen communication strategy reflects the changes that occurred over the three-year period, both in terms of the level of goal achievement and the ranking positions of the cities.

In 2020, Kielce and Gorzów were the cities with a very high level of the synthetic measure for communication strategy implementation. The group of cities with a high level of this measure included

Olsztyn, Lublin, Gdańsk, and Łódź. The third group consisted of cities with a average level of communication strategy implementation as measured by the synthetic indicator (SM), including Białystok, Toruń, Bydgoszcz, Poznań, Zielona Góra, Warsaw, Wrocław, Kraków, and Katowice. The last, fourth group included only one city—Szczecin—which represented the lowest level of communication strategy implementation. Notably, Szczecin remained in this lowest-ranked group throughout the entire three-year study period.

In 2021, some changes occurred. Kielce and Gorzów moved to the second group, while the cities with a very high communication strategy implementation indicator were Łódź (previously ranked in 2020) and Zielona Góra (which had ranked 11th in 2020). The second group, apart from Gorzów and Kielce, also included Gdańsk, which in 2020 was already in this group, ranking 5th overall. The third group, representing an average level of the synthetic measure of communication strategy implementation, included, in order: Warsaw, Toruń, Lublin, Poznań, Olsztyn, Białystok, Bydgoszcz, Wrocław, Kraków, and Katowice.

In 2022, the first group (very high SM) included five cities: Zielona Góra, Wrocław, Poznań, Kielce, and Gorzów. Łódź, which ranked first in 2021, dropped to 10th place in 2022. The largest number of cities was in the third group—cities with an average level of the synthetic measure of communication strategy implementation—which, in ranking order, included Gdańsk, Bydgoszcz, Kraków, Łódź, Toruń, Olsztyn, Lublin, Białystok, and Katowice.

The dynamics of change in the indicator for achieving the objective of the cities' communication strategy are shown in Figure 1.

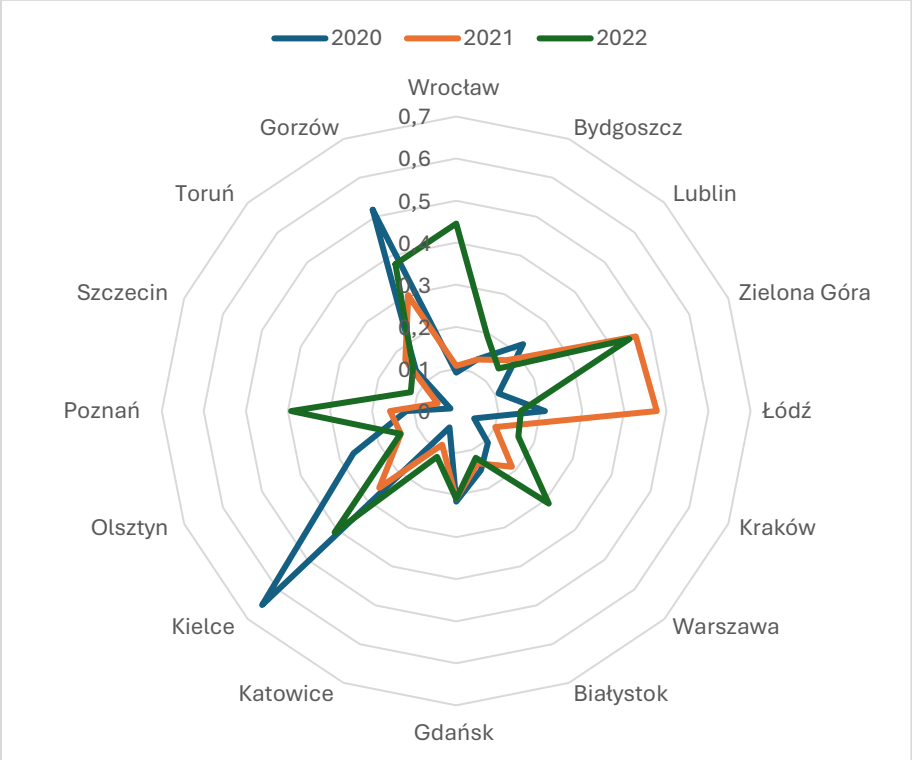


Figure 1. The average level analysis synthetic measure of the **implementation of the city's communication strategy with residents** in the years 2020, 2021 and 2022

Source: own elaboration

In order to understand which aspects of the city's communication strategy were most focused on, the second part of the study analysed the synthetic measures built for all 4 categories on which the indicators were built. The results of this part of the analysis are presented in Figures 2, 3, 4 and 5.

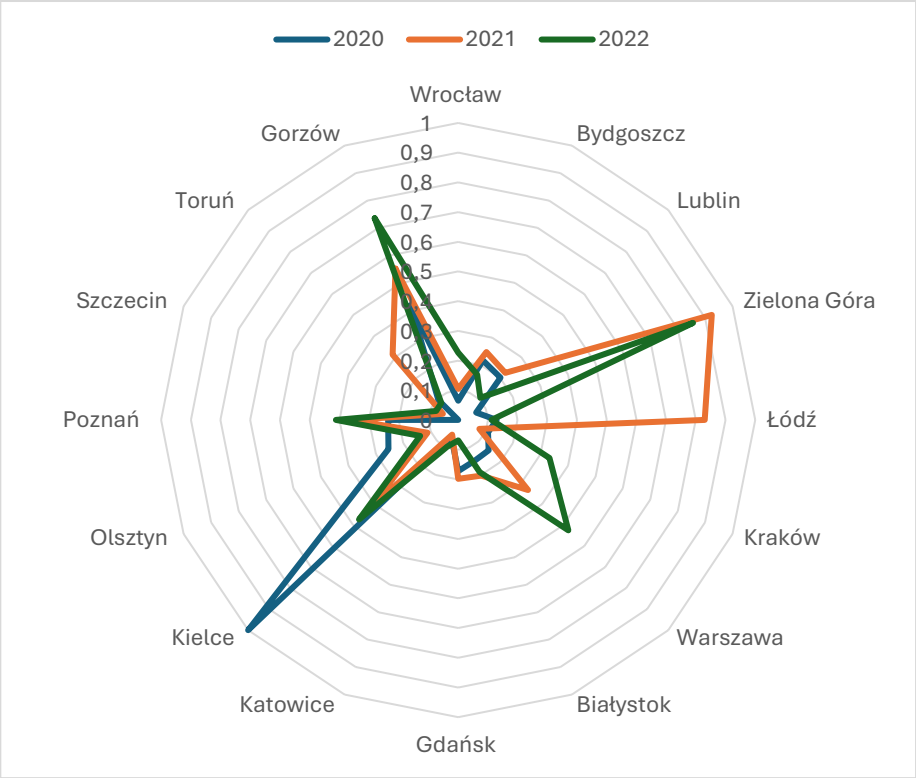


Figure 2. Average level of implementation **of the city's communication strategy with residents** in the "E - services" category in 2020, 2021 and 2022
Source: own elaboration.

The analysis of the synthetic measure (SM) in the "E-services" category for 16 cities in Poland between 2020 and 2022 allowed for an assessment of changes in the use of social media for communication with residents regarding projects, social initiatives, events, and other aspects related to e-services.

Among the cities with the most significant increase in the "E-services" index, Warsaw, Poznań, and Gorzów stand out. Warsaw experienced a notable rise from 0.1057 in 2020 to 0.3671 in 2022, indicating growing engagement in electronic communication. A similar trend was observed in Poznań, where the index increased from 0.1709 to 0.2913. Gorzów, in turn, demonstrated a stable upward trend between 2020 and 2022, reaching a value of 0.4644 in 2022.

Some cities exhibited significant fluctuations in index values. Zielona Góra achieved the highest score in the dataset (1.00) in 2021 but declined to 0.6458 in 2022, suggesting a one-time intensification of communication efforts. Łódź, which recorded an index of 0.5966 in 2021, saw a sharp decrease to 0.0802 in 2022, indicating a temporary peak in activity in the previous year.

Conversely, Lublin, Bydgoszcz, and Gdańsk showed a downward trend in the e-services index. In Lublin, the index fell from 0.1247 in 2020 to 0.0699 in 2022, possibly reflecting reduced engagement in electronic communication. Bydgoszcz peaked in 2021 with an index of 0.1748 but declined to 0.1326 the following year. Similarly, Gdańsk, which had an index of 0.1119 in 2020, dropped to 0.0404 in 2022. Some cities showed minimal changes in their index values over time. Katowice maintained a low level of activity, with values of 0.0527 in 2020, 0.0400 in 2021, and 0.0755 in 2022. Szczecin, recorded no measurable activity in 2020 (index of 0.0000), showed a slight increase in subsequent years. Toruń experienced a rise to 0.2129 in 2021, followed by a decline to 0.0525 in 2022.

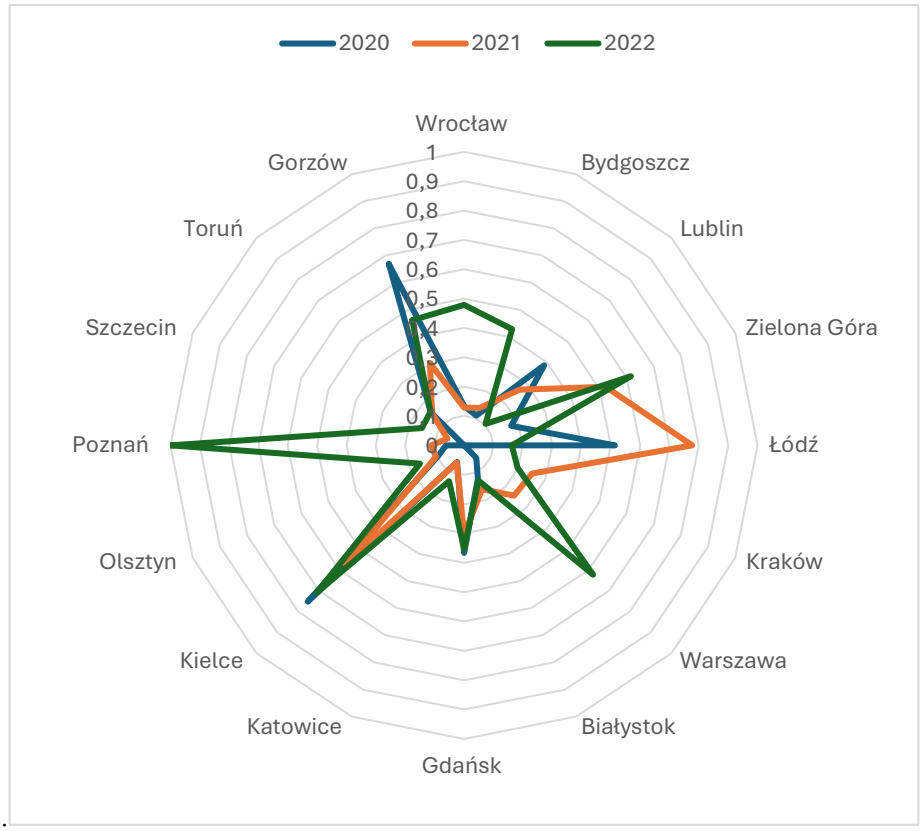


Figure 3. Average level of implementation **city's communication strategy with residents** in the "Ex-ante information" category in 2020, 2021 and 2022

Source: own elaboration.

The analysis of the synthetic measure (SM) for the "Ex-ante Information" indicator from 2020 to 2022 assessed how cities utilized Facebook to inform residents about upcoming cultural, entertainment, and commemorative events.

In Wrocław, the index remained stable in 2020 and 2021 (0.134 and 0.128, respectively), followed by a sharp increase to 0.479 in 2022. A similar trend was observed in Bydgoszcz, where a slight increase in 2021 (from 0.109 to 0.138) was followed by a rise to 0.429 in 2022. Conversely, Lublin exhibited an opposite trend—after a relatively high value in 2020 (0.386), the index declined in subsequent years to 0.269 and 0.103. Zielona Góra demonstrated a consistent increase over the study period, from 0.173 in 2020 to 0.522 in 2021 and 0.616 in 2022, indicating growing engagement in information dissemination. Meanwhile, in Łódź, the index significantly increased in 2021 (from 0.514 to 0.777) but dropped drastically to 0.163 in 2022. Kraków experienced an increase in 2021 (from 0.0005 to 0.250), but the index declined to 0.198 in 2022. Warsaw followed an upward trend, rising from 0.060 in 2020 to 0.241 in 2021 and 0.622 in 2022, suggesting an increasing number of event announcements. In contrast, Białystok's index remained relatively constant over the study period, fluctuating between 0.122 and 0.162. Gdańsk saw a decline in 2021 (from 0.367 to 0.304), followed by a slight increase to 0.354 in 2022.

Stable index values were observed in Katowice, where the measure ranged between 0.061 and 0.132. Kielce experienced a decline in 2021 (from 0.753 to 0.571) but rebounded to 0.708 in 2022. Olsztyn showed a gradual increase from 0.095 in 2020 to 0.162 in 2022.

The most significant growth over the study period was recorded in Poznań, where the index increased from 0.062 in 2020 to 1.000 in 2022, indicating very high engagement in information dissemination. In Szczecin, the index, initially at 0.000 in 2020, rose to 0.061 in 2021 and 0.155 in 2022, among the lowest recorded values. In Toruń, the index remained stable between 2020 and 2022, ranging from 0.152 to 0.161. Gorzów showed a sharp decline in 2021 (from 0.668 to 0.303), followed by a partial recovery to 0.462 in 2022.

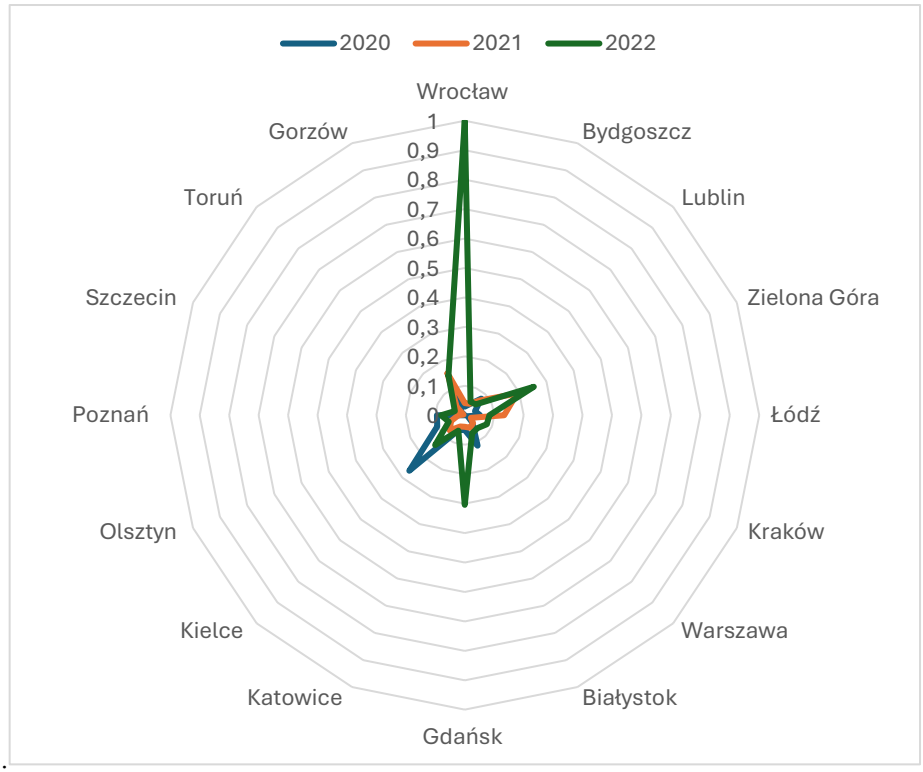


Figure 4. Average level of implementation **city's communication strategy with residents** in the "Ex-post coverage" category in 2020, 2021 and 2022
Source: own elaboration.

An analysis of the synthetic measure (SM) for the 2020-2022 Ex-post indicator assessed how cities used social media, such as Facebook, to inform residents about coverage of events involving public authorities and politicians and coverage of events involving members of the local community - highlighting the presence of residents in the post. During the analyzed years, the synthetic measure (SM) values exhibited diverse dynamics across different cities. Wrocław stood out with a significant increase, reaching a value of 1 in 2022, representing a sharp rise compared to previous years. A considerable disparity was observed between Wrocław and other cities, as the SM values for the remaining cities ranged between 0 and 0.3. For instance, Zielona Góra demonstrated a consistent upward trend, with the index increasing from 0.037 in 2020 to 0.192 in 2021 and 0.254 in 2022, suggesting a growing presence of ex-post event reporting. A similar trend was observed in Gdańsk, where after a slight decline in 2021, the value increased to 0.305 in 2022. Some cities experienced stability or minor fluctuations in the index. Bydgoszcz exhibited moderate but gradual growth, from 0.040 in 2020 to 0.049 in 2022. Warsaw, Katowice, and Olsztyn maintained relatively stable values, oscillating around 0.04–0.06. In contrast, Lublin and Białystok experienced a decline in SM values over the years, which may indicate reduced interest in reporting events after their conclusion. Szczecin recorded an increase, rising from a zero value in 2020 to 0.036 in 2022, indicating growing activity in ex-post event reporting, although still insufficient to reach at least the medium SM values. In Poznań, after a drop in 2021, the index rebounded to 0.08 in 2022, suggesting renewed interest in this type of content. Kielce presented an interesting case, having recorded the highest value in the dataset in 2020 (0.267), but subsequently experiencing a decline, stabilizing at 0.143 in 2022. Meanwhile, in Łódź, an increase was observed in 2021 (0.134), followed by a drop to 0.084 in 2022.

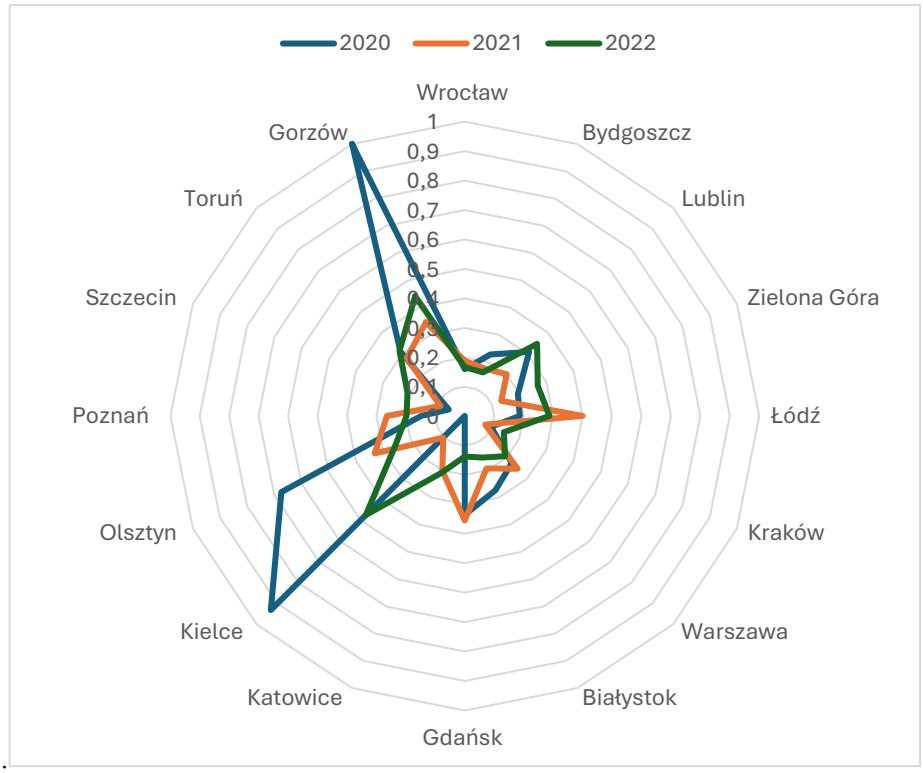


Figure 5. Average level of implementation **city's communication strategy with residents** in the "Photo/panorama" category in 2020, 2021 and 2022
Source: own elaboration.

The analysis of the synthetic measure (SM) in the "Photo/Panorama" category revealed significant changes in the number of posts related to city photography, panoramas, and promotional materials showcasing local attractions between 2020 and 2022. These results indicate varying dynamics in promotional activities across different cities. In 2020, the highest SM values were recorded in Gorzów (1.000), Kielce (0.9319), and Olsztyn (0.6742), suggesting intensive city promotion through photographic posts. Additionally, Gdańsk (0.3355), Lublin (0.3088), and Toruń (0.3098) also achieved relatively high values. In contrast, Katowice exhibited no promotional activity in this category.

In 2021, significant declines were observed in several cities, particularly in Kielce (dropping to 0.1036) and Gorzów (falling to 0.3448), which may indicate reduced promotional efforts, potentially influenced by the COVID-19 pandemic or a shift in marketing strategies. Meanwhile, Łódź experienced an increase to 0.4001, and Katowice saw the emergence of promotional activity, reaching 0.2007. Warsaw, Gdańsk, and Poznań maintained relatively stable values, whereas Lublin, Zielona Góra, and Białystok saw declines. In 2022, the situation changed again, with some cities experiencing a resurgence in activity, such as Lublin (0.3464), Zielona Góra (0.2682), Szczecin (0.2108), and Kielce (0.4756). Despite a previous decline, Gorzów recorded an increase to 0.4404. However, Gdańsk showed a sharp decrease to 0.1372, indicating reduced photographic promotion of the city. Declines were also observed in Warsaw, Białystok, and Bydgoszcz. Notably, Toruń maintained a stable index throughout the entire analysis period.

5. RESEARCH FINDINGS AND DISCUSSION

The results of the conducted study indicate significant differences in the effectiveness of city communication strategies with residents. They also clearly show that most cities do not have clearly defined forms in which they aim to achieve this goal. Among the cities with the highest communication efficiency between the city and its residents are Wrocław, Poznań, Zielona Góra, Kielce, and Gorzów, which have implemented the most effective practices for engaging citizens through interactive social media tools. These cities actively utilized digital platforms, such as Facebook, to increase public

participation in governance and city branding. On the other hand, Szczecin consistently ranked among the lowest in communication effectiveness, primarily due to an inconsistent branding strategy and infrequent, irregular or uncoordinated content publication. The lack of a clear city identity strategy, including an ambiguous social media page name (Facebook account under the name: SzczecinFloatingGarden), contributed to low resident engagement levels. A more detailed analysis by thematic groups reveals several key observations. In the area of e-services, Warsaw, Poznań, and Gorzów showed a significant increase in engagement within this category, reflecting their proactive approach to integrating services with social media. Meanwhile, Lublin and Bydgoszcz recorded a decline in interactions in this category, which may indicate the inefficiency of their communication strategies. Regarding ex-ante information, Poznań demonstrated the highest growth, effectively utilizing social media to promote events and mobilize citizens. Conversely, Lublin and Gorzów recorded a decrease in engagement in this category. Ex-post information, covering event reporting and social participation, was most effectively utilized by Wrocław, whereas Lublin and Białystok showed lower levels of resident activity. In terms of visual content (Foro), Gorzów and Kielce showed fluctuations in branding activity, while Toruń maintained a stable presence, consistently using high-quality visual materials to strengthen its digital identity.

The results emphasize the importance of a consistent branding strategy and the quality of content used in the digital communication between cities and their residents. Cities that maintained recognizable and well-structured online profiles recorded higher levels of resident engagement. The case of Szczecin highlights the risks of ineffective branding—an unclear identity and irregular postings negatively impacted social interaction. Another key success factor was the promotion of two-way communication. Cities such as Poznań and Wrocław actively responded to resident inquiries and engaged in digital discussions, enhancing social engagement and their credibility in public communication.

In the context of the growing role of artificial intelligence in digital management, future research should focus on optimizing communication using AI. The automation of municipal interactions could significantly impact engagement patterns, especially since, from 2024, an increasing amount of content in local administration may be generated by AI algorithms. Additionally, it is necessary to establish frameworks for long-term monitoring of communication strategy effectiveness. Regular assessment of municipal digital communication efficiency should become an integral part of smart city management strategies to ensure continuous improvement in social interactions and administrative transparency.

6. CONCLUSIONS

This study reinforces the central role of digital communication as a pillar of smart city governance. It reveals that the effectiveness of municipal communication strategies hinges not only on content frequency or aesthetics, but also on their interactivity, strategic coherence, and alignment with citizen expectations. Cities that combined branding consistency with proactive engagement mechanisms—such as responding to comments or using multimedia—demonstrated significantly higher levels of digital engagement.

Looking forward, the evolution of city-citizen interactions will be increasingly shaped by the application of advanced artificial intelligence tools. Future research should explore the potential of large language models (LLMs), such as GPT-based platforms, in generating responsive and context-aware content for social media. Additionally, municipal chatbots trained on local administrative data could be deployed to facilitate two-way communication, automate responses to frequently asked questions, or provide tailored services to residents.

Other promising directions include the integration of recommender systems to personalize urban information flows and the use of natural language understanding (NLU) to analyze sentiment and emerging needs in resident feedback. Longitudinal studies could also assess how the use of these tools affects citizen trust, administrative transparency, and social participation in smart cities over time. To remain effective and inclusive, municipal communication must not only adapt to technological change but actively co-evolve with it. In this light, AI should be viewed not as a one-time solution, but as a dynamic partner in shaping the future of digitally empowered urban governance.

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ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE WINE INDUSTRY: AI-DRIVEN MANAGEMENT IN VITICULTURE, WINE PRODUCTION AND ENOTOURISM

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ABSTRACT

Purpose: *This study examines the role of Artificial Intelligence (AI) in enhancing sustainability and efficiency within the wine industry. It focuses on AI-driven intelligent management in viticulture, wine production, and enotourism.*

Need for the Study: *As the wine industry faces environmental and economic challenges, AI offers innovative solutions to optimize resource use, reduce environmental impact, and improve customer engagement. Understanding AI's potential in sustainable winemaking is crucial for fostering responsible and efficient industry practices.*

Methodology: *The research is based on a questionnaire survey conducted among Polish winemakers, combined with a comprehensive analysis of AI methods applicable to viticulture, production, and tourism. Key AI technologies, including predictive analytics, machine learning, and computer vision, are explored.*

Findings: *AI enhances vineyard monitoring, optimizes irrigation, and streamlines production processes, contributing to sustainable resource management. In enotourism, AI-powered chatbots, recommendation systems, and virtual tastings personalize consumer experiences. The study underscores AI's impact on economic, environmental, and social sustainability, supporting local wine enterprises and cultural heritage.*

Practical Implications: *AI in winemaking and enotourism can lead to more efficient, sustainable operations that benefit producers and consumers. AI-driven solutions promote responsible tourism, enhance wine tourism experiences, and ensure the industry's long-term viability.*

Keywords: Artificial Intelligence, Sustainable Development, AI-Driven Management, Viticulture, Wine Production, Enotourism, Wine Enterprises, Local Communities

JEL codes: A13, A14, C55, D81, L66, L83, M31, O33, Q01, Q13, Q16, Z32

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1. INTRODUCTION

Sustainability in the wine industry encompasses environmental stewardship, economic viability, and social responsibility. Sustainable viticulture aims to minimize environmental impacts while maintaining product quality. Environmental issues have become very important among winemakers. They are strongly linked to corporate image (Santini et al., 2013), especially when winery customers push for environmentally friendly practices (De Castro et al., 2024). Additionally, the adoption of organic and biodynamic farming methods has increased in recent years (Baiano, 2021), contributing to the overall sustainability of vineyards. In wine production, sustainability efforts focus on reducing resource consumption and waste or implementing energy-efficient technologies. This approach contributes to reducing carbon emissions, which the wine industry is increasingly compelled to do by market and regulatory factors that force it to assess, reduce and communicate its carbon footprint (da Silva & da Silva, 2022). In addition to viticulture and wine production, an important part of the wine industry is enotourism. Many authors emphasize that wine tourism may become an additional source of income and contribute to the preservation of cultural heritage and cultural wine landscapes in regions facing various economic and demographic problems (Lourenço-Gomes, Pinto & Rebelo, 2015; Montella, 2017; Senkiv et al., 2022). Considerably fewer studies address wine tourism in a complex way, paying equal attention to the three pillars of sustainable development – economic, environmental and social impact. Among them is undoubtedly the report „Sustainable Wine Tourism: A Global Survey" (Szolnoki et al., 2022). After a survey involving indices of sustainable development, these authors assert that wine tourism could be the key element for the sustainable development of wine regions worldwide. Many studies highlight that sustainability in wine tourism is increasingly linked to competitive advantages, influencing consumer preferences and industry practices (Martínez-Falcó et al., 2024). Despite advancements, challenges remain in fully integrating sustainability into the wine industry. Future research should focus on developing innovative solutions to these challenges, including applying artificial intelligence solutions (Newlands, 2021).

The primary objective of this study is twofold: (a) to present the findings of a survey conducted among Polish winemakers regarding their approach to sustainability, and (b) to identify potential applications of artificial intelligence (AI) that can enhance sustainability in viticulture, wine production, and enotourism. The study is grounded in the three pillars of sustainability - environmental, social, and economic - and seeks to comprehensively analyze current attitudes in the Polish wine industry and their potential for AI-driven innovation.

The research was designed as a full-population study rather than a sample-based survey, as the questionnaire was distributed to all officially registered vineyards in Poland at the time of the study. This methodological approach allows for capturing the Polish wine industry in the initial stage. In the environmental dimension, the study examines pro-environmental viticulture methods, sustainable wine production practices, and the availability of organic and natural wines. The social dimension focuses on the role of wineries in shaping the cultural landscape, their architectural impact, and their contributions to local communities. The economic dimension explores how viticulture, wine production, and enotourism contribute to regional economic development.

The analysis of collected data suggests that Poland's relatively small-scale production and limited vineyard acreage—characteristic of an early-stage winemaking industry—create favorable conditions for sustainable development. However, potential expansion and a shift toward mass production may challenge the sector's sustainability. Consequently, the study discusses how AI-driven solutions can help maintain environmentally and socially responsible winemaking practices.

2. LITERATURE REVIEW

Vineyards and viticulture are closely linked to a territory and its natural and cultural heritage. In Poland, it is assumed that the development of viticulture, as a cultural phenomenon and an economic enterprise, can be divided into three distinct phases: from the adoption of Christianity (with the culmination of development at the turn of the thirteenth and fourteenth centuries) to the decline of the First Polish Republic, the 20th century (especially the 1930s and 1950s) and the Third Polish Republic and the present day (Jęczmyk, 2019).

Grape growing was widespread in Poland centuries ago. The oldest evidence of vines found on the hillsides of the Wawel Royal Castle in Kraków dates from the turn of the 9th and 10th centuries, but proper development began in the 12th century (Dylik-Ostrowska et al., 2021; Fundacja Galicja Vitis, 2017; Kapczyński, 2021). Grapes came to Poland with Christianity, and the first winemakers were the Benedictine and Cistercian monks, who cultivated these plants on monastery farms and used the wine for liturgical purposes (Wawro, 2011). At first, viticulture in Poland was not easy, as it required previously unknown techniques, and the work could only be done by adequately trained people. It is believed that this is why vine-growing first took place on land belonging to churches, monasteries, or princes. Only later did vineyards appear near hospitals, as wine was used to cure various diseases (Myśliwiec, 2013). In the 13th century, winemaking was of little economic importance in Poland and wine was the luxury drink of the wealthy. It was not until the 14th century that a revolutionary change took place and this was when this activity became most widespread in Poland. At this time, wine-making was also taken up by the bourgeoisie, who saw that it was a profitable profession (Poczta & Zagrocka, 2016). The crisis of Polish winemaking began in the 16th century, when wine began to be imported from countries where viticulture was much easier (mainly from Hungary, France and Italy), and Polish wine slowly gave way to cheaper foreign wine. However, this was not the only factor that caused a decline in interest in setting up one's vineyards. Unfavorable climatic conditions were also a contributing factor (including the so-called Little Ice Age), effectively destroying the crop, making cultivation more expensive and less profitable. However, the most significant damage to Polish vineyards was caused by wars in the 17th and 20th centuries (Dylik-Ostrowska et al., 2021; Myśliwiec, 2013; Olewnicki, 2018). The phylloxera plague decimated vineyards across Europe, another factor stopping Poland's winemaking development.

World War II was a time of devastation for vineyards and the moving borders on the map of Europe. The post-war authorities initially planned to rebuild the wine infrastructure, but the freezing winter of 1956/1957 made the planned winemaking ventures seem doomed to failure. More important were the large, socialist state farms, the collectivization of agriculture through its control by the state and the forced amalgamation of individual farms into huge cooperatives, and the distraction from the mistakes made with this. It was not until the collapse of communism that economic and cultural changes revived history and made changes possible (Kapczyński, 2021).

The current history of wine making in Poland began in the second half of the 20th century, in the 1980s. (Dylik-Ostrowska et al., 2021; Wawro, 2011). The growing interest in food, cooking, culinary programs and the fashion for preparing meals together has also led to an increased interest in beverages, including wine, which is often not only a component of a dish but also an essential accompaniment to a meal (Mazurkiewicz-Pizło, 2010). The warming of the climate and the successive introduction of new vine varieties, resistant or less sensitive to disease and above all resistant to frost (known as hybrids), make it possible to establish vineyards in areas with a more difficult climate (Olewnicki, 2018). Not insignificant is the legislation, which is changing in favor of winemakers, concerning the conduct of broadly defined winemaking activities. The development of winemaking in Poland is the most dynamic in Poland's history, and there are more and more vineyards every year. New vineyards are being established not only in regions long associated with wine, but all over the country, an example of which is the north-western region of Zachodniopomorskie.

The area of cultivated vineyards in Poland varies from a dozen or so acres to several dozen hectares. The largest vineyard in Poland is the Turnau Vineyard, which covers 41 hectares. (Winnica Turnau, 2024). Polish vineyards also have a diverse character - they are family-owned, non-commercial vineyards, and organized enterprises conducting business activities.

A relatively thorough basis for understanding domestic wine production is the lists of the National Agricultural Support Centre (Krajowy Ośrodek Wsparcia Rolnictwa KOWR, Wykazy i Rejestry, 2023). In 2023, there were 530 registered entrepreneurs authorized to engage in the business of making or bottling wine products. However, this number does not reflect the phenomenon's scale under analysis. According to popular internet portals run by winemakers, in March 2023, over 580 vineyards were operating in Poland. The relatively large number discrepancy has to do with the fact that not all winemakers register their winemaking activities, some vineyards are tiny and produce wine only for their own needs, and others are very young plantings where the vines do not yet produce adequate fruit. Three regions can, however, be recognized as Poland's wine-growing centers in terms of the number of vineyards and acreage planted: Małopolskie, Lubuskie and Dolnośląskie, which have the highest

number of wine producers reported to the KOWR for the 2022/2023 wine year - 77, 55 and 51, with 103, 115 and 78 hectares respectively.

Observing the Polish wine market, one can conclude that it is developing quickly. Such a situation is probably also correlated with the fact that the preferences of Polish consumers regarding the consumption of alcoholic beverages are changing. The percentage of persons most willingly choosing wine has been increasing since 2007 (Polacy piją mniej piwa, więcej wina i alkoholi wysokogatunkowych, 2019). From November 2019 to October 2020, wine retail sales increased year-on-year by 9.9% in value terms and by 6.5% in volume terms by number of bottles and by 6.1% in liters (W Polsce, krainie wódki i piwa, pije się coraz więcej wina, 2020). The consequence of such a state of affairs seems to be the further development of winemaking in Poland.

3. METHODS

The questionnaire survey was performed electronically, using the Microsoft 365 platform. 75 vineyards participated in the survey. The questionnaire was accessible from May 2022 until February 2023. The invitation to participate in the survey was sent, along with the link to the online questionnaire, to all vineyards registered in the official Register of Vineyards managed by the National Support Centre for Agriculture. It was either involved in wine sales in the economic year in agriculture 2021/2022 or intended to do so. The register included 376 vineyards, yet it was subject to verification using other sources of information, wine-related Internet portals and the authors' previous research. In effect, considering repetitions (several plots in different localities belonging to one vineyard) and vineyards that terminated their activity, the number of active vineyards involved in vine cultivation and wine selling was reduced to 308. Requests to fill out the questionnaire were sent to all these vineyards. Accordingly, we undertook a comprehensive survey of all active vineyards in the country, which provides a substantial sample of the enotourism business at this nascent stage of development, despite the 24% response rate. While a higher response rate is typically sought in quantitative studies, achieving a sample representing at least 20% of the population is sufficient to draw meaningful insights within sociological research.

Contact data were retrieved from the Enotourist Guide “Polish Wine” (Dylik-Ostrowska et al., 2021), wine-related Internet portals, official websites of vineyards, and social media. Since the questionnaire return rate was relatively small, reminder letters were sent twice in September and October. In addition, direct phone calls and informal meetings with wine owners were used to encourage participation.

Regarding qualitative data analysis, we employed a deductive approach to coding, with guidance from the principles of qualitative research methodologies set forth by Creswell (2013) and Patton (2002). The responses to the open-ended questions were subjected to systematic coding according to the themes that emerged from the survey questions. The initial codes were defined by the structure of the questions, and were subsequently refined based on the responses received. This approach enabled the data to be categorised effectively. A numerical code was assigned to each theme and subsequently linked to the relevant fragments of respondents’ answers. The deductive coding approach provided a structured method for analysing qualitative data, allowing for a systematic comparison of themes across responses and facilitating a comprehensive understanding of enotourism dynamics in Polish vineyards.

A comprehensive overview of AI solutions was then carried out, systematically assigning them to the various aspects of sustainability identified by winemakers, including environmental impact reduction, economic efficiency enhancement, and social responsibility improvements.

4. RESULTS

4.1 Environmental aspects of wine production in Poland

Regarding environmental aspects of wine making and viticulture, respondents were asked if they consider environmental issues in wine production. Of the 75 respondents in our research, 58 (77%) indicated that they do, 17 said it is hard to say, and no one chose a negative answer.

In the follow-up question related to providing examples of such actions, the following aspects were mentioned:

A. Absence/reduction of crop protection products (16 indications)
B. Renewable energy sources (photovoltaics, heat pumps, windmills) (4 indications)
C. Economic management of materials like glass, cardboard, plastic (8 indications)
D. Utilization of post-production organic waste (yeast, seeds, peels, pomace) (19 indications)
E. Organic and/or moderately applied fertilizers (4 indications)
F. Proper water management (9 indications)
G. Organic and/or vegan products in winemaking (e.g., yeast) or no/limited use of chemicals in oenological processes like low-intervention wines (16 indications)
H. Harvesting and processing manually (3 indications)
I.. Use of natural cork (3 indications)
J. Other (13 indications)

In the category "Other," a few general answers could not be coded (like "we care about the environment. However, some stated that the law undertakes activities, e.g., using substances authorized for use. This can hardly be considered a specific pro-environmental measure because it simply means compliance with legal requirements. Table 1 shows the proposed scope of AI applications and possible methods linked to the winemakers' area of interest related to environmental issues.

Table 1. Possible scope and methods of AI application in the environmental aspects of the wine industry

Winemakers' areas of interest	**Scope of AI applications**	**AI Methods & Tools**
Absence/reduction of crop protection products Organic and/or moderately applied fertilizers Harvesting and processing manually	Vineyard Cultivation Management	• AI-Driven Drone Monitoring of Vineyards: • *Multispectral Imaging from drones – analyzing vineyard health using images captured in different light spectra.* • *Image Segmentation with CN – detecting vine diseases through neural networks for image processing*. • Intelligent Irrigation Systems: • *IoT-based Water Management – AI processes data from soil moisture sensors to adjust irrigation.* • *Weather Prediction AI – Weather forecasting helps optimize irrigation strategies.* • Predictive Systems for Yield Forecasting • Yield Prediction with ML – analyzing historical data to predict future harvests. • Satellite Data Fusion – AI integrates data from various sources to assess plant health more accurately.
Renewable energy sources Economic management of materials like glass, cardboard, plastic Utilization of post-production organic waste Organic and/or vegan products in winemaking	AI am in Wine Production Optimization	• Automation of the Fermentation Process: • *AI-driven Process Control – AI monitors and adjusts real-time fermentation conditions.* • *Time Series Analysis for Fermentation Monitoring – AI detects anomalies in the fermentation process.* • Wine Quality Control through Chemical Analysis: • *AI-enhanced Spectroscopy – chemical analysis of wine composition to detect contaminants.* • *Neural Networks for Wine Classification – classifying wine quality based on chemical patterns.* • Minimization of Production Waste: • *AI-driven Waste Optimization – AI analyzes ways to reuse waste materials.* • *Predictive Maintenance & Waste Reduction – AI forecasts moments of increased waste in the production process.*

Harvesting and processing manually		
Renewable energy sources Economic management of materials like glass, cardboard, plastic Proper water management Harvesting and processing manually	Carbon and Water Footprint of Production	• AI-based Energy Monitoring – AI tracks energy consumption and recommends ways to reduce CO_2 emissions.
Absence/reduction of crop protection products Organic and/or moderately applied fertilizers Harvesting and processing manually	Biodiversity Management	• AI-driven Biodiversity Monitoring – AI monitors the impact of cultivation on ecosystems.
Site choice	Sustainable Spatial Planning	• AI-based GIS Analysis – AI analyzes topography and historical data to identify optimal locations for new vineyards.

Source: own elaboration based on: Parvini, 2025; How AI can boost Europe's wine industry, 2025; Applications of AI in Agriculture to Reduce Carbon Emissions, 2024; Pizzuto, 2023; Jurišić, Stanisavljević & Plaščak, 2010.

4.2 Economic aspects of wine production in Poland

Economic aspects of wine tourism relate to supporting local economies, quality of life and employment. Of the 75 respondents in our research, 36 respondents (48%) indicated that they very often deliberately take actions to enhance the local economy and economic well-being of the local citizens (e.g., by employing locals, using local services, buying local products). At the same time, 24 respondents (32%) indicated that they sometimes take such actions, and 12 (16%) indicated that they do them from time to time. Only 3 survey participants (4%) said they have never taken such actions. The responses altogether presented very positive and proactive attitudes towards local economy enhancement. The vast majority (96%) indicated that they contribute to improving local development and only 4% denied taking any action on the matter.

In the follow-up question related to providing examples of such actions, the following aspects were mentioned:

A. Employment provision for the local people, employing locals (23 indications)
B. Purchasing from local stores or entrepreneurs, buying local products (38 indications)
C. Using local services (23 indications)
D. Promoting local products and services (7 indications)
E. Providing our products for local shops (2 indications)

The respondents took the suggestions on the possible influence on the local economy from the former question. In the answers, local cooperation and support were often manifested by buying local products and services, followed by employing local people. Moreover, promoting local products and services and providing our products for local shops were also indicated. Table 2 shows the proposed scope of AI applications and possible methods linked to the winemakers' area of interest related to economic issues.

Table 2. AI Applications in Wine Business Management Focused on Local Economic Development

Winemakers' areas of interest	**Scope of AI applications**	**AI Methods & Tools**
Employment provision for local people Using local services	AI-Supported Workforce Planning	• AI-Powered Hiring Platforms: AI-based systems optimize recruitment by matching local job seekers with wineries based on skills and availability. • Chatbot-Based Training Systems: AI-driven chatbots provide vineyard employees with localized training and skill development programs.
Purchasing from local stores or entrepreneurs	AI-Powered Local Supply Chain Optimization	• AI-Driven Procurement Matching: AI connects wineries with local suppliers by analyzing pricing, availability, and sustainability factors. • Geospatial AI for Sourcing Local Products: AI maps regional suppliers and recommends optimal local sources for vineyard needs. • Examples: • *Llamasoft Supply Chain Guru – AI for supply chain modeling and optimization.* • *ArcGIS AI – AI-powered geospatial analysis for supplier location optimization.* • *Google Earth Engine AI – AI-based geospatial analysis tool for supply chain planning.* • *SAP Ariba AI – AI-driven procurement optimization for local sourcing.* • *Coupa AI Procurement – AI-powered procurement management and automation.*
Providing products to local shops	AI-Powered Smart Distribution	• AI-Assisted Route Optimization: AI minimizes transportation costs and carbon footprint by optimizing delivery routes for local wine distribution. Examples: • *ORTEC Route Optimization: This tool utilizes AI to optimize delivery routes, aiming to reduce fuel consumption and improve delivery efficiency* • *UPS ORION: UPS's On-Road Integrated Optimization and Navigation (ORION) system uses AI to optimize delivery routes, significantly reducing fuel consumption and improving delivery times.*
Promoting local products and services	AI-Enhanced Community-Based Commerce	• AI for Local Business Visibility: AI enhances winery partnerships with local businesses by identifying collaboration opportunities through data analysis. Examples: • *IBM Watson Natural Language Processing (NLP): This tool analyzes customer opinions by interpreting text data, providing insights into sentiment and intent.* • *Hootsuite AI: This platform offers AI-driven social media trend analysis, helping businesses monitor and respond to emerging trends effectively.* • *Sprinklr AI: Utilizing artificial intelligence, Sprinklr provides comprehensive social media analytics to identify patterns and trends across various platforms.* • *Sentiment Analysis for Local Branding: AI evaluates online customer reviews to tailor marketing strategies supporting local brands.*

Fair Trade and Ethical Consumption Awareness	AI-Powered Consumer Awareness Tools	• Fair Trade Chatbots: AI-powered assistants educate consumers about local and ethical wine production through personalized recommendations. Example: • *A language model developed by OpenAI that can be implemented as a chatbot to educate consumers about ethical practices in wine production. It can answer questions regarding the origin of wine, Fair Trade practices, and sustainable agriculture.*

Source: own elaboration based on: Choi & Lim, 2019; Sanders & Wood, 2020; Fosso Wamba et al, 2021; Leonard, 2021; Fontanella, 2024; HireVue, 2025; Intercom, 2025; Coupa, 2025; Esri, 2025; Google Earth Engine, 2025; Sap, 2025; Ortec, 2025; Ibm, 2025; Hootsuite, 2025; Sprinkl, 2025.

4.3 Social aspects of wine production in Poland

Social relations, including those with residents of the area surrounding the vineyard are significant from the perspective of wine industry sustainability. Our survey research indicates that vineyard owners rate their relations with these residents highly: 66 out of 75 responses were either 'good' or 'rather good,' with no responses indicating 'rather bad' or 'very bad.'

It is also crucial to examine the specific nature of the cooperation between winemakers and residents and identify potential conflicts. Such conflicts are particularly concerning in sustainable tourism and community relations. To this end, we analyzed answers to open-ended questions. The question on positive cooperation with residents surrounding the vineyard was explored through an open-ended question: "Can you provide examples of good cooperation with residents in the vineyard area?" This question received responses from 63 respondents.

The responses were categorized into the following content areas:

A. Community Involvement and Support (e.g. mutual equipment support, shared assistance, residents joining in grape harvesting, local help with vineyard tasks, and mutual lending of agricultural equipment (41 indications)
B. Brand and Business Development (e.g. job creation and financial support for those in need) (8 indications).
C. Collaboration with Local Businesses and Organizations (e.g. partnerships with local authorities, cultural organizations, gastronomy, hoteliers, foundations, women's associations, transport companies, and tour guides) (8 indications).
D. Social and Cultural Participation (e.g. engagement in local cultural activities, organizing winery events, and numerous community initiatives (4 indications).
E. No Cooperation: 2 responses indicated no cooperation.

The proposed scope of AI applications and possible methods linked to the winemakers' area of interest related to social issues are shown in Table 3.

Table 3. AI Applications in Community Engagement, Business Development, and Cultural Participation in the Wine Industry

Winemakers' areas of Interest	**Scope of AI applications**	**AI Methods & Tools**
Community Involvement & Support (e.g., mutual equipment support, shared assistance, grape harvesting)	AI-Powered Resource Sharing Platforms	• Blockchain-Enabled Equipment Sharing: AI-based platforms utilizing blockchain technology for secure and transparent sharing of agricultural machinery. • AI-Driven Task Coordination: AI schedules and optimizes shared labor and resource allocation. • AI-Powered Smart Volunteering Platforms: AI facilitates task-matching for vineyard work, encouraging local participation. • Examples: • *AgriChain (blockchain for supply chain management).* • *Taranis (AI for precision agriculture & labor coordination).* • *Grapeworks (AI vineyard management).*

Brand & Business Development (e.g., job creation, crowdfunding)	AI-Enhanced Marketing & Customer Engagement	• AI-Driven Customer Insights: AI analyzes market trends, customer data, and competitor strategies. • AI-Powered Chatbots: AI virtual assistants handle customer inquiries, wine selection, and order processing. • AI-Based Crowdfunding: AI-powered platforms help wineries fundraise for social and community initiatives. • AI evaluates online reviews and customer sentiment. • Examples: • *Vinous (AI-driven wine market analysis).* • *WineBot (AI-powered chatbot for wine recommendations).* • *BM Watson NLP (AI for sentiment analysis).* • *MonkeyLearn (AI for stance detection)*.
Collaboration with Local Businesses (e.g., partnerships with hotels, restaurants)	AI-Enhanced Business Networking	• AI-Driven Partnership Optimization: AI identifies and enhances strategic collaborations. • AI-Powered Sentiment & Stance Analysis: AI monitors reviews and consumer trends, aligning strategies with market demand. • AI Chatbots for Community Engagement: AI chatbots facilitate real-time communication and support between wineries and business partners. • Examples: • *ReviewPro (AI-driven sentiment monitoring).* • *CommuneBot (AI chatbot for local collaborations).* • *Google AI NLP (customer review sentiment analysis).* • *Hugging Face Transformers (stance detection models).*
Social & Cultural Participation (e.g., winery events, cultural engagement)	AI-Driven Cultural Engagement	• AI-Powered Event Planning: AI assists in automating winery event logistics. • AI for Digital Cultural Heritage: AI reconstructs historical wine traditions from historical data. • AI-Driven Social Media Analysis: AI tracks trends and optimizes audience engagement. • Sentiment & Stance Analysis for Cultural Engagement: AI evaluates public perception of winery events. • Examples: • *EventAI (AI-powered event planning and scheduling).* • *HeritageAI (AI for preserving wine cultural heritage).* • *SocialTrend (AI-driven social media analytics).* • *Sprinklr AI (social media sentiment analysis).*

Source: own elaboration based on: Alturayeif, Luqman & Ahmed, 2023; Alturayeif, Luqman & Ahmed, 2024; Saha, Lakshmanan & Ng, 2024; Mishra & Lourenço, 2024; Sprinkl, 2025; Yousaf, 2025; Hugging Face, 2025; AgriChain, 2025; Taranis, 2025; Google Cloud, 2025; Maar, 2025; Wine Industry Advisor, 2025; Shapes, 2025; Reviewpro Reputation, 2025; Medallia, 2025; WineBot, 2025; Ibm, 2025.

4.4 Wine tourism in Poland

Analysis of websites and social media portals reveals that the majority (ca. 80%) of registered Polish vineyards provide an option for tourist visits. As much as 83% of vineyards taking part in the survey declare openness to visitors and another 12% intend to include such an opportunity in the future, and only 5% of respondents indicate that they are not interested in providing this type of service.

Winemakers who offer the opportunity for tourists to visit a vineyard, i.e. 83% of respondents, were asked about the services they provide as part of their enotourism offer. The three most frequently provided services are wine tasting and purchase opportunity (58 indications), tour of the vineyard accompanied by the winemaker (57 indications) and guided tour of the winery and other buildings (e.g. wine ageing cellar) by the winemaker (44 indications). One in three wineries with a tourism function offers accommodation for tourists, workshops, training courses, lectures, speeches, and shows (20 indications each). The fewest wineries offer self-guided tours of the winery and other facilities (5 indications), spa/wellness services (3 indications) and packages with other service providers, for example a winery tour combined with a visit to another local tourist attraction (only 1 indication).

Respondents were also asked about the benefits of enotourism activities. This question was answered by 71 out of 75 respondents. The winemakers considered the most important benefits to be increased wine sales (58 indications), brand promotion (57 indications), additional sources of income, and strengthening the winemaker's social relations, including contacts, relationships, cooperation, and image (48 indications each). The least frequently reported benefit appeared to be financial security in the case of emergency events through diversification of business activities (only 1 indication). Two respondents found it difficult to indicate any benefits of enotourism activities.

The benefits of enotourism were complemented by an open-ended question on respondents' reasons for undertaking/planning an enotourism activity. This question was answered by 60 out of 75 respondents. The responses received can be categorized into the following content areas:

A1. Economic issues: wine sales (16 indications)
A2. Economic issues: additional income, e.g. from paid tastings (7 indications)
B. Promotional issues: vineyard, Polish winemaking (13 indications)
C1. Social issues: social relations (15 indications)
C2. Social issues: passion, hobby (7 indications)
C3. Social issues: feedback from customers, e.g. on wine quality (2 indications)
D. Development issues: diversification and expansion of activities (8 indications)
Z. Other (4 indications)

According to the survey, the most frequent reasons for undertaking/planning enotourism activities by respondents include economic issues, understood as the possibility of additional wine sales, social issues, understood as the possibility of contact with people, and promotional issues, understood as the possibility of promoting one's vineyard, wine and Polish winemaking in the broadest sense. These results, coded as A1 and B, correspond with the highest number of indications, with the results received in the question on the benefits of enotourism activities.

Table 4 shows the proposed scope of AI applications and possible methods linked to the winemakers' area of interest in sustainable tourism.

Table 4. Possible scope and methods of AI application in sustainable wine tourism

Winemakers' areas of interest	**Scope of AI applications**	**AI Methods & Tools**
Economic issues: wine sales Economic issues: additional income, e.g. from paid tastings Promotional issues Social issues: feedback from customers, e.g. on wine quality	AI Chatbots as Virtual Sommeliers	• Natural Language Processing (NLP) – chatbots analyze customer queries and provide answers about wines and tastings. • Machine Learning (ML) based on user preferences – AI systems recommend wines tailored to customer tastes based on purchase history.
Development issues: diversification	Intelligent Mobile Applications for Visit Planning	• Predictive Analytics – analyzing historical booking data to forecast vineyard occupancy.

and expansion of activities		• Geolocation and traffic analysis – AI collects GPS data and adjusts tourist routes to current conditions.
Development issues: diversification and expansion of activities	AI in Tourist Behavior Analysis	• Computer Vision (image recognition) – analyzing camera footage to identify tourist movement and detect overcrowding. • Deep Learning for visit pattern analysis – AI analyzes tourist behavior in real-time and adjusts offerings accordingly.
Promotional issues: vineyard, Polish winemaking	Translation and Content Adaptation	• Neural Machine Translation (NMT, e.g., Google Translate AI) – automatic content translation into multiple languages. • NLP-based recommendation systems – adjusting educational content to the tourist's knowledge level.
Economic issues: wine sales Economic issues: additional income, e.g. from paid tastings Development issues: diversification and expansion of activities Promotional issues	Virtual Wine Tasting Simulations	• Virtual Reality and Augmented Reality (VR/AR) – AI generates realistic tasting experiences in VR. • AI-driven Sensory Analysis – AI systems analyze users' sensory reactions to optimize virtual tastings.

Source: own elaboration based on: Lewis, Gemma K., et al., 2021; Roach, 2023; Aivin, 2025; Lighthouse, 2025; Wagner, 2025; Sommelier Business, 2025; Maar, 2025.

5. STUDY LIMITATIONS AND FUTURE RESEARCH

The research presented in this study focuses on winemakers. A complete picture of the wine industry's social, economic, and environmental impacts requires including the perspective of other local actors (residents and local authorities) as well as tourists. Additionally, economic analysis of statistical data might prove to be useful. The real impact of viticulture and wine production on the environment should be demonstrated through research based in natural and earth sciences, such as long-term ecological observations of biodiversity, or studies of changes in soil and water quality. Another significant issue is the relationship between Polish winemaking and climate change. Warming temporarily improves the conditions for viticulture, but the intensification of extreme weather events in the future may negatively affect this crop. Adaptation to climate change is therefore another determinant of winemaking sustainability and an important field of research.

Future research should focus on longitudinal studies to monitor the evolution of Polish enotourism, notably the transition from small-scale family operations to potentially larger, commercial ventures. Studies could also investigate the perspectives of tourists visiting Polish vineyards, exploring their expectations, satisfaction levels, willingness to engage in sustainable tourism practices, and AI tools. Future research on AI in sustainable viticulture should focus on developing agriculture techniques, AI-driven climate adaptation strategies, and intelligent resource management systems to enhance vineyard resilience, optimize yields, and minimize environmental impact. Similarly, research on sustainable wine production should explore waste reduction and organic production technologies to minimize environmental impact. Additionally, further analysis of the role of digital technologies, such as virtual vineyard tours or online wine tastings, in promoting sustainable tourism could provide insights into modernizing the sector.

6. DISCUSSION AND CONCLUSIONS

The questionnaire survey results show that Polish winemakers' activities fit in well with the crucial goals of sustainable development. Regarding the social pillar of sustainability, the Polish wine industry contributes to building social capital in localities where the vineyards are located. Social relations are important for winemakers. Most of them establish good relations with the people living near the winery and can show many examples of positive cooperation. Social relations were also an important benefit of a tourist offer. Winemakers' activities support the maintenance of local traditions (intangible heritage), among them culinary traditions (promotion of local meat and dairy products, local dishes). Winemakers willingly share the passion and knowledge they have gained during vineyard visits and commented that wine tastings are not limited to information about the wines and vines themselves. Winemakers also disseminate the knowledge about the region and its cultural heritage. Winemakers often become local animators of culture, organizing cultural events in wineries (mainly concerts, picnics, festivals). Tourism products created by winemakers can potentially increase the popularity of the location of the vineyard. Polish wine brands often incorporate geographical designations – names of villages or regions where they are produced and their wine labels frequently feature distinctive symbols of the locality or region. This serves as an additional form of promotion, contributing to greater recognition of the areas where vineyards are located. Many vineyards are situated in regions not traditionally considered particularly attractive for tourism. Therefore, the development of enotourism offerings can act as a magnet, attracting visitors to these areas and contributing to the deglomeration of tourist traffic.

Regarding the economic pillar of sustainability, the Polish wine industry and wine tourism create additional employment opportunities in rural areas and contribute to developing non-agricultural functions of rural areas. Most winemakers indicated that they contribute to improving local development and well-being. This mostly includes providing employment for the local people, purchasing from local stores or entrepreneurs, buying local products, and using local services. Wine tourism supports local suppliers of products and services, thus diversifying sources of income and providing opportunities to earn money beyond the main season of agricultural activities.

In the environmental pillar of sustainability, winemakers are aware of the significance of biodiversity and current trends in wine production – ecological and organic winemaking – and try to reduce their negative environmental impact. Environmental awareness in the broadest sense includes landscape protection, so winemakers are usually aware of the value of rural cultural landscapes. They aim to preserve traditional architecture and other cultural heritage elements, so, for example, when building new infrastructure, they try to follow local style and tradition. The question remains whether the sustainability of Polish winemaking, viticulture and wine tourism is just a matter of scale, and thus whether it will be lost with the shift to mass production.

Polish winemakers are increasingly aware of the impact of climate change, which both benefits and challenges viticulture. While warming temperatures have facilitated the re-emergence of vineyards, the growing frequency of extreme weather events poses risks to crop yields and long-term sustainability. Adaptation strategies, such as cultivating disease-resistant grape varieties, improving water management systems, and investing in renewable energy, are critical for mitigating these challenges. Further research should assess how these strategies can be systematically implemented across the industry.

The first question is whether such a shift toward mass production of wine will occur. Another problem is whether the principles of sustainable development can carry out such a transformation. Whether the next generations will take over wine activity, or in what form and approach is uncertain. Mass tourism is becoming increasingly troublesome for local communities and is facing protests, so developing enotourism into a mass trend is not a foregone conclusion. Since we are dealing with a new phenomenon that is developing under conditions of significant climatic (increasing likelihood of extreme weather events), social (likely demographic crisis) and economic (unstable or rising energy prices) uncertainty, it must be assumed that various development scenarios of Polish viticulture and related wine tourism are possible.

Artificial Intelligence (AI) has the potential to support the sustainable development of Polish winemaking by providing tools for optimizing production processes, reducing resource consumption, and increasing the efficiency of enotourism activities. Predictive systems based on machine learning can assist in managing irrigation and crop protection, minimizing the use of chemical agents, and reducing

environmental impact. AI can also help winemakers monitor biodiversity and implement eco-friendly cultivation methods.

In the social aspect, AI tools can support the promotion of local traditions and products through personalized recommendations for tourists and automated interaction systems, such as chatbots acting as virtual sommeliers. In the economic context, intelligent data analysis algorithms can help optimize supply chains, reduce losses, and tailor offerings to changing consumer preferences.

Regarding the natural environment, it is crucial to implement solutions that minimize the negative impact of winemaking on ecosystems. AI can support soil and groundwater quality monitoring, helping to limit erosion and chemical pollution. Intelligent image analysis systems can be used to identify plant diseases at an early stage, allowing for a reduction in pesticide and fungicide use. Additionally, predictive technologies can aid vineyard adaptation to climate change by selecting more resistant grape varieties and optimizing microclimate management within vineyards.

In conclusion, implementing AI solutions in Polish winemaking can contribute to the industry's further development in line with sustainability principles. However, it will be essential to tailor technology to the specifics of local vineyards and ensure adequate support for winemakers so that innovative solutions are accessible and effectively implemented. Future research should continue to examine the long-term impact of AI on the sustainability of winemaking, particularly in climate change and its consequences for Polish vineyards.

Most winemakers in Poland are not currently using advanced technologies, including AI to support the management of viticulture, wine production and enotourism. Perhaps the demand for such solutions will increase when the size of vineyards, the scale of production and the number of tourists grow significantly.

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AI IN SMART MOBILITY - APPLICATION OF SOLUTIONS, DECISIONS, DETERMINANTS AND DEVELOPMENTS ON THE EXAMPLE OF SELECTED CITIES

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ABSTRACT

Purpose*: The aim of this article is to identify areas for the use of intelligent management in urban mobility, to identify factors determining further development in this area and to define a strategic decision-making framework for the integration of artificial intelligence in urban mobility.*

Need for the study*: Decisions to implement management based on modern intelligent mobility solutions can improve efficiency, reduce costs and increase passenger comfort. This article addresses the need to fill the research gap identified in the literature in the area of decision-making for the implementation and operation of AI-based smart mobility.*

Methodology*: The first part of this article presents a literature review of AI solutions used in smart urban mobility and the factors influencing the decision to implement them. This forms the basis for further practical research based on case studies showing examples of the application of these solutions in the intelligent management of selected cities and the conditions and further developments in this area. The final section of the article also provides a strategic view of the decision-making process in the development of smart urban mobility.*

Findings*: The research presented has identified the practical key elements of the AI-enhanced smart mobility concept and its framework conditions. In addition, the authors presented a model approach to strategic decision-making for the AI-enhanced smart mobility concept.*

Practical Implications*: The research carried out will identify good practices in the use of artificial intelligence (AI) in the management of sustainable urban mobility and will identify the main factors influencing decisions related to the use of AI in smart mobility.*

Keywords: smart mobility, decisions, intelligent management, sustainable development, artificial intelligence, public transport, smart city, decision-making process
JEL: O18, O33, R41

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1. INTRODUCTION

There are high expectations for the application of intelligent management in sustainable urban development, mainly including modern technologies used in decision-making, infrastructure management and urban services. The scope of application of AI in sustainable urban mobility goes far beyond the hitherto basic traffic control solutions. AI-based systems are expected to revolutionise traffic management, improve safety for drivers, pedestrians and cyclists, and provide equal access to mobility services for all residents. There is a gap in the literature related to a comprehensive presentation of the application of AI-based intelligent management in smart mobility, covering all the most important aspects of the concept, including in the context of inclusive mobility, as well as the factors determining the decision to implement such solutions. The aim of this article is to identify possible areas of application of AI technologies in smart urban mobility, as well as to create a decision-making model for the development of smart urban mobility.

2. LITERATURE REVIEW

The authors conducted an analysis of publications indexed by Scopus. Using the search engine, it can be determined that there are more than 520,000 articles indexed with the keyword 'artificial intelligence' and almost 4,000 articles with the keyword 'smart mobility' in this database (data as of 9 March 2025). The search results are shown in Table 1.

The authors performed the analysis on the basis of articles with topics covering both AI and smart mobility in terms of the intersection of these two concepts. In terms of the number of articles that are simultaneously described with the keywords 'artificial intelligence' or 'AI' and 'smart mobility', the search showed that 194 such articles were published.

Table 1. The search results

Keywords	Number of articles between 2022 and 2025 (all/open access)	Number of articles in Scopus database (all/open access)
artificial intelligence	159,399 / 69479	521 064 /139 187
smart mobility	1 423/ 535	3 969/1 276
artificial intelligence, smart mobility	67/ 29	153/ 49
AI, smart mobility	31/ 7	41/ 9

Source: own elaboration.

By choosing 'artificial intelligence' (AI) and 'smart mobility' as keywords to search for articles, the authors aimed to capture different perspectives on the field. By choosing these broad terms, they ensured that the review would cover the various applications of artificial intelligence in the context of mobility. This enabled the authors to provide a comprehensive overview of the current state of research and emerging trends. In addition, the focus on these keywords enabled the identification of literature that directly addresses the intersection of advanced technologies and the challenges and opportunities of sustainable mobility, which is closely aligned with the objectives of this review. The authors chose to review a selection of 194 articles.

Due to the large number of articles, it was decided to select them for further more detailed analysis. For this purpose, certain criteria were adopted for the selection of articles for the next stage of the research. These criteria are:

(1) connection to the topic of the article;
(2) articles that talk about current issues of smart mobility using AI;
(3) articles that have a practical dimension;
(4) open access articles.

Based on the aforementioned criteria, the authors made a selection by reviewing the abstracts of 58 articles and, as a result, 43 open access articles were left for the next stage. These articles were reviewed in full-text and described in this article.

In the next step, the papers were categorised into:
1. Areas of application of AI in smart mobility.
2. Determinants of smart mobility development based on AI.
Areas of application of artificial intelligence in smart mobility spotted in the literature are:
(a) autonomous vehicles,
b) intelligent traffic management, Intelligent Transport Systems (ITS) and support to public transport,
c) shared mobility,
d) support for micro-mobility,
e) inclusive mobility,
f) support for public services,
g) support for mass events,
h) mobility-as-a-Service (MaaS),
i) intelligent mobility in tourism,
j) smart parking.
The results of the study are presented in Table 2.

Table 2. Areas of application of artificial intelligence in smart mobility

Area of application	Description	Articles
Autonomous vehicles (AV, CAV, PAV, UAV)	identification of cyber threats and their link to CAV	Khan S.K., Shiwakoti N., Stasinopoulos P., Chen Y., Warren M. (2024)
	management of autonomous vehicles in the context of ITS	Louati A., Louati H., Kariri E., Neifar W., Hassan M.K., Khairi M.H.H., Farahat M.A., El-Hoseny H.M. (2024)
	relevance of the perception system in autonomous vehicles	Rolen L.R., Bhat S.J., Santhosh K.V. (2024)
	key initiatives (CAV), (PAV i UAV)	Nikitas A., Michalakopoulou K., Njoya E.T., Karampatzakis D. (2020)
	the use of autonomous vehicles (AVs) for „last-mile" mobile services	Bucchiarone A., Battisti S., Marconi A., Maldacea R., Ponce D.C. (2021)
	supporting autonomous mobility through optimised control systems	Mahrez Z., Sabir E., Badidi E., Saad W., Sadik M. (2022)
	a new challenge for automotive projects around the world,	Trovao J.P. (2021)
	applying artificial intelligence to the design of future cars	Martínez I. (2021)
	pointing to an overly optimistic timeline for CAV development and adoption	Nikitas A., Njoya E.T., Dani S. (2019)
	implementing AI algorithms in EV and TV to optimise travel costs, developing a realtime ecological traffic map.	Jendoubi F., Pradeep V., Khemmar R., Berradia T., Rossi R., Sibbille B., Fourre J., Ohayon A., Jouni M. (2024)
Shared mobility	improving the management of shared mobility systems	Kubik A. (2023)
	automated ride-sharing platforms	Ong Y.C., Protopapas N., Yazdanpanah V., Gerding E.H., Stein S. (2024)
Support for micromobility	support of cycling transport	Costa D.G., Silva I., Medeiros M., Bittencourt J.C.N., Andrade M. (2024) Fontes T., Arantes M., Figueiredo P.V., Novais P. (2022)
	supporting the transport of electric scooters	Al-Habaibeh A., Watkins M., Shakmak B., Javareshk M.B., Allison S. (2024)
Inclusive mobility	real-time data collection to improve the livability of the city and the amenities of its residents	Anedda M., Fadda M., Girau R., Pau G., Giusto D. (2023)
	advanced wheelchair technology for wheelchair users	Li L., Chen W., Chen K. (2024)

	social inclusion and secure mobility to improve mobility services outside the home for seniors	Bokolo A.J. (2023)
	conceptualising transport as one of the main domains of age-friendly cities	Loos E., Sourbati M., Behrendt F. (2020)
	smart home model for safe and robust mobility for blind people..	Tayyaba S., Ashraf M.W., Alquthami T., Ahmad Z., Manzoor S. (2020)
Intelligent traffic management	real-time traffic flow measurement, tackling traffic jams	Badidi E. (2022) Tayeb F., Chihaoui H., Filali F. (2023)
Intelligent Transport Systems (ITS) Support for public transport including AI in rail transport (metro)	traffic management in the city in the event of traffic incidents	Lenatti M., Narteni S., Paglialonga A., Rampa V., Mongelli M. (2023) Jadhav B., Kulkarni A., Khang A., Kulkarni P., Kulkarni S. (2025) Cirianni F.M.M., Comi A., Quattrone A. (2023) Albuquerque V., Oliveira A., Barbosa J.L., Rodrigues R.S., Andrade F., Dias M.S., Ferreira J.C. (2021)
	advanced surveillance and algorithms to regulate pedestrian signalling	Sepehr P. (2024)
	technologies to ensure the safety of road users when driving	Mahrez Z., Sabir E., Badidi E., Saad W., Sadik M. (2022)
	research areas for different ITS systems	Gamboa-Rosales N.K., Celaya-Padilla J.M., Hernandez-Gutierrez A.L., Moreno-Baez A., Galván-Tejada C.E., Galván-Tejada J.I., González-Fernández E., Gamboa-Rosales H., López-Robles J.R. (2020)
	support for train (metro) infrastructure in the fight against congestion, accidents, overloading of wagons and maintenance	Asad S.M., Ahmad J., Hussain S., Zoha A., Abbasi Q.H., Imran M.A. (2020)
Support for mass events	Anticipate high crowd density in specific areas that could lead to disasters. Reducing the risks associated with increased mobility in a specific area..	Bellodi E., Zese R., Petrovich C., Frascella A., Bertasi F. (2024)
Support for public services	implementation of a pathfinder service for paramedics in emergency situations	Charef A., Jarir Z., Quafafou M. (2022)
MaaS	exploration of IoV-based vehicle-mounted media scenarios and proposals for an IVI solution for MaaS.	Yu Z., Jin D., Song X., Zhai C., Wang D. (2020)
	mobility as a service (MaaS), but also transport-enabled technologies such as the Internet of Things (IoT) and the Physical Internet (PI)	Nikitas A., Michalakopoulou K., Njoya E.T., Karampatzakis D. (2020)
	sustainable mobility behavior	Schwinger F., Krempels K.-H. (2019)
Intelligent mobility in tourism	development of an intelligent mobility system combined with the presentation of video information to tourists about local attractions	Smirnov A., Kashevnik A., Shilov N., Mikhailov S., Gusikhin O., Martinez H. (2019)
Intelligent parking system	automating the parking process using the Internet of Things, artificial intelligence and multi-functional systems	Belkhala S., Benhadou S., Boukhdir K., Medromi H. (2019)
	use of multiple visual sources to monitor the wider parking area from different perspectives	Ciampi L., Gennaro C., Carrara F., Falchi F., Vairo C., Amato G. (2022)
	developing intelligent parking systems that provide real-time information on parking space availability	Belkhala S., Benhadou S., Medromi H. (2019)

Source: own elaboration.

Based on the literature survey, it can be concluded that AI technologies in relation to mobility most often refer to intelligent transport systems (ITS) and autonomous vehicles.

ITS integrate information and communication technologies (ICT) with transport infrastructure and, in a broader context, also with autonomous cars (Alanazi F., 2023). The data collected by the systems from sensors and devices implanted in vehicles and infrastructure provide relevant information about the state of the transport system at a given time and place. They can improve the efficiency of traffic management and the convenience of people in urban areas, by reducing congestion or journey times and thus reducing fuel consumption and air pollution (Meneguette R.I., De Grande R., Loureiro A.A., 2018). The integration of ITS into the transport system infrastructure and vehicles, can benefit the safety of road users. ITS has many other applications in intelligent mobility among others maintenance management, traffic signal management and public transport control systems (Maldonado Silveira Alonso Munhoz, P.A., da Costa Dias F., Kowal Chinelli C., Azevedo Guedes A.L., Neves dos Santos J.A., da Silveira e Silva W., Pereira Soares C.A., 2020).

The use of AI in vehicles allows them to move autonomously and participate in city traffic (Meneguette R.I., De Grande R., Loureiro A.A., 2018). Modern vehicles are often equipped with global positioning systems (GPS) and wireless communication devices. These can detect events in their environment and draw conclusions about route and navigation decisions without human intervention. However, there are concerns about their use, as even small faults in an intelligent vehicle system can lead to a serious safety problem (Rolen L.R., Bhat S.J., Santhosh K.V., 2024). These concerns necessitate large investments in automotive electronic systems for safety, comfort and also efficiency. There are also concerns about the possibility of cyber-attack, fully connected and automated CAVs (Khan S.K., Shiwakoti N., Stasinopoulos P., Chen Y., Warren M., 2024). Intelligent or autonomous vehicles (AVs) are already on the roads in many countries, and these vehicles already communicate with each other to ensure the safety of road users. One application of AVs is the use of autonomous vehicles (AVs) for 'last mile' mobility services. Autonomous shuttle transport as a service, various applications targeting last-mile delivery of goods, travel experiences and shared and integrated mobility (Bucchiarone A., Battisti S., Marconi A., Maldacea R., Ponce D.C., 2021).

Another application area for AI is a service that supports mobility planning and the use of different forms of transport within a single Mobility-as-a-Service (MaaS) platform. It provides users with a seamless integration of different modes of transport and customised mobility options to meet individual requirements. In addition, it allows users to pay for these services as well as obtain the necessary information for the traveller. With the help of MaaS and appropriate incentives, it is possible to move users towards a more sustainable mobility behaviour. This reduces congestion and relieves congestion in urban mobility networks (Schwinger F., Krempels K.H., 2019).

The solutions being introduced that make use of AI also relate to inclusive mobility projects. An inclusive transport system enables easy movement and provides unrestricted access to jobs and services for all potential passengers and people, regardless of their situation. Regardless of age, gender, economic or social status or disability, every citizen should be able to move efficiently (EC, 2023). Important solutions that can make use of AI are also micromobility systems related to cycling, or scooters, which as forms of sustainable transport are promoted in cities. Related to this form of transport are shared mobility systems, where a resident can use different modes of transport including cars without owning them. Smart mobility and in particular automated ride-sharing platforms promise efficient, safe and sustainable modes of transport in urban environments (Ong Y.C., Protopapas N., Yazdanpanah V., Gerding E.H., Stein S., 2024).

The problem in cities is often the problem of parking cars and the lack of information about parking availability. AI supports parking management by providing real-time updates of availability information, automated payment systems and predictive parking analysis, thus reducing traffic congestion and increasing parking efficiency (Belkhala S., Benhadou S., Medromi H., 2019).

The introduction of the solutions described, the way they function and their level of advancement in individual cases (cities) depends on a number of factors. Among these we can distinguish:

- ICT availability, interoperability, ability of systems and infrastructure to work together (Bokolo A. Jnr, 2024; Arora A., Jain A., Yadav D., Hassija V., Chamola V., Sikdar B., 2023; Fontes T., Arantes M., Figueiredo P.V., Novais P., 2022; Nikitas A., Michalakopoulou K., Njoya E.T., Karampatzakis D., 2020);

- the feasibility of ensuring system performance (Munhoz P.A.M.S.A., Dias F.D.C., Chinelli C.K., Guedes A.L.A., Dos Santos J.A.N., E Silva W.D.S., Soares C.A.P., 2020);
- the costs of using new solutions for users and also the savings that can be achieved through these solutions (Jendoubi F., Pradeep V., Khemmar R., Berradia T., Rossi R., Sibbille B., Fourre J., Ohayon A., Jouni M., 2024);
- regulations including sustainability and inclusive mobility (Sawhney N., 2023; Anedda M., Fadda M., Girau R., Pau G., Giusto D., 2023; Li L., Chen W., Chen K., 2024; Bokolo A.J., 2023; Loos E., Sourbati M., Behrendt F., 2020);
- urban development and urban mobility plans including the creation of car parks (Costa D.G., Silva I., Medeiros M., Bittencourt J.C.N., Andrade M., 2024);
- opportunities and willingness of the private and public sectors to cooperate (Schwinger F., Krempels K.-H., 2019; Bjørgen, A., & Ryghaug, M., 2022);
- privacy and data security concerns and opportunities to ensure security (Papyshev G., Yarime M., 2021; Wolniak, R.,Stecuła, K., 2024; Khan S.K., Shiwakoti N., Stasinopoulos P., Chen Y., Warren M., 2024; Rolen L.R., Bhat S.J., Santhosh K.V., 2024);
- residents' attitudes, competences, needs and social acceptance of the solutions offered (Costa D.G., Silva I., Medeiros M., Bittencourt J.C.N., Andrade M., 2024; Anedda M., Fadda M., Girau R., Pau G., Giusto D., 2023);
- the need to develop shared mobility (Kubik A., 2023; Ong Y.C., Protopapas N., Yazdanpanah V., Gerding E.H., Stein S., 2024);
- the need to enhance safety in transport (Al-Habaibeh A., Watkins M., Shakmak B., Javareshk M.B., Allison S., 2024; Albuquerque V., Oliveira A., Barbosa J.L., Rodrigues R.S., Andrade F., Dias M.S., Ferreira J.C., 2021).

3. METHODOLOGY

This article uses a literature review as the primary research method. In addition, the next part of the discussion analyses the practical dimension of the issues raised based on selected cities, namely: Singapore and Copenhagen. These cities were chosen because of the high level of sophistication of AI solutions implemented in smart mobility and the possibility to identify good practices for other cities. According to the Smart City Index ranking from IMD (IMD, 2024), which is one of three rankings assessing smart city development, Singapore and Copenhagen are among the most advanced smart cities in the world. In this ranking, Singapore is ranked fifth, closely followed by Copenhagen in sixth place. The authors deliberately chose cities in similar high positions and at the same time located on two different continents, which may show the different approaches to smart mobility development in these different environments. In addition, the main directions for the development of smart mobility in Central and Eastern European cities are presented. The final section of the paper presents a model approach to decision-making for implementing and developing AI in smart city transport. Figure 1 shows the subsequent research stages.

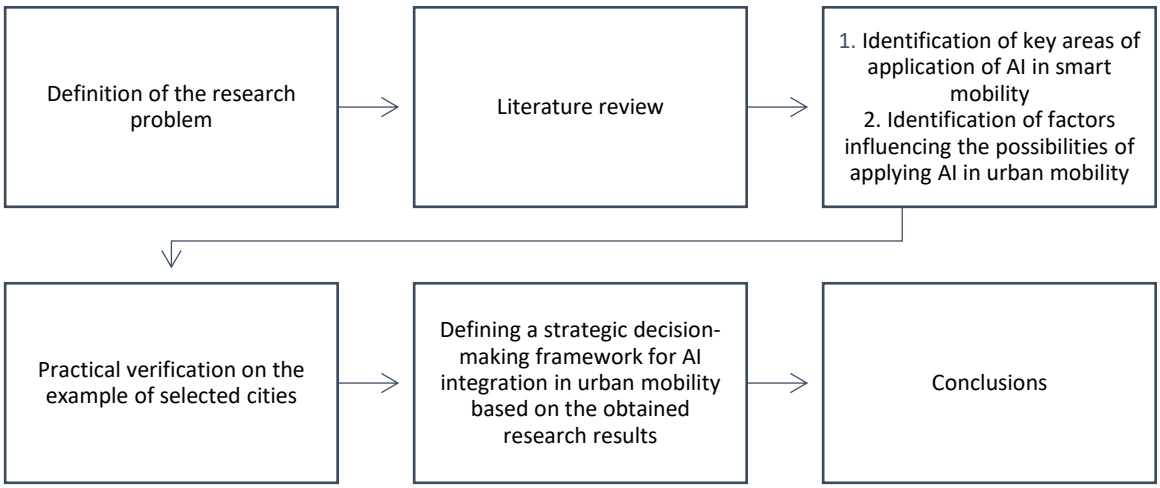


Figure 1. Stages of research
Source: own elaboration.

4. AI APPLICATION IN SMART MOBILITY IN SELECTED CITIES - RESEARCH FINDINGS

The literature research carried out provides a reference base for the practical implementation of AI in smart mobility in cities. Case studies were used to investigate the practical application areas and determinants of AI in smart mobility. Developed cities such as Singapore and Copenhagen, as well as cities in Central and Eastern Europe that are also taking steps towards AI-supported sustainable mobility and following the good practices of the aforementioned cities, were examined.

B. Singapore

One of the world leaders in smart mobility solutions is the city-state of Singapore. Within this city-state, a number of initiatives have been implemented to increase transport efficiency, reduce traffic problems and promote sustainable mobility. It is important to note that between 2017 and 2022, Singapore has seen an almost doubling of the intensity of people's movement - both residents and tourists. These dynamics have necessitated policymakers to trigger a decision-making process based on the use of an intelligent transport system, using innovative solutions and new technologies It should be noted that Singapore has been a forerunner of intelligent transport solutions. As early as 2005, a smart transport system was established there. This experience has given it a significant advantage over other cities that have not taken steps to digitise urban mobility. Among the measures implemented are:

- implementation of an electronic road pricing system to regulate access to the city centre;
- the development of a motorway monitoring system to inform drivers in real time of traffic accidents on major roads;
- mandatory priority rules on the road for buses. In Singapore, it is prohibited to restrict buses from joining traffic;
- a shift away from the use of private vehicles. Only 15% of Singaporeans own cars because obtaining a private vehicle involves acquiring an expensive certificate that is only valid for 10 years.

It should be pointed out that the development of Intelligent Transport System (ITS) has been ongoing for two decades. In Singapore, advanced ITS system has been introduced to maintain road safety and improve traffic flow. The ITS system provides many intelligent transport services to residents. The

potential of ITS is the result of a holistic approach to traffic management. This includes a number of transport initiatives such as free public transport during peak hours, a vehicle limit system and the need to pay a fee to enter the city centre.

Singapore, using advanced ITS technologies, has the ability to manage traffic efficiently. These technologies allow for real-time traffic monitoring, dynamic message signs and intelligent traffic control systems that optimise signal times based on road conditions, reducing congestion and travel time. These technologies also improve journey planning and informed travel decisions. ITS helps optimise traffic flow, reduce congestion and increase overall transport efficiency in Singapore. By analysing data and using smart technologies, ITS contributes to safer and more convenient journeys for residents and visitors (Zhong et al., 2016). An example of a smart solution, is One Motoring, a comprehensive portal that serves all drivers and vehicle owners in Singapore. By installing GPS-equipped surveillance cameras on roads and taxis, up-to-date traffic data can be obtained. The information collected is available to residents on an online portal. In addition, pictures of the roads are taken at short intervals (about 5 minutes) and are available through One Motoring - Traffic Smart. However, while maintaining safety considerations, real-time close-ups and images from moving cameras are not made available online. The One Motoring portal collects information routes where roadworks are in progress, current ERP (Electrical Road Pricing) toll rates, as well as car parks. A travel time calculator is also available. As well as providing traffic information, it is a portal that offers residents tips on selling and buying vehicles, as well as vehicle maintenance. The portal is also available on mobile devices. It should be emphasised that a fast, smooth and safe response to traffic incidents is possible thanks to EMAS (Expressway Monitoring Advisory System). It provides intelligent incident management and is responsible for quickly restoring traffic flow when a traffic incident, accident or vehicle breakdown is detected. This intelligent tool allows drivers to make decisions regarding the choice of optimal travel routes. Located along expressways, electronic message signs display messages and graphics about the current traffic situation. The actual travel time is also taken into account. EMAS serves the main traffic routes, so that traffic flow is improved throughout the island. Another smart solution is the 'Your Speed Sign' (YSS), a smart sign that displays the speed of oncoming vehicles in real time. The sign is designed to warn drivers when a vehicle's speed is exceeded, but also to encourage more conscious driving that is within a certain limit. This solution contributes to improving road safety. The 'Parking Guidan-ce Service' has been in operation in Singapore since 2008. This is a tool designed to provide drivers with real-time access to information on available parking spaces. Efficient use of available parking spaces contributes to reducing traffic congestion. The information is displayed both on the electronic notice board and online in the One Motoring portal. Provision is also made for the use of the MyTransport app. SG app for mobile devices. This application informs commuters about the traffic situation, thus improving their travelling comfort. It should be emphasised that everything is done in real time. The information is regularly updated. Recently, the Land Transport Authority (LTA) worked with SBS Transit and SMRT to install and test a new centralised system that determines the location of a bus in real time, so that more accurate public bus arrival information can be provided. Seat availability information is colour-coded, with green indicating available seats, yellow indicating standing room, and red indicating that standing room is limited (Wolniak, Grebski, ,2023).

In addition to the development of the MyTransport.SG mobile app, Singapore has implemented a number of systems, integrating various solutions. These include:

- an automated track inspection system, using imaging sensors and scanners to monitor track condition in real time;
- a rail asset management system, gathering information from all trains and other supporting equipment to better assess and predict the condition of the entire network and its components;
- predictive analytics and data visualisation tools to analyse traveller behaviour and preferences;
- artificial intelligence used to improve pedestrian safety and facilitate urban planning.

Singapore has also introduced a number of instruments to prioritise buses on roads, including dedicated bus lanes, bus priority traffic lights and bus priority boxes at intersections. These instruments are aimed at improving bus speeds, increasing reliability and encouraging more people to use public transport. It should be pointed out that Singapore was also one of the first cities to introduce electronic road pricing as a way to manage congestion. The ERP (Electronic Road Pricing) system charges vehicles

for road use during peak hours in congested areas, effectively controlling traffic congestion and encouraging the use of public transport (Chin, 2021).

Singapore has also embraced shared mobility options, including bike-sharing and e-scooters. In Singapore, bike-sharing services provide a convenient mode of transport for short trips. Users can easily locate available bikes using mobile apps, which show real-time bike availability at various docking stations across the city. Once located, users can unlock the bikes using the mobile app or their membership card. These bikes are designed for easy riding and are usually equipped with features such as adjustable seats, baskets and built-in GPS systems (Joo, 2023).

The decision to introduce bike sharing and electric scooter systems has had a positive impact on urban mobility in Singapore. These services are an easy and convenient solution, replacing private transport. As a result, the capacity of major arteries is increased while reducing the carbon footprint. The solution also encourages residents and tourists to enjoy an active lifestyle. Bike sharing and electric scooters offer connectivity to public transport hubs, making multimodal travel more accessible. In addition, the availability of shared mobility options supports the government's plan to create a car-free society in Singapore. It should be noted that by reducing reliance on private cars, these systems contribute to a more sustainable and efficient transport network (Ferro-Escobar et al., 2022).

A description of the implementation of the main factors of the smart mobility concept in Singapore is presented in Table 3.

Table 3. Key drivers of the smart mobility concept in Singapore

Pillars of smart mobility in Singapore	**Method of implementation**
Integration and connectivity	Singapore emphasises the integration of different modes of transport into a unified network. The city's rapid transit (MRT) system, buses, taxis and other mobility options are interconnected, allowing passengers to easily switch between different modes of transport.
Modern infrastructure	The city-state has invested heavily in building a comprehensive and advanced transport infrastructure. This includes a well developed road network, efficient public transport systems for public transport, dedicated bus lanes and pedestrian-friendly pavements. Intelligent Transport Systems (ITS) Singapore uses ITS technologies to improve traffic management and provide real-time information to commuters. This includes traffic monitoring, dynamic message signs and smartphone apps to help users make travel planning decisions
Planning and optimisation using data	The government uses data analytics to analyse travel patterns, traffic flow and passenger demand. This data-driven approach helps to optimise transport systems, identify bottlenecks and make informed decisions about infrastructure development and service improvements. infrastructure development and service improvements.
Smart payments and ticketing systems	Singapore has introduced contactless payment systems and smart ticketing options on various modes of transport. Commuters can use contactless smart cards or mobile cards to pay for their journeys, facilitating convenient and hassle-free travel.
Sustainable and green initiatives	Singapore is promoting sustainable mobility solutions such as electric vehicles and bike-sharing services and the use of a bike-sharing service. The government has implemented a system of incentives and infrastructure support to increase the use of electric vehicles and reduce carbon emissions.
Multimodal integration	Mobility-as-a-Service (MaaS) platforms are the underlying tool for Singapore's smart mobility. MaaS applications integrate various transport options, including public transport, ride-sharing services and micromobility solutions, allowing users to plan, book and pay for their entire journey.
Intelligent traffic management	Singapore uses technology such as the Electronic Road Toll (ERP) system to manage traffic. The ERP dynamically adjusts tolls based on demand, encouraging

	the use of public transport and reducing the use of private vehicles during peak periods.
Traffic management Autonomous vehicles	Singapore is at the forefront of testing and deploying autonomous vehicles. Autonomous vehicles are being tested in a variety of applications, such as autonomous shuttles for first and last mile connectivity and autonomous taxis for on-demand transport.

Source: own elaboration based on (Wolniak, Grebski2023).

In summary, the decisions made and the set of actions taken by Singapore on smart transport systems shows that their leadership is based on a coherent strategy, innovation and a willingness to implement modern solutions. Other cities are also introducing smart transport systems decision-making models that improve quality of life and sustainability.

The role of policy makers must be clearly emphasised. The Singapore government plays a proactive role in implementing smart mobility solutions. It sets policy, provides funding and incentives, works with industry stakeholders and actively engages the public to ensure the successful adoption of smart mobility initiatives.

C. Copenhagen

The City of Copenhagen is the first city to take the decision and introduce an innovative traffic control system that adapts in real time to changing traffic conditions and is the first in the world to introduce an all-electric freefloating car sharing system to be integrated into public transport in Copenhagen. Copenhagen has also introduced a range of smart mobility solutions to improve safety and accessibility. And inclusive mobility projects are particularly relevant here. Overwhelmingly, the decisions made are mainly about initiatives that affect pedestrians and cyclists, who are a priority. It is also extremely important for decision-makers to ensure adequate accessibility of mobility services including the provision of low-floor buses and tactile surfaces for visually impaired pedestrians (Bager, Mundaca, 2021). The key drivers of smart mobility in Copenhagen are presented in Table 4.

Table 4. Main drivers of the smart mobility concept in Copenhagen

Key drivers of smart mobility in Copenhagen	**Implementation of factors**
traffic control system	By analysing data from sensors and cameras, algorithms optimise traffic signal timings, reducing congestion and minimising the impact on pollution. The city also uses machine learning to predict traffic patterns, allowing it to proactively adapt to potential accidents. This method not only improves overall traffic flow, satisfying drivers of different types of vehicles, but also dovetails with the city's commitments to environmental sustainability.
Advanced infrastructure adapted to the needs of different residents	An extensive system of bicycle paths enables efficient movement around the city area Low-floor buses and tactile surfaces for visually impaired pedestrians
Urban bike sharing system	enables residents and tourists to rent bicycles for a small fee. It has been a great success and has contributed to an even greater development of the use of bicycles as the main means of transport in the city
Solutions that increase safety	detection systems for pedestrians and cyclists at key intersections, alerting drivers to the presence of pedestrians and cyclists and reducing the risk of accidents
Integration of public transport systems	a comprehensive network of buses, trains and metro lines that are integrated into a single ticketing system, making it easier and more enjoyable for residents and tourists to use public transport

Intelligent traffic management system for the city	an intelligent parking system that uses sensors to detect available parking spaces and directs drivers to the nearest available space, reducing the time spent looking for a parking space and minimising traffic jams
Collection and use of big data	Copenhagen Connecting aims to improve travel times for public transport and cycling by 10% (GPS on buses and intelligent control of lighting and traffic signals), more efficient water and waste management real-time air quality monitoring
Interaction between public and private actors	The City Data Exchange programme is a private-public project that aims to explore the buying, selling and sharing of a wide range of data between all users in the city - citizens, public institutions and private companies. The vision is to create a shared data centre to foster innovation, improve the quality of life in Copenhagen, stimulate economic activity and contribute to the success of the CO2 neutralisation programme.
Promoting sustainable mobility	The city prioritises buses and cyclists on the roads. Intelligent lighting at intersections, organised through the Copenhagen Intelligent Traffic Solutions platform, is part of this approach. A network of Wi-Fi-enabled devices on the roads provides data for officials to monitor and stimulate transport. Smart lights can vary in brightness, for example increasing light intensity when a nearby cyclist is detected, which improves traffic safety and has so far resulted in more than 70% savings on public lighting.
	Copenhagen residents' smartphones transmit anonymous information to wireless sensors along the city's streets, allowing traffic lights to adjust to the number of pedestrians, cyclists and drivers using the roads at any given time. Traffic lights can also communicate directly with city buses, giving them longer green lights when they are late or crowded with passengers. These systems will ensure better traffic flow so that as many people as possible save time in the most environmentally friendly way.
	The safety of cyclists is also served by the so-called "green wave" programme implemented in Copenhagen to synchronise traffic lights for cyclists. It means that cyclists riding on a road with a white-green sign at 20 km/h during rush hour will not encounter a red light on their way
Supporting traffic organisation during mass events	Buses have longer green lights, which can reduce journey times by up to 30 per cent, and traffic systems help to clear mass crowds, such as from concerts or sports meetings, much faster than at present
Car-sharing	Car-sharing allows residents to use their cars only when necessary, reducing the number of vehicles on the road and the need for parking spaces.
	The fully electrified car sharing DriveNow is the world's first all-electric freefloating car sharing system to be integrated into public transport in Copenhagen. It is also a test platform to measure how electric cars can influence passengers' patterns and behaviour over the last mile, from the bus stop to their doorstep.

Source: own compilation based on Cenre, 2017; Bager, Mundaca, 2021; Eltved et al, 2021; Doost, Rezaie, 2020.

Copenhagen's mobility development plans include the implementation of GoA4, the latest upgrade to the S-bane network, using state-of-the-art technology. This technology allows trains to run completely without human intervention, using advanced sensors, artificial intelligence and complex communication systems. The system provides high-precision operation, using real-time data analysis to optimise route management and energy consumption. This level of automation not only increases train efficiency and frequency, but also enhances safety by minimising human error and inconsistencies.

Key technical specifications of Siemens Mobility's GoA4 technology:

- fully automated operation: trains run without drivers on board, managed entirely by automated systems;
- advanced sensor systems: Uses a combination of radar, lidar and optical sensors to provide accurate real-time perception of the environment;
- artificial intelligence: artificial intelligence algorithms interpret sensor data, make operational decisions and learn from vast amounts of operational data to improve performance and safety;

- real-time data processing: Ability to process and react to real-time data to make immediate decisions on speed adjustments, routes and station stops;
- remote monitoring: Equipped with a central monitoring system that monitors all train operations from a remote location, ensuring that any potential problems are quickly resolved;
- communications-based train control (CBTC): Uses CBTC technology to precisely control train movements, increasing the capacity and reliability of rail services;
- emergency management systems: Integrated systems designed to deal autonomously with emergency situations with contingency options (Drab- Kurowska, Drożdż, 2021);
- energy efficiency optimisation: Has built-in mechanisms to reduce energy consumption, adjusting operations based on real-time conditions and demand.

In summary, the decisions made in Copenhagen regarding intelligent transport systems indicate that the decisions made were definitely based on the needs of the citizens and the transport specificities of the city. In the case of Copenhagen, this is primarily cycling, sustainable mobility or pedestrian movement and safety. It is important to emphasise that decision-making on smart mobility in Copenhagen is based on a consistent strategy, based on modern solutions, with a particular focus on sustainability.

D. Cities in Central and Eastern Europe

Singapore and Copenhagen are among the most developed cities and are leaders in smart mobility. Other cities, including those in central and eastern Europe, are also striving to provide their citizens with comfortable yet sustainable mobility options and the aforementioned cities are leading by example. For example, the Slovak capital, Bratislava, has implemented an integrated transport system that includes a combination of electric buses, trams and trolleybuses, as well as a bike-sharing system. Meanwhile, a mobile app allows users to plan journeys and pay for tickets. Prague has implemented a smart parking system that uses sensors to monitor parking spaces and provide drivers with real-time information. One component of this system is a mobile app that indicates available parking spaces to drivers and allows online payment. Smart technologies in cities should also serve to improve public safety. One example of such solutions is a platform that integrates data from various sensors and systems, including CCTV cameras, traffic management systems and emergency services, which Warsaw has implemented.

According to a recent PwC report (PwC, 2024), the biggest challenge for smart cities in central and eastern Europe is currently improving air quality, this is due in part to traffic jams. Of the cities surveyed, only one city Tallinn meets the safe air standard set by the World Health Organisation. Action on environmentally friendly forms of urban mobility is therefore required. CEE cities are implementing the Green Transformation of Public Transport programme. Progress in electrification of public transport fleets is evident in almost all cities, as well as experiments with hydrogen buses and other innovations.

A second major problem is the underdeveloped infrastructure for battery electric vehicles (BEVs), which is mainly led by the private sector. An important factor, as in Copenhagen, in guiding the development of smart mobility is Sustainable Urban Mobility Plans (SUMPs), which should be developed with the involvement of different stakeholder groups, especially citizens themselves. The need for cross-sectoral cooperation in financing new projects and providing solutions to support the smart mobility concept is also recognized.

The use of modern AI technology is primarily used to ease congestion and speed up traffic flow, while prioritising public transport, cyclists and pedestrians. In addition, these cities are implementing data- and cloud-based smart mobility for long-term and short-term traffic management.

5. DISCUSSION

On the basis of the research carried out, it can be concluded that today, smart mobility is considered a driving force of modern cities and an important economic factor and facilitator of smart, sustainable development. Smart cities in terms of smart transport systems are developing urban transport infrastructures that use innovation to optimise resource management, improve urban transport and enhance the quality of life for residents as well as all those moving around in the city.

Hence, it is very important to carry out the decision-making process properly, taking into account the cities' resources, its potential and internal and external determinants. It should be emphasised that planning smart mobility that provides efficient and optimal urban mobility solutions is one of the key challenges facing cities around the world. Current and future smart mobility challenges require effective smart mobility solutions using AI solutions. AI takes cities to the next level, allowing them to use this data and knowledge to support decision-making. This will facilitate collaboration across ecosystems (including information ecosystems) and achieve sustainability goals. It is important to emphasise that these challenges are part of the rapidly changing landscape of urban mobility, as perceived by decision-makers responsible for planning and environmental decisions of smart cities. The decision-making process of the planned strategies, aims to address and solve urban mobility challenges. Figure 2 shows the elements that should be included in the process of building a smart mobility strategy.

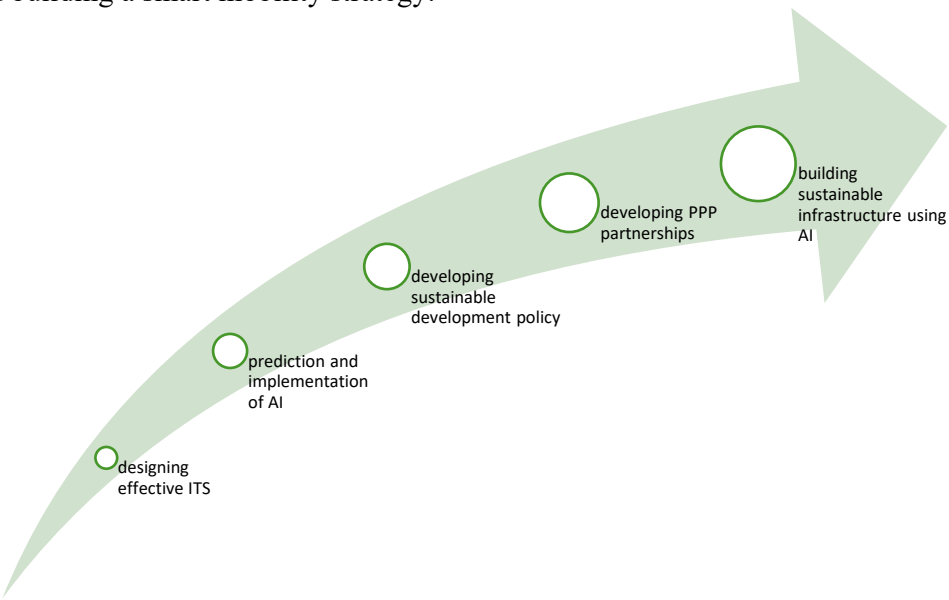


Figure 2. Elements of the smart mobility strategy building process
Source: own elaboration.

The starting point of the decision-making process is the project, which should respond to the identified needs. The high level of specificity of each city should be emphasised here (Budziewicz-Guźlecka, Drab-Kurowska, 2017). It is important to design efficient, equitable, safe and secure public transport systems that are integrated with mobility services (MaaS) and other platforms. The next element of an effective decision-making process is predisposition and implementation of AI. A key activity throughout the decision-making process is the development of policies and strategies to promote adherence to air quality and other measures to improve quality of life. Another area requiring the right decisions by decision-makers is the development of public-private partnerships (PPPs) and collaboration with scientific institutions to address air quality, traffic congestion and sustainability issues. The bonding element between the above elements is the construction of sustainable infrastructure - based on the use of AI.

However, it should be emphasised that achieving a high level of sustainable urban mobility requires not only investment in infrastructure, but also a change in the context of the decision-making process, the mindset and the daily habits of the inhabitants. Despite even the developed capabilities of AI and the willingness of institutions to implement the use of the opportunity provided by these systems, if the inhabitants of a city do not have the skills to use these capabilities, the concept of smart city, including smart mobility, will not develop smoothly (Budziewicz-Guźlecka, 2017). Therefore, it is also important to support the residents' skills in the opportunities offered.

The common platform for the above, on the other hand, is society's needs for safe, clean, reliable and affordable ways to get around. One of the key roles AI plays in the evolution of the smart city, is its ability to analyse data to improve public safety: pedestrians and drivers, optimising traffic management.

The challenge for policy makers, is to find ways to improve urban mobility while reducing congestion, accidents and pollution. A particular challenge for all major cities in the world is to reduce pollution caused by CO2 emissions. It is crucial to take measures to reduce and control pollution levels. It is also important to point out that among the challenges facing societies and economies is the challenge of car/public transport dependency. Urbanisation processes and continued car dependence inevitably lead to road disruptions[4], emissions and mobility safety issues that transport policy makers and city planners are grappling with. While cities are recognising the benefits of public transport in terms of pollution and congestion reduction, local government efforts to deliver these benefits can clash with disruptive business models such as Uber and other ride-hailing services. Ridesharing services and other forms of sharing that complement public transport are a solution that deserves attention (Budziewicz-Guzlecka, 2017; Drobiazgiewicz, Pokorska, 2023). However, the challenge is to overcome the first-mile, last-mile problem and enable citizen-oriented travel by integrating public transport with ride ordering, ride sharing, ride sharing and smart ticketing services. Another challenge facing decision-makers is safety. Despite high investment in improving the safety of urban mobility, "road fatalities are increasing in many cities" (Glasco, 2019). It should be emphasised that urban population density, combined with cars, trucks and public transport vehicles "sharing congested streets with vulnerable road users (pedestrians, cyclists and motorcyclists), makes the task of ensuring safe mobility a complex challenge. The safety problem is further complicated by unsafe driving habits and insufficient infrastructure for bicycle and micromobility users.

6. CONCLUSION

The examples of solutions presented in the article generate questions. Could similar intelligent management solutions be applied universally? Are other cities ready for smart mobility? Would authorities and residents be willing to change their habits in favour of more sustainable urban mobility?

In order to obtain answers, it is necessary to focus on carrying out a broad analysis as a route to smart mobility, taking into account a number of determinants, as shown in Figure 3.



Figure 3. Areas of analysis on the way to AI-based smart mobility
Source: own elaboration.

This in-depth analysis will be the starting point for action, which is depicted in Figure 4. Decision makers in the field of AI and smart mobility can use this model solution, which will guide them step by step to implement AI-based smart mobility solutions efficiently, depending on the level of intensity of the impact of each dimension.

[4] According to the European Joint Research Centre, "the cost of traffic jams in Europe is around 1% of GDP, and mitigating them is a top priority for most infrastructure measures, traffic management and road pricing. [...] The cause of traffic jams in many cases is not a lack of road infrastructure capacity, but rather a demand management issue."

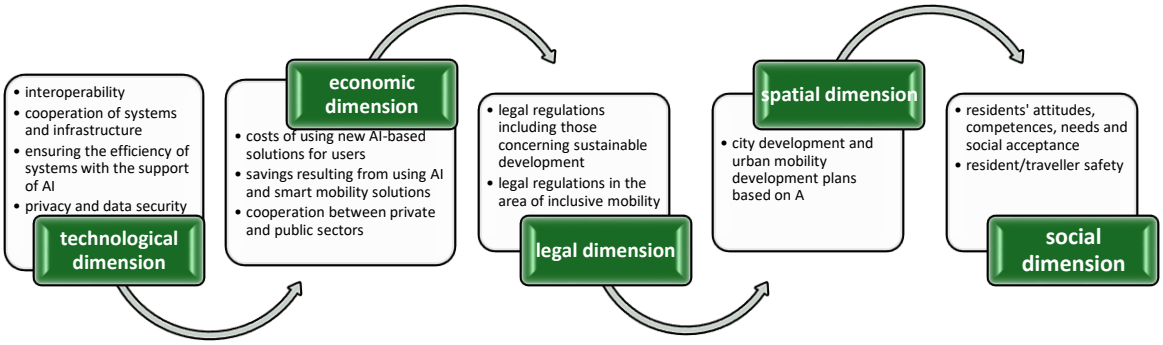


Figure 4. AI implementation model in smart mobility
Source: own elaboration.

The starting point is an analysis of the determinants influencing the development of smart mobility. The dimensions identified are important at each stage of building an AI implementation model for smart mobility.

As a first step, decision-makers need to verify the potential of the AI infrastructure in terms of its interoperability and compatibility with other systems operating in the city. The issue of ensuring data privacy and security is also important. This determines the next action, which is the economic dimension of the model. Decision-makers, when deciding to use AI, have to estimate the costs and benefits both at the level of the administration and for the resident using AI-based smart mobility technology. Particularly valuable are analyses showing savings made in the context of using AI. Openness in AI implementation is also important, especially in the area of broadly understood cooperation between the private and public sectors. Legislative issues, often different at the level of different countries, are then considered. In particular, an analysis of the regulation of inclusive mobility is necessary, targeting the openness of regulation in the development of smart mobility concepts or the support of AI. Another area that needs to be addressed in the context of implementing smart mobility solutions with AI support is the potential of cities and their ability to adapt smart solutions. The assumptions made by decision-makers in the context of urban infrastructure. It should be emphasised that a prerequisite for the implementation of smart mobility solutions is dialogue between all stakeholders and, above all, openness to change and commitment to long-term strategies. Cooperation between the community and urban decision-makers is a key element in the successful development of smart cities. Artificial intelligence can be used to increase community engagement through communication platforms that allow residents to share their ideas and opinions on city development. The model also needs to be socially validated. Artificial intelligence can be used to gather residents' opinions. Through mobile apps and online platforms, residents can make suggestions about the development of the city, making the decision-making process more democratic and accessible to all. The right steps and taking the correct course of action will benefit both current and future generations.

In conclusion, to be able to implement the above model, it is not only necessary to have knowledge of reality, but it is necessary to anticipate the future. The importance of AI-enabled management in shaping the future of urban life will continue to grow. The synergy between artificial intelligence and urban planning for intelligent transport solutions is becoming increasingly important. The integration of

artificial intelligence goes beyond simple efficiency improvements; it becomes the foundation for a more regenerative, resilient urban future. The road to intelligent urban transport management is undoubtedly a challenge, but with artificial intelligence as a driving force, cities around the world are poised to discover new possibilities and define a new essence of urban existence.

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28th European Conference on Artificial Intelligence (ECAI 2025)

AUTONOMOUS VEHICLES AS A TOOL FOR IMPROVING ROAD SAFETY

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ABSTRACT

Purpose: *This article aims to evaluate autonomous vehicles based on artificial intelligence as a tool to influence road safety*

Need for the study: *The large number of road accidents and their consequences make it necessary to look for new solutions to improve road safety. Autonomous vehicles using artificial intelligence in road traffic can be a valuable solution supporting road traffic management.*

Methodology: *The article presents the benefits and risks associated with the implementation of autonomous vehicles as a road safety management tool. In the empirical layer, the resources of institutions and operators related to autonomous vehicles were used. The indicators of road incidents and disabled autonomous driving systems were presented in relation to the distance traveled (per 1 million km).*

Findings: *Autonomous vehicles have not brought a breakthrough in the number of road incidents in the areas where they are tested, in relation to the distance traveled. Although there is an improvement, the indicator remains higher than the indicator of road incidents involving motor vehicles. It should be remembered, however, that autonomous vehicles in most cases do not generate collisions or accidents. The results for the second analyzed indicator – system deactivation – are ambiguous.*

Practical Implications: *Road accidents rarely occur due to the fault of autonomous vehicles. However, the results concern a relatively small number of vehicles and the area of operation. Hence, it is worth conducting further research involving autonomous vehicles in the context of their safety. In addition, a reduction in passenger injuries in autonomous vehicles can be observed.*

Keywords: Autonomous Vehicles, Road Safety, Road Traffic Collision Rate Autonomous Vehicle Shutdown Rate, Traffic Management, Artificial Intelligence

Jel codes: O320, O180

1. INTRODUCTION

In 2021, approximately 1.2 million people were killed and 50 million were injured on roads worldwide. This represents an approximate 5% decrease in road casualties (1.25 million) compared to 2010. It should be noted that the decline in fatalities between 2010 and 2021 worldwide was associated with the

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rapid growth in the number of motor vehicles and the increase in population (from 6.8 billion to 7.9 billion).

Road accidents remain the 12th cause of death globally, but it is worth noting that as of 2019, they have become the primary cause of death for children and young people. In addition, road accidents generate high economic costs. The costs associated with them are estimated to be around USD 1 trillion, which, according to the WHO, is worth around 3 % of the world's gross domestic product (Global status, 2023).

Notably (Table 1), an above-average number of accidents and victims occur in low- and middle-income countries. High-income countries are home to about 16% of the population, which has 28% of the world's vehicles, 88% of non-urban paved roads, and where about 8% of all traffic accident victims die. By comparison, low-income countries have about 9% of the population with less than 1% of the world's vehicles and paved roads, with about 13% of the total road accident victims killed.

Table 1. Road accidents in countries with different income levels

State income level	Population (%)	Estimated road fatalities (%)	Powered vehicles (%)	Paved roads (%)
High-income	16	8	28	88
Upper middle-income	32	35	38	2
Lower middle-income	43	44	34	10
Low-income	9	13	1	1

Source: Global status report on road safety 2023, *WHO, p. 7.*

Worldwide statistics on road safety allow the following conclusions (Global status, 2023).

1. The most dangerous, from the point of view of the number of road accidents in the world, is Southeast Asia. This area accounts for about 30% of road fatalities

2. The most significant decrease in the number of fatalities between 2010 and 2021 was recorded in Europe. This area reduced fatalities by about 40% during the above period.

3. Globally, there is variation in the distribution of fatalities considering the type of road use. In general, the largest share of road casualties is associated with passenger cars (about 30%), followed by two – and three-wheeled motor vehicles (21%), pedestrians (23%), and cyclists (6%). The share of others is 21% (including buses).

4. Road accidents are the leading cause of death for children and adolescents as of 2019. In addition, 66% of victims are people of working age (19-60 years).

The UN has recognised the problem of global traffic safety. This is alluded to in the UN program Decade of Action for Road Safety 2021-2030 (Global Plan, 2020). It identifies measures to improve Road Safety regarding infrastructure development, improving the safety of vulnerable road users (cyclists, pedestrians), and public transport. It assumes, like previous EU programs, a decrease, between 2021 and 2030, in the number of victims on the roads by 50%.

The impact of road traffic accidents varies and depends on each country's population wealth. They are greater in developing countries with low and middle national incomes. The risk of dying as a result of being involved in a road traffic accident in these countries is three times higher than in highly developed and, therefore, high-income countries. This may be due to the lower road safety standards and poor infrastructure quality in low-income countries.

From the point of view of traffic participants involved in road accidents, passengers and drivers of passenger cars account for the largest share of victims in the EU, at about 45%. The share of pedestrians is about 18%, motorcyclists and their passengers 16%, cyclists about 10% and others 10%. Taking into account another parameter, the place of the accident, by far the most significant number took place on rural roads (52%); while 38% of accidents took place on urban roads. Only about 9% of accidents took place on highways.

Transport policy also influences road safety. A valuable example is the European Union's (EU) transport policy, which includes road safety as one of its pillars. The policy emphasises the need to

reduce the number of accidents and the negative consequences associated with them, particularly fatalities and injuries.

Measures taken to reduce the risk of loss of life and injury in road traffic (legislative changes, good practices) have not led to significant improvements in road safety worldwide. It is therefore necessary to look for new and innovative solutions to improve road safety. Autonomous vehicles, as a tool related to traffic management, offer such opportunities. The artificial intelligence-based technology used in them, using algorithms and machine learning, increases the possibility of improving safety in transport. It is assumed that traffic management based on autonomous vehicles can be safer than by current passenger cars, especially those that are not equipped with any driver assistance devices. The intelligent system used in autonomous vehicles does not get tired or distracted like the average passenger car driver.

Research into levels of vehicle autonomy has been developed over many years. Commonly analysed and used in the literature is the Society of Automotive Engineers (SAE) classification, which distinguishes 6 levels of vehicle autonomisation, where 0 means no autonomisation at all in the driving process, 1 equipping vehicles with driver assistance systems, 2 limited autonomisation in the driving process, 3 conditioned autonomisation, 4 high autonomisation and 5 full driving autonomisation. Currently, the highest level of autonomous driving allowed is level 3. This means that the vehicle can drive autonomously under certain conditions, although it can also hand over control e.g. in adverse weather conditions to the driver (SAE, 2021)..

Their software is the basis for a properly functioning system based on autonomous vehicles. At successive levels, it must be increasingly reliable. Its role is to process large amounts of data based on which optimal decisions are made. Their operation is influenced by the following components, which are responsible for perception, prediction, planning and control (B. Paden et al 2016, p. 33-55, Takacs et al 2018, p. 106-112, C. Badue et al 2021, A. Yoganandhan et al, 2020, no 33, p. 3303-3310).

1. Perception module, which collects and processes sensor data, e.g. detects objects, maps the environment.

2. Prediction module, which predicts the behaviour of other traffic participants.

3. A planning module that determines the vehicle's navigation route using the perception and prediction module.

4. The control module, which controls the vehicle using the planning modules.

The autonomous system's basis is control and operation in various conditions. Lidar elements are essential to launch the autonomous system, which maps the vehicle's launch using laser pulses, cameras, and radar.

A well-developed infrastructure is required to properly implement and operate autonomous vehicles. It is formed by the following components: physical infrastructure: roads, vertical and horizontal markings, parking spaces, communication networks (4.5G), digital infrastructure sensors, transmitters, smart signals, high-resolution maps, etc. (Duvall T. et. al. 2019).

The artificial intelligence used allows navigation and real-time optimal decisions to be made independently of humans. This is all thanks to advanced technology and computing systems. The collaboration of these elements allows the autonomous vehicle to select optimal decisions.

When analysing autonomous vehicles, it is essential to keep in mind the risks associated with them. For example, they may be legal and relate to liability for accidents. Another problem seems more serious and is related to risks of an IT nature. It concerns the possible interference with the software of autonomous vehicles or the transport system (the issue of cybersecurity of autonomous vehicles).

Despite these reservations, autonomous vehicles can be a valuable solution for improving road safety. This can be facilitated by several constantly developing technical and technological solutions that support the driver or allow the information system to take full control of the vehicle. Autonomous vehicles, transport infrastructure adapted to their service, and mapped terrain facilitating vehicle movement support intelligent traffic management. Their emergence represents an important moment in the development of intelligent transport systems and, simultaneously, the new challenges involved.

2. LITERATURE REVIEW

Research on autonomous vehicles has been ongoing for many years and in various contexts. One of them concerns the possibility of improving road safety through autonomous vehicles.

In research related to autonomous vehicles, analyses are conducted in the context of their advantages and disadvantages. The literature points to safety as an advantage and the primary reason for developing autonomous vehicles. In this context, research focuses on analysing the impact of autonomous vehicles on preventing traffic accidents and, in particular, their negative effects, i.e., minimising fatalities and injuries (M. Abdel-Aty, S . Ding, 2024).

The assessment related to autonomous vehicles can be presented in the context of benefits and threats related to road traffic management. As a benefit, safety is indicated in the literature as the primary reason for implementing autonomous vehicles. In this context, the analyses focus on assessing the impact of autonomous vehicles on preventing road accidents and in particular, their negative effects, minimising casualties and injuries. (Abdel-Aty, S . Ding, 2024)

The operating system in autonomous vehicles allows for more precise vehicle control, relative to the driver's capabilities. This is facilitated by the artificial intelligence that controls the vehicle based on algorithms and cameras, radar and lidar. In addition, the autonomous system supported by the mapped terrain accurately detects threats and can respond to threats faster than humans. Importantly, the possibilities of reducing road accidents thanks to artificial intelligence are related to excluding drunk people from driving motor vehicles, distracting drivers by using mobile phones while driving, not exceeding speed limits, and better control of the environment (360 degrees) in which vehicles move. Undoubtedly, the arguments presented above indicate that autonomous vehicles can positively impact improving road safety. An AI-based accident avoidance feature used by an autonomous vehicle can reduce the number of road accidents and fatalities caused by distracted driving or human error in controlling the vehicle, and warn drivers of hazards (C.D. Harper et al., 2016, p. 1-9).

Taking control of an autonomous vehicle by artificial intelligence allows the driver to control work and entertainment while driving (V. Nagy, B. Horváth, 2020, 235-240). There may be a risk of shortening travel time to the destination or additional support when parking vehicles. (L.-J. Tian, at al, 2019, 258-278).

In the literature, it is also possible to see views highlighting the risks associated with developing autonomous vehicles. The main ones are related to the IT sphere of autonomous vehicles. They concern the failure of sensors, software, interference in the transmission of information between the vehicle and the infrastructure- V2I (D. González, 2016, pp. 1135-1145) the taking of wrong decisions by autonomous vehicles and the necessary reaction of the driver in such a case (A. Eriksson, N. A. Stanton, 2017, pp. 1233-1248, A. Calvi, at al., 2020. pp. 58-67) difficult for autonomous vehicles to assess the behaviour of other road users i.e. vehicle drivers, pedestrians, cyclists (J. Wang at al, 2020 p. 13).

In the technical-technological context, significant risks resulting in autonomous vehicle accidents can be software errors and traffic-related circumstances. It is important to emphasise that the system continuously analyses the traffic situation and selects optimal decisions through the algorithm. It is impossible to exclude a situation on the road that will not be included in the algorithm. Then, external assistance will be required, most likely from the human driver of the autonomous vehicles. The problem of the autonomous vehicle remains the system's failure to plan for all possible situations that may arise in traffic (M. L Cummings, 2021). The system may misjudge the traffic situation, which can lead to dangerous traffic situations, including accidents. Another risk associated with autonomous vehicles is that the autonomous vehicle system confuses traffic signs,

A significant challenge related to the development and deployment of autonomous vehicles remains the legal system that will ensure that society is adequately addressed in terms of liability for possible traffic incidents. Artificial intelligence applied to autonomous vehicles can reduce the number of traffic incidents, but they cannot be 100% excluded. Hence, it is also necessary to manage this issue by introducing appropriate regulations to assign liability for traffic incidents involving autonomous vehicles (Association for Computing Machinery). It is possible to identify several potential actors who could take responsibility for possible traffic incidents involving autonomous vehicles, i.e. the driver (tester), the vehicle owner, the system operator, the vehicle manufacturer and the software manufacturer. Perhaps, following the example of drivers, a separate fund should be set up to collect funds related to autonomous vehicles, dedicated to the consequences of accidents. Furthermore, the literature emphasises that artificial intelligence systems can make mistakes that humans do not make (M. Wansley, 2024) and, in addition, autonomous vehicles can make their own mistakes - coding errors (M. L Cummings, 2021 pp. 6-15).

Currently, there are no uniform regulations on the liability for accidents involving autonomous vehicles worldwide. There are also no such solutions at the European level. Appropriate regulations are only being created at the national level, but with numerous restrictions. For example, in Germany, it is possible to use level 3 autonomous vehicles but with a limited speed (up to 60 km per hour) on mapped sections. This allows for autonomous driving in Germany on approximately 13,000 km of motorways (Bundesamt für Güterverkehr). Regulations are also being introduced in the USA, but only at the federal level (R. Beidgelall, 2024). Legal regulations do not keep up with technological changes in autonomous transport. Some legal provisions block the possibility of testing autonomous vehicles. The basic challenge is related to liability for possible road accidents. The occurrence of such events cannot be ruled out. In the case of autonomous vehicles, it is necessary to determine the liability of the driver (vehicle owner) and the manufacturer. In this respect, regulations are needed at the national and European levels. At the moment, the Vienna Convention is the applicable legal act. Without legal changes, testing of autonomous vehicles is severely limited. On the other hand, without testing autonomous vehicles, it will not be possible to develop autonomous technologies, which is necessary for their mass implementation. Testing is an important process in preparing for the implementation of vehicles, because without gaining the trust of potential passengers, it will not be possible to gain trust in autonomous vehicles and, consequently, the process of their commercialization will be very difficult. Another threat remains cybersecurity. Criminals can exploit the imperfections of the IT system of autonomous vehicles to take control of them, e.g. over the steering system, braking, thus endangering other road users and passengers of the autonomous vehicle. The threat of cybersecurity increases with the development of software in autonomous vehicles and related network systems. (G. Bathla, 2022, pp. 1-36). The consequences of taking control of the vehicle can be tragic. They can lead to improper driver reactions, accidents and even death. This is related to the manipulation of the autonomous vehicle's operating system. The main threats related to the cybersecurity of autonomous vehicles are related to (S.F. Meyer, 2021 pp. 227-247, O. Sharma, 2021): disruptions in the operation of autonomous systems. Criminals hacking into the software of an autonomous vehicle can gain control over individual elements of the operating system, causing disruptions in its operation and thus exposing passengers and other road users (pedestrians, cyclists) to various dangers - data theft, data may be related to passengers but also to the autonomous vehicle, - disruptions in communication. Disruptions may concern data transfer between vehicles (V2V) and between vehicles and infrastructure (V2I). - threat of software destruction. Threats may be related to immobilization and a ransom demand for restoring the proper functioning of the autonomous vehicle. Reducing cybersecurity threats requires preparing appropriate security measures in the software. Cyberattacks are possible thanks to the constant connection of the vehicle to the network. This is necessary for the vehicle to communicate properly with its surroundings, including infrastructure. To some extent, protection against cyberattacks can be achieved by limiting access to external information transfer and downloading/transmitting information from specific locations.

Despite the continuous improvement of autonomous vehicles, there are concerns about their safety, and diverse views on this subject can be observed. Young, well-educated people and men are positively disposed towards autonomous vehicles (L. M. Hulse, at al,.2018, p. 1-13). From a different perspective, territorially, a difference in the perception of autonomous vehicles can be seen. In Europe, there is more pessimism, whereas in Asian countries, the population is more optimistic about autonomous vehicles in terms of their safety. Hence, it can be thought that in Asian countries, autonomous vehicles may, on a larger scale, emerge more quickly.

Despite the continuous improvement of autonomous vehicles, there are concerns about their safety while travelling, although diverse views on this subject can be seen. Young, well-educated people and men have a positive attitude towards autonomous vehicles. There is also a visible difference in the perception of autonomous vehicles in territorial terms. In Europe, there is greater pessimism, while in Asian countries, residents are more optimistic about autonomous vehicles in the context of their safety. Hence, it can be assumed that autonomous vehicles may appear on a larger scale and faster in Asian countries (J. Moody et al., 2020, pp. 634-650). Moreover, taking into account the accident rate that occurs in the global system (Table 1), greater acceptance of motor vehicles in Asian countries may bring more positive effects in terms of improving road safety than in European countries.

From the point of view of the article, it is essential to analyse the impact of autonomous vehicles on the level of road safety. Human error is estimated to influence more than 94% of road accidents (Critical Reasons..., 2015). This group includes road accidents caused by speeding, alcohol, non-compliance with

traffic regulations and other causes. In this context, autonomous vehicles have the potential to reduce the number and consequences of road accidents fundamentally. This is alluded to in research by the Insurance Institute for Highway Safety (J. M. Anderson at al., 2016). Already, basic vehicle features such as frontal collision warning, lane assist and adaptive headlights can reduce the risk of an accident by 33%.

Ongoing tests of these vehicles can provide valuable opinions on the safety level of autonomous vehicles. This allows them to be developed effectively. Currently, most autonomous vehicle tests are conducted in the USA. This approach seems reasonable, as there is a lack of scientific and research work in the literature relating to road traffic incidents involving tested autonomous vehicles in the context of their safety (Wang J., 2020). For this reason, the research section of this article presents an analysis of road incidents related to autonomous vehicles based on data from the California Department of Motor Vehicles (USA), Waymo, the market leader in the number of kilometres travelled with autonomous vehicles, and the National Highway Traffic Safety Administration.

Statista, using databases from the US Department of Transportation and the California Highway Patrol, presented the collision rate for autonomous and traditional vehicles (www.statista.com). For 1 million miles travelled, the rate for autonomous vehicles in California is 26.3, for traditional vehicles it is about 0.7, and for the US, it is about 1.9. Other values are presented in the National Law Review studies, according to which 9 road accidents involving autonomous vehicles and 4 other vehicles per 1 million miles travelled (www.nstlaw.com). The above studies show that vehicles traditionally controlled by drivers cause fewer road accidents.

In addition to the assessment of autonomous vehicles taking into account the number of collisions and the distance travelled, the literature also examines autonomous vehicles in other cross-sections. The basic ones include:

- identification of challenges related to safety, including autonomous vehicle software, such as the need for reliable detection of errors in software, robust algorithms for decision-making (P. Penmetsa, 2021, pp. 485–492).
- Determination using statistical methods of the reliability of autonomous vehicles in the context of the distance they must travel to be competitive in terms of safety as vehicles controlled by drivers (N. Kalra, 2016, pp. 182–193).
- Analysis of the severity of accidents (S. Yan, 2023, pp. 1–28).

The tests of these vehicles can provide valuable opinions on the level of safety of autonomous vehicles. Thanks to them, they can be effectively developed while contributing to improving road traffic management. Currently, most autonomous vehicle tests are carried out in the USA. This approach seems valuable, because the literature lacks scientific and research works relating to road incidents related to tested autonomous vehicles in the context of their safety (J .Wang, 2020, pp. 1-13). For this reason, the research part of the article presents an analysis of road incidents related to autonomous vehicles based on the California Department of Motor Vehicles (USA) database. In the overall assessment, however, it should be noted that autonomous vehicles are used in a specific, limited area. Hence, the results in comparing autonomous vehicles and those driven by drivers should be cautiously approached. Importantly, the overall accident results of motor vehicles driven by drivers compared to autonomous vehicles are not worse. For example, in the USA in 2022, there will be 1 fatality per 100 million miles travelled, and excluding people under the influence of alcohol or drugs, there will be 1 fatality per 200 million miles travelled (Ph. Koopman, 2023).

There is no clear opinion in the literature on the level of safety of autonomous vehicles. (N. Norris, at al, 2023, pp. 251-260). .Generally, two different approaches can be distinguished (S. Ding, at al.).The first one indicates the advantage of autonomous vehicles over those controlled by drivers. This opinion was formulated based on research on autonomous vehicles and those driven by drivers in the context of fatalities. Analysis conducted on Google vehicles showed that there was no accident involving an autonomous vehicle in which a passenger died. In contrast, in vehicles controlled by drivers, 1 victim occurred every 108 million miles. The second approach questions the view that autonomous vehicles are safer than driver-driven ones. This is indicated by research considering the limited movement conditions of autonomous vehicles. It was also pointed out that autonomous vehicles often hit each other from behind, at a higher speed than conventional vehicles. This can be associated with the lower speeds that autonomous vehicles travel and with lower driver concentration (F.M. Favarò, et al, 2017).

Synthesising the opinions presented above on the possible impact of autonomous vehicles in the context of their safety, it can be seen that the advantages of autonomous vehicles are inspiring. However, it is premature to state that an autonomous vehicle is better than one driven by a human driver. Further multidisciplinary research is required in this area, considering autonomous vehicles, machine learning, software development and necessary changes in legal regulations (Ph. Koopmann, M. Wagner, 2017, pp. 90-99). It should also be noted that drivers of other vehicles cause the vast majority of accidents involving autonomous vehicles. Autonomous vehicles using artificial intelligence should be developed, although it is difficult to clearly determine when they will be safer than vehicles controlled by humans.

In general, it can be assumed that the effectiveness of the autonomous system will increase due to the development of its algorithms. Additionally, increasing the share of autonomous vehicles and extending the range of their functioning may contribute to safety.

The process of implementing autonomous vehicles will undoubtedly be long-term and will be evolutionary in nature. This will be partly due to technical and financial reasons. In addition to vehicles, the development of infrastructure (mapping, readers, etc.) will be necessary for the proper functioning of autonomous vehicles. Therefore, it is necessary to prepare for a situation where both types of vehicles (driver and autonomous) will operate on the same infrastructure for longer. In addition to changes in infrastructure, the challenge for the development of autonomous vehicles will be the necessary legal changes.

In summary, autonomous vehicles are a future solution for improving road safety. Higher levels of autonomy of means of transport reduce the role of humans in the movement process, which in some cases may reduce the risk of an accident and its consequences. In some cases, artificial intelligence may detect a threat faster than humans and more effectively prevent an accident, or reduce its negative consequences.

3. METHODOLOGY

The research methodology adopted for the purpose of the article included collecting data on autonomous vehicles, analysing them in the next stage, and proposing indicators reflecting the safety level of autonomous vehicles. Subsequently, the indicators of traffic incidents and disengagement of an autonomous vehicle controlled using artificial intelligence were calculated. Data for the empirical part came from three sources:

1. The National Highway Traffic Safety Administration.
2. Department of Motor Vehicles (DMV).
3. Entities developing software for autonomous vehicles with a focus on Waymo, the leader in autonomous transportation.

The National Highway Traffic Safety Administration is a government agency that publishes safety data in the USA. This institution presents general data on road safety in the USA, including the number of fatalities and injuries. Data for this article was obtained in this area.

The Department of Motor Vehicles (DMV) has, since 2014, introduced an autonomous testing program to test autonomous vehicles with a driver and, since 2018, without a driver. It should be noted that testing an autonomous vehicle without a driver is subject to much stricter rules than testing an autonomous vehicle with a driver (tester). The obtained license for testing an autonomous vehicle precisely defines the location (street names), weather conditions, time of day, and maximum speed for testing autonomous vehicles. failure by the company to submit an annual report will result in automatic revocation of the license.

The DMV administers the vehicle testing program and collects information about road incidents and autonomous mode deactivations. The results are published on the website. The report cannot be made later than 10 days after the collision. By April 2025, over 800 reports on road incidents had been published on the DMV website. In the article, those concerning 2019-2024 were used for statistical analysis.

There are currently 37 autonomous vehicle test operators active in California. However, in terms of annual mileage travelled, Waymo has become the leader in this market.

Based on information from the DMV, two indicators relating to the safety of autonomous vehicles, i.e., road incidents and outages, were calculated. The road incident indicator was calculated as a quotient,

considering the number of road incidents and the total mileage of these vehicles. On the other hand, the takeover indicator shows the average distance travelled by the autonomous vehicle until the tester (driver) takes control of the vehicle, which was previously signalled by the vehicle.

The analysis was limited to California and DMV data because it is the only jurisdiction worldwide that publishes publicly available and reliable data on autonomous vehicle testing.

4. RESULTS

As of July 2024, about 4,000 traffic incidents related to autonomous vehicles have been recorded in the US, with about 12% of them in 2024. The data includes vehicles with ADAS, which supports the driver while driving (level 1-2 autonomization) and ADS, with limited or no driver support per vehicle (level 3-5 autonomization). To date, the highest number of traffic incidents recorded in 2022 was about 1,450. Among vehicles with ADAS, the highest number of road incidents was associated with TESLA (about 54%) and among vehicles with ADS, with Waymo (about 10%). This would imply that vehicles with higher levels of autonomization account for a smaller share of traffic incidents (nhtsa.gov)./. About half of the traffic incidents involving autonomous vehicles were reported in California. From the point of view of the autonomization of means of transportation, this is an important place on the world map, where the most autonomous vehicles are being tested. The number of autonomous vehicles tested in 2024 autonomous vehicles was about 2,800 (dmv.ca.gov). In previous years, it was respectively about 1.6 thousand (2023), about 1.5 thousand (2022), and about 1.1 thousand (2021).

The share of total kilometres driven, in 2021-2024, by Waymo autonomous vehicles in the state of California was: 58% (2021); 50% (2022), 68% (2023), and 62 % (2024). By comparison, during the same period, the shares of major competitors, in terms of miles travelled, were as follows:

- Cruse - 20% (2021), 30% (2022), 10% (2023), as of October 2023, due to an accident, the company suspended its services with autonomous vehicles

-Zoox 3% (2021), 9% (2022), 13% (2023),25% (2024).

The number of kilometres driven by driverless autonomous vehicles is also worth noting. In total, all companies licensed for such transportation drove about 900 thousand km (about 14.5%) in 2024, about 5.2 million km (about 56%) in 2023, about 990 thousand km (about 10%) in 2022, and 49 thousand km (about 0.6%) in 2021.

Autonomous cars with Waymo software (named after a new way forward in mobility) have driven a total of about 52 million km (about 33 million miles) since licensing, including about 2 million km (more than 1 million miles) without a driver. The autonomous transportation service is available in San Francisco, Los Angeles, Phoenix, and Austin (along with Uber). It covers an area of about 500 square miles, i.e. about half the area of the cities served. Approximately 100,000 customers use Waymo's services per week. In 2025, the company plans to expand its service to two more cities, Atlanta and Miami (waymo.com).

Commercial passenger transportation with Waymo's autonomous vehicles (with tester) began in 2021. However, since March 2022, autonomous vehicles have been controlled solely by artificial intelligence (driverless travel). After two years of driverless autonomous vehicles, surveys were conducted among passengers according to which (waymo.com):

-Only 37% of travellers said that the ride in an autonomous vehicle was comfortable, a decrease of 5pp. This may be due to the longer ride time. Compared to a driver-driven vehicle, it is longer by more than half

- There is a problem with space to get in and out of the vehicle, and the waiting time for an autonomous vehicle increases. According to passengers, the problem is the limited area served by autonomous vehicles.

- Advantages include a quiet ride, greater freedom of conversation (no tester), and more rigorous compliance by the autonomous vehicle system.

The higher cost of the trip relative to cabs (about $10 on average for the same distance) persists due to the fact that the technology used in autonomous vehicles is still expensive. However, it is anticipated that the development of autonomous vehicle technology and accompanying infrastructure should, in the future, contribute to lowering the cost of operating an autonomous vehicle system.

Since the introduction of autonomous vehicles with Waymo software, 3 accidents have been reported. According to Waymo's calculations, the risk of an autonomous vehicle accident ranges from 0.4-0.5 versus 1.2-3.9 for passenger cars driven by a driver over 1 million miles. This means that autonomous cars are between 3 and 6 times safer than human drivers. Considering the unit cost of traffic incidents, these are about 55% lower for autonomous vehicles. This may be due to the overriding principle associated with the speed limits of autonomous vehicles, which essentially leads to property damage while reducing the risk of injury to passengers (K. D. Kusano, 2024, p. 66).

It is also worth noting that other data shows safety improvements, using Waymo as an example. In doing so, it should be noted that the data presented considers the same distance and place on which autonomous vehicles and those driven by a human driver travel. Taking these assumptions into account, Waymo's autonomous vehicles had fewer airbag deployments (by 81%), injuries (by 78%) and fewer collision reports to the police (by 62%). It is worth noting at this point that companies with autonomous vehicles are more stringent when it comes to reporting collisions of their effects to both the Department and the police (waymo.com).

Driverless autonomous vehicles with Waymo software have driven more than 1.5 million km by January 2023. During this time, 20 road incidents were recorded, most of which were road collisions related to reversing another vehicle (8 out of 20 cases). At this point, the autonomous vehicle was not moving. The second most common road incident was a rear-end collision with an autonomous vehicle (6 out of 20 cases). Another 5 cases were related to objects lying on the road. One side impact was also recorded. A garbage truck hit an autonomous vehicle. Most road incidents caused minor damage, and nine out of 20 events did not cause any damage. 55% of road incidents occurred with a stationary Waymo vehicle, and 40% were related to parking. (V. Safety, 2023).

Most road incidents were recorded during the day. This may be because between 8:00 a.m. and 4:00 p.m. 22:00 6:00, cyclists' traffic is lower by about 85%, motorcyclists' by 83% and pedestrians' by 63%. The share of road accidents at night was about 10%. It should also be emphasised that the demand for trips at these hours is lower. Only about 20% of trips were made at night. This result contrasts with general studies, because the risk of road accidents for vehicles that move at night and are driven by drivers is higher (Varghese & Shankar, 2007). This may be facilitated by alcohol abuse by drivers, excessive speed or driver fatigue.

It should be emphasised that among the 20 cases of road incidents, none were recorded as related to any passenger injuries. This results from the company's general strategy, indicating that the primary goal is to ensure safe, responsible and defensive driving. Hence, the algorithm developed by Waymo effectively eliminates the risk of serious accidents. Autonomous vehicle safety research may concern the frequency of road collisions and the driver (tester) taking control of the autonomous vehicle. They can be presented using the road incident indicator, the quotient of the number of road incidents and their total mileage (Tables 2 and 3) and the shutdown indicator, which reflects the average distance to the moment the driver takes control of the vehicle (Table 4). The analysis presented in the article includes data from the DMV database from 2019 to 2024. At the outset, it should be emphasised that the presented indicators should be approached with caution, which results from area restrictions, the speed of autonomous vehicles and, additionally, the underestimation of road incidents in the case of vehicles driven by drivers. It is estimated that about ¼ of accidents and 60% of collisions are not reported to the police (L., Blincoe, 2023).

Table 2. Road collision rate of autonomous vehicles in 2021-2024

Name	2019	2020	2021	2022	2023	2024
Number of road accidents	104	44	117	150	127	102
Mileage of autonomous vehicles (in million km)	4,48	3,12	6,48	9,54	9,2	6,26
Collision rate of autonomous vehicles	**23,21**	**14,10**	**18,05**	**15,72**	**13,68**	**16,29**

Source: own elaboration own elaboration based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

There has been a visible decline in autonomous vehicle-related collisions in California since 2019. However, the significant decline in autonomous vehicle miles travelled over the past year (by about 1/3) has caused the overall autonomous vehicle collision rate to increase. The number of collisions per 1 million kilometres travelled decreased from 23 to 16, or about 30%. This fact should be considered positive because it indicates the technological development of autonomous vehicles, including autonomous systems based on artificial intelligence. The low number of collisions and distances travelled by autonomous vehicles in 2020 may be due to the restrictions that occurred at that time and were related to the COVID-19 pandemic.

Table 3. Autonomous Vehicle Road Collision Rate for Leading Companies 2019-2024

Company name	2019	2020	2021	2022	2023	2024
Waymo	10,77	11.0	20,1	15,3	8,4	17,1
Zoox	70,0	65,0	33,3	33,0	13,2	15,1
Apple	83,3	-	300,0	35,0	12,5	8,333
Cruse	46,2	12,3	22,1	12,0	40,0	-

Source: based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

The road collision rate for individual companies varies. Only in the case of Apple can we see an annual decrease in the rate, which may indicate an improvement in the quality of the autonomous vehicle software of this entity. In the case of Waymo, apart from 2024, the collision rate also had a downward trend. For Cruse, 2022 was a relatively good year regarding the number of road collisions. In 2023, there was a tragic accident involving an autonomous vehicle with Cruise software. This situation caused the company to withdraw from testing autonomous vehicles.

Another measure reflecting the degree of reliability of autonomous vehicles is the disengagement rate. It determines the average distance vehicles can travel in autonomous mode, after which the driver (tester) intervenes. This is conditioned by the occurrence of a dangerous situation on the road or a suggestion from the system about the need for a human to take over such control. The tester's takeover of control is intended to prevent potential collisions/road accidents, or to find ways out of a difficult situation on the road in which the autonomous algorithm cannot be divided independently.

Table 4. Disengagement rate – 3 best results in the year under review (in thousands of km)

2019	2020	2021	2022	2023	2024
Baidu 28,8	Waymo 47,9	AutoX 80,1	Cruse 153,4	Zoox 44,7	Zoox 283,2
Waymo 20,8	Cruse 45,2	Cruise 66,7	AutoX 79,6	WeRide 30,0	WeRide 33,7
Cruse 19,2	AutoX 32,4	Argo.AI 58,7	Zoox 49,1	Pony AI 27,3	Waymo 27,6

Source: based on 2019- 2024 Autonomous Vehicle Disengagement Reports 2019-2024 Autonomous Mileage Reports.

In the analyzed years, the rate was very diverse. The best rate was obtained by Zoox (in 2023, the driver took control of the vehicle on disengagement average every 290,000 km). However, it must be borne in mind that it is the companies that decide what to include and report as the driver taking control of the vehicle and in which areas the autonomous system is tested. In the case of Waymo, autonomous vehicles move in city centers and in the case of other companies in the areas of smaller towns or rural areas. Hence, in order to obtain reliable data, it is required that the technologies are tested in the same conditions.

5. CONCLUSION AND DISCUSSION

Autonomous vehicles seem to be a promising solution for improving road safety. Equipping autonomous vehicles with technical and technological tools that support the driver or allow the driver to take full control of the vehicle will facilitate this.

The presented research results indicate a further need to improve autonomous driving systems. This is indicated by the still-high rates of road accidents and system disengagement, at which point the driver takes control of the vehicle.

However, it is worth noting that road accidents decrease with increased vehicle autonomy. Although the rates of road collisions and shutdowns cannot be considered satisfactory, a year-on-year improvement in this area should be noted (especially until 2023). Methodological discrepancies should also be taken into account when determining them. Firstly, there is a general agreement that the number of road accidents involving drivers is underestimated. Secondly, road accidents are not caused mainly by autonomous vehicles. In most cases, cars driven by drivers hit autonomous vehicles. Various objects that appear on the road are also a problem. It is difficult for autonomous vehicle systems to predict driver behaviour, let alone prevent it. Therefore, it can be assumed that as the number of autonomous cars on the roads increases, the risk of road accidents will decrease, especially since autonomous vehicles will communicate with each other, thus preventing certain events resulting from a lack of concentration among drivers (rear-end collisions, front-end collisions of autonomous vehicles). In addition, the development of autonomous vehicle systems should consider learning the behaviour of drivers, pedestrians or cyclists, thus influencing the autonomous vehicle systems' learning (development) process.

Autonomous vehicles comply with road traffic regulations more than drivers (road signs, speed, and alcohol). Additionally, their operation is limited in speed, time of service or weather conditions. This means that even if a road collision occurs, the effects are relatively small compared to those of vehicles driven by drivers. This thesis is confirmed by data from insurance companies such as Swiss Re (one of the leading reinsurers in the world). The costs of road accidents generated by autonomous vehicles are lower than those caused by humans. The highest costs associated with road accidents concern people killed or seriously injured (service involvement, medical costs, etc.). And there are a few of these in the case of autonomous vehicles.

The decrease in the number of kilometres travelled by autonomous vehicles in 2024 may result from the loss of passenger confidence in this form of transport. This may have been influenced by October 2023, when one of the autonomous vehicles hit a pedestrian. This event resulted in the company's withdrawal, but it may also be affecting passenger confidence in autonomous vehicles.

A drawback of the autonomous vehicle system is the limited area of operation. This is due, among other things, to the necessary infrastructure that conditions the proper and safe operation of autonomous vehicles. Including motorways and expressways would be a desirable action conducive to more efficient use of autonomous vehicles. Drivers could spend long, monotonous routes in more comfortable conditions. Another concern is the possibility of uninterrupted use of services. The current system does not guarantee continuous operation, which is important in transport. Some companies restrict providing services at night during unfavourable weather (heavy rainfall, thick fog, etc.). The limited speed means that the service provided by autonomous vehicles is slower; the lack of convenient designated places for boarding and alighting compounds the problem.

The development of autonomous vehicles and their wider implementation are expected to reduce the number of road collisions and their severity in the long term. This will be correlated with the need for:

1. Increasing acceptance of autonomous vehicles. This will be related to the need to increase public awareness of road safety, including the indication that most often (over 90%) accidents are caused by improper human behaviour.

2. Further development of autonomous vehicles towards reducing road incidents involving them. In this respect, we can cite the example of air transport, where since the 1950s we have been observing a significant improvement in safety thanks to technological development Statistical Analysis)

3. Development of infrastructure, changes in legal regulations (the issue of changes in liability for road accidents) and social acceptance. The perception of autonomous vehicles could improve if autonomous solutions are cheaper than traditional driver-based solutions.

In summary, autonomous vehicle technology, although promising, requires continuous development, and its full use depends on the development of autonomous vehicle systems, infrastructure development and unification of regulations. The issue related to protection against cyberattacks of the autonomous vehicle system is crucial for the functioning of autonomous systems.

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TRANSFORMING CITIES THROUGH SMART MANAGEMENT: ALIGNING ORGANISATIONAL INNOVATION WITH SUSTAINABILITY GOALS

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ABSTRACT

Purpose: *This research aims to identify best practices and strategies of intelligent management that can be employed by cities to enhance their efficiency, improve residents' quality of life, and protect the environment.*

Need for the study: *In the face of global challenges (i.e. climate change, urbanisation, and population growth), there is a pressing need to investigate how innovations in city management can contribute to its sustainable development while simultaneously enhancing residents' quality of life. This study addresses this need by bridging theory and practice.*

Methodology: *The study is based on the analysis of qualitative and quantitative data from three cities: Copenhagen, Madrid, and Singapore. A comparative analysis framework is applied to assess how the selected cities implement intelligent urban management for sustainable transformation.*

Findings: *The examination of smart city initiatives underscores that effective political leadership, active engagement of citizens, and innovative financing models (such as public-private partnerships) are integral to the successful incorporation of technology in urban management. Conversely, disparities in resource accessibility among the examined cities underscore the ongoing need for initiatives aimed at social equity.*

Practical Implications: *The findings highlight several key practical implications, including the imperative to reinforce public-private partnerships, which may facilitate the rapid deployment of innovative solutions. Moreover, the engagement of citizens in decision-making processes through participatory platforms emerges as crucial for the effective advancement of smart city initiatives. Finally, the establishment of robust data governance frameworks is essential for safeguarding citizen privacy and fostering trust in urban technologies.*

Keywords: smart management; sustainable development; city; city management, innovation; city transformation

Jel codes: R53, R58, O32, O33, O35

1. INTRODUCTION

As the world grapples with pressing challenges like climate change, resource limitations, and socio-economic disparities, cities around the globe are looking to smart governance solutions for driving

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sustainable urban transformation. Smart urban management refers to the use of digital technologies in an efficient and innovative way when managing cities and urban areas, leveraging data-driven decisions and new organisational paradigms to make urban agglomerations more efficient, liveable and resilient. This idea goes beyond simply introducing smart technologies, underscoring the need for integrated and cross-cutting approaches that connect digital innovations to the nexus of sustainable development objectives (Boulton et al., 2020; Cardullo & Kitchin, 2019).

Technological progress can spark real change in addressing urban sustainability issues, but smart city ideas only work when leaders reshape how their offices operate. City officials must tweak old routines, change processes, and boost skills. New ways of organizing – mixing fresh management moves, policy tweaks, and unexpected teamwork setups – help turn tech into genuine gains for the environment, the economy, and everyday community life. By nurturing locally tuned, innovative approaches, cities can unleash smart solutions and weave them into an overall, socially minded plan (Nesti, 2018; Yigitcanlar & Inkinen, 2019).

This chapter dives into how smart urban governance meshes with sustainable development, looking at how cities might adjust their methods to match global goals like the Sustainable Development Goals (SDGs). It reviews case stories from places such as Copenhagen, Madrid, and Singapore to spotlight what helps, what hinders, and what best practices emerge when municipal structures are adapted for technology-driven, socially responsible urban transformation. The chapter is structured as follows: the literature review explores theoretical perspectives on social responsibility in cities and the relationship between technological advancement and urban change; the methodology section outlines the qualitative and quantitative analysis of the selected case studies; the results section presents the comparative analysis of the cities' experiences and key findings; the discussion examines the implications for policy and practice, as well as future research directions; and the conclusion summarises the central insights and strategic recommendations for further developing technology-driven, socially responsible cities.

2. LITERATURE REVIEW

The concept of social responsibility within an urban context has been the focus of considerable academic discussion, incorporating various theoretical frameworks. Over the past few decades, this concept has undergone significant evolution. Traditional perspectives on urban governance have expanded, embracing a more comprehensive understanding of the role cities play in promoting sustainable and equitable development. Today, social responsibility in urban settings is recognized as a multifaceted concept that intertwines environmental management, economic prosperity, and social equity (Fung, 2015).

One of the foundational works in this domain was conducted by Harvey (1973), who explored the influence of urbanization on social and economic landscapes. Harvey's research established a framework for understanding how urban planning and governance can shape social equity and environmental sustainability. He advocated for a comprehensive approach to urban development that acknowledges the intricate relationships among social, economic, and environmental factors (Harvey, 1973). In contrast, stakeholder theory highlights the necessity for cities to balance the interests and well-being of a diverse array of stakeholders, including citizens, businesses, civil society organisations, and the environment (Freeman, 1984; Bryson, 2004). A similar viewpoint was expressed by Sen (1999), who asserted that development should be viewed as a process that expands human capabilities and freedoms. Sen's capability approach has been extensively utilized in urban studies to assess the impact of policies and initiatives on the well-being of city residents. This perspective emphasizes the significance of social responsibility in ensuring that urban development benefits all community members, especially the most vulnerable (Sen, 1999).

The literature on sustainable urban development emphasizes the significance of adopting a triple-bottom-line approach, which incorporates the interrelated dimensions of environmental protection, economic prosperity, and social equity (Elkington, 1997; Littig & Grießler, 2005). Moreover, the capability approach, as articulated by Sen (1999) and Nussbaum (2011), highlights the essential role of cities in enhancing the substantive freedoms and capabilities of their inhabitants, thereby promoting inclusive and equitable growth.

Essentially, the pursuit of socially responsible urban transformation encompasses three critical dimensions: environmental, economic, and social equity. Within the environmental realm, cities face mounting pressure to tackle urgent issues such as climate change, resource depletion, and environmental degradation by adopting sustainable practices and technologies (Rosenzweig et al., 2018; Seto et al., 2012). The economic dimension focuses on fostering inclusive, innovation-driven growth that generates decent employment opportunities, supports local businesses, and mitigates socio-economic disparities (Sachs, 2015; United Nations, 2015). Meanwhile, the social equity dimension underscores the necessity for cities to prioritize affordable housing, accessible public services, and inclusive decision-making processes, ensuring equitable outcomes for all residents (Fainstein, 2010; Soja, 2010).

Technological innovations are increasingly acknowledged as pivotal facilitators of sustainable urban transformation, with the concept of the smart city emerging as a significant paradigm for the application of digital technologies aimed at enhancing efficiency, liveability, and resilience (Anthopoulos, 2017; Chourabi et al., 2012). However, the successful incorporation of smart solutions within a broader socially responsible agenda necessitates a nuanced understanding of the organisational, institutional, and governance aspects involved (Cardullo & Kitchin, 2019; Yigitcanlar et al., 2018). Recent empirical studies underscore the necessity of aligning technological innovations with progressive organisational structures, management practices, and collaborative frameworks to achieve measurable progress towards the Sustainable Development Goals (SDGs) (Angelidou et al., 2018; Meijer & Bolívar, 2016).

Smart city technologies, encompassing the Internet of Things (IoT), big data analytics, and artificial intelligence (AI), present novel opportunities for augmenting the efficiency, livability, and resilience of urban areas. Batty et al. (2012) delineate the transformative potential of smart city technologies in reshaping urban infrastructure and services, positing that the integration of digital innovations into urban systems can enhance resource management, mitigate environmental impacts, and elevate the quality of life for urban inhabitants. They advocate for a holistic approach to smart city development that duly considers the interconnected social, economic, and environmental dimensions of sustainability.

Nevertheless, the effective implementation of smart city technologies is contingent upon urban entities' capacity to adapt their organisational structures, processes, and competencies. Organisational innovation emerges as a critical determinant to ensure that the deployment of smart technologies translates into meaningful benefits for cities and their populations. In their analysis, Nam & Pardo (2011) investigate the significance of organisational innovation in propelling smart city initiatives, contending that urban governments must cultivate new management practices, policy frameworks, and collaborative models to fully exploit the potential inherent in smart technologies. Furthermore, they emphasise the necessity of fostering a culture of innovation and experimentation within city administrations as a catalyst for sustainable urban transformation.

2.1. Smart City Management and Innovative Solutions

Smart city management refers to the integration of digital technologies, data-driven decision-making, and innovative governance models to improve urban efficiency, sustainability, and quality of life. Existing studies indicates that successful smart city initiatives rely on key factors such as technological infrastructure, citizen participation, environmental protection, diversity and cross-sector collaboration (Batty et al., 2012; Meijer & Bolívar, 2016). Several cities worldwide have adopted smart governance strategies, leveraging the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimize resource management and urban services. For instance, Barcelona, Amsterdam, Zurich, New York and Dubai have pioneered the implementation of open data platforms to enhance transparency and facilitate citizen engagement in urban planning (Ojo et al., 2014). As another example, Singapore’s "Smart Nation" initiative demonstrates how digital transformation can be systematically applied to governance, healthcare, transportation, and public safety (Smart Nation Singapore, 2019).

A central pillar of smart city management is the adoption of real-time monitoring systems. Copenhagen, for instance, integrates IoT sensors to track air quality and traffic congestion, enabling responsive policy interventions (City of Copenhagen, 2019). Similarly, energy-efficient smart network systems are gaining drawing as a means to reduce urban carbon footprints, as exemplified by initiatives in cities like San Diego and Vienna (Silva et al., 2024).

Despite the promising potential of smart cities, challenges remain in terms of data privacy and protection, digital inclusion, and governance structures. Ethical considerations surrounding surveillance

technologies and the equitable distribution of smart city benefits require further exploration as well (Cardullo & Kitchin, 2019).

2.2 Organizational Innovations for SDG Best Practices and Strategies

Organizational innovations can play a crucial role in aligning smart city strategies with the Sustainable Development Goals (SDGs). Key innovations in this stage may include public-private partnerships, stakeholder-driven governance models, and institutional frameworks that facilitate sustainable urban growth (Meijer & Bolívar, 2016). Existing literature about this approach suggests that cities that integrate participatory governance mechanisms achieve higher levels of sustainability. For instance, Madrid's participatory budgeting system allows residents to directly allocate municipal funds, fostering a sense of civic ownership, inclusion and identity with the city management (Ayuntamiento de Madrid, 2019). Similarly, urban co-governance models in Stockholm and Helsinki have enhanced resilience by involving multiple stakeholders in decision-making processes (Yigitcanlar et al., 2019).

Efficient urban sustainability strategies have to prioritize environmental management, social equity, and economic viability. For example, the European Commission's Smart Cities Marketplace supports urban innovation projects that align with SDG targets, emphasizing energy efficiency, green mobility, and circular economy models (European Commission, 2020). Singapore's Green Plan 2030 also illustrates a structured approach to integrating SDG principles into urban policy (OECD, 2018).

However, the scalability of organizational innovations remains a concern, particularly in cities with limited financial resources or institutional capacity. Therefore, upcoming studies should explore how smaller municipalities can adopt adaptive governance strategies to facilitate sustainability transitions (Angelidou et al., 2018).

3. METHODOLOGY

This study employs a comparative case study methodology to investigate the role of smart urban management in facilitating the transition of cities towards sustainability. The analysis includes: cross-case comparison – identifying patterns, similarities, and differences in the approaches taken by the three cities, success and failure analysis – examining key achievements and challenges faced in integrating smart governance with sustainability, policy impact evaluation – assessing the effectiveness of institutional innovations in advancing urban social responsibility. The case study approach enables an in-depth examination of the diverse methods employed by various cities in implementing organizational innovations aimed at achieving sustainable development goals (SDGs). The selected case studies (Copenhagen, Madrid, and Singapore) are esteemed for their leadership in technology-driven, sustainable urban transformation.

Copenhagen stands as a European frontrunner in sustainable development, persistently striving to meet ambitious climate and environmental objectives through the integration of cutting-edge technologies and innovative organizational frameworks. In contrast, Madrid exemplifies a city that has markedly increased its initiatives to evolve into a more intelligent and sustainable metropolis in recent years. Singapore, as a sovereign city-state, presents a compelling case of a jurisdiction that has systematically implemented comprehensive sustainable development policies for several decades, effectively synthesising technological innovations with enhancements in municipal governance.

The analysis of these three cities promises to yield significant insights into the critical conditions, challenges, and strategies necessary for the integration of smart solutions with social responsibility objectives. These findings will provide valuable perspectives that can be applied to other urban contexts seeking to navigate the complexities of sustainable urban development.

For the purpose of conducting a comprehensive qualitative analysis, this study has selected three prominent cities that are widely recognised as exemplars of technology-driven and sustainable urban transformation: Copenhagen, Madrid, and Singapore. These cities have been chosen for their diverse geographical, socio-economic, and cultural contexts, which enable a more nuanced exploration of both universal trends and locally-specific conditions in urban development.

The analysis will be informed by data drawn from a variety of authoritative sources, including:

- scholarly articles and academic studies that focus on urban governance and the concept of smart cities, alongside research reports from reputable organisations such as C40 Cities, ICLEI, and the World Bank, which critically examine specific instances of urban transformation;
- document analysis that encompasses policy papers and government reports on smart urban management and sustainability, as well as strategic urban plans and sustainability roadmaps specific to Copenhagen, Madrid, and Singapore;
- urban performance data to facilitate a robust quantitative analysis, utilising official datasets and information from open data portals to ensure a comprehensive evaluation. Key resources include the Copenhagen Open Data Portal (https://international.kk.dk/; https://cphsolutionslab.dk/en/projekter/data-platforms), Statistics Denmark (https://www.dst.dk/en), and the European Environment Agency (https://www.eea.europa.eu/). Additional valuable datasets can be sourced from the Madrid Open Data Portal (https://datos.madrid.es/portal/site/egob/) and the Spanish National Institute of Statistics (https://www.ine.es/). Moreover, the European Commission Urban Data Platform (https://urban.jrc.ec.europa.eu/), the Singapore Government Data Portal (https://data.gov.sg/), the Urban Redevelopment Authority (https://www.ura.gov.sg/), and the Singapore National Environment Agency (https://www.nea.gov.sg/) collectively contribute to the comprehensive understanding of urban dynamics;
- key performance indicators, encompassing environmental factors (such as air quality, carbon emissions, energy efficiency, and waste management), economic indicators (including GDP per capita, the integration of smart industry, and employment in digital sectors), and social indicators (notably citizen participation in smart city initiatives, equity in access to digital resources, and the quality of public services).

The integration of these diverse data sources is essential for enhancing the analytical robustness of urban studies. This multifaceted approach will contribute to a holistic understanding of the mechanisms driving sustainable urban transformation across these diverse urban landscapes.

3.1. Research Apparatus

The analytical framework encompasses the following components:

1. Smart City Readiness Assessment. This component evaluates the technological infrastructure, digital literacy, and innovation ecosystem of each city. It includes metrics such as ICT connectivity, digital skills penetration, and the presence of innovation hubs and living labs. This assessment draws upon methodologies developed by Cohen (2012) and the European Commission's Smart Cities Marketplace.
2. Organizational Innovation Analysis. This component examines the institutional arrangements, governance structures, and management practices that support smart city initiatives. It includes indicators such as cross-departmental collaboration mechanisms, public-private partnership frameworks, and citizen participation platforms. The analysis is informed by frameworks developed by Nam & Pardo (2011) and Meijer and Bolívar (2016).
3. Sustainable Development Impact Evaluation. This component assesses the contribution of smart city initiatives to sustainable development goals. It includes environmental metrics (e.g., carbon emissions, energy efficiency), economic indicators (e.g., green jobs creation, innovation output), and social measures (e.g., inclusivity, quality of life). This evaluation is guided by methodologies developed by the United Nations' Sustainable Development Solutions Network and the World Council on City Data.
4. Comparative Policy Analysis. This component examines the policy frameworks, regulatory environments, and institutional settings that shape smart city developments in each city. It includes indicators such as smart city strategies, sustainability policies, and digital governance frameworks. The analysis employs comparative policy analysis techniques as outlined by Dolowitz and Marsh (2000) and Benson and Jordan (2011).

The research apparatus also includes a data collection protocol and analysis framework, which guides the systematic collection and interpretation of data across the selected cities. This protocol ensures consistency in data collection and facilitates cross-case comparison.

3.2. Analysis of Measurement Data

In analysis a comparative analysis framework is applied to evaluate smart city solutions across three dimensions. We can call this type of analysis as theoretical analysis in which the existing literature directs us in determining the dimensions to be checked in data sources. These are:

1. Environmental sustainability: renewable energy adoption, waste management efficiency, CO_2 emissions.
2. Economic growth and innovation: digital economy performance, smart industry integration, employment rates in tech sectors.
3. Social inclusion and equity: accessibility of smart services, digital literacy programs, public engagement in governance.

Each city's performance is assessed using key performance indicators (KPIs) aligned with the SDGs.

4. RESULTS

4.1. Global Best Practices in Integrating Technology for Social Responsibility in Urban Areas

The integration of technology into urban management has become an essential element in promoting social responsibility and sustainability within cities. Key best practices observed globally include:

1. Integrated real-time environmental monitoring systems – through the use of IoT technologies and data analytics, cities can monitor and address environmental concerns such as air quality, noise pollution, and waste management (Batty et al., 2012; C40 Cities, 2019). Cities are increasingly utilising big data analytics to guide policy decisions and enhance service delivery. For example, the deployment of smart sensors in urban infrastructure enables real-time monitoring of air quality, traffic patterns, and energy consumption, allowing for timely and informed interventions (Albert et al., 2012).
2. Citizen participation platforms to enhance social engagement – mobile applications and online portals empower residents to actively engage in decision-making processes related to urban development (Ojo et al., 2014; Cardullo & Kitchin, 2019). Numerous cities have established digital platforms that facilitate resident participation in decision-making processes. A notable example is Barcelona's participatory budgeting initiative, which empowers citizens to direct a portion of the municipal budget towards projects they prioritise (Fung, 2015).
3. Intelligent transport and mobility systems – innovations like autonomous vehicles, e-bikes, and data integration are enhancing accessibility, efficiency, and sustainability in transportation networks (Yigitcanlar et al., 2019; Shaheen & Cohen, 2019). Cities such as Copenhagen and Singapore are at the forefront of implementing innovative mobility solutions. These include real-time public transport tracking systems and bike-sharing programmes designed to alleviate congestion and promote sustainable transport options (Xia et al., 2018).
4. Innovative circular economy models (Huang et al., 2018; Kirchherr et al., 2017). Cities are adopting strategies such as waste recycling, resource management, and industrial symbiosis to minimise resource consumption and lessen environmental impacts.

These practices exemplify how technology can be harnessed to create more responsive and responsible urban environments.

4.2. Comparative Analysis of Selected Cities

Copenhagen, Madrid, and Singapore exemplify cities that have successfully embraced intelligent and sustainable urban management strategies. Copenhagen is renowned as one of the most sustainable cities globally, demonstrating a strong commitment to ecological transformation through substantial investments in cycling infrastructure, circular waste management systems, and ambitious CO_2 emission reduction targets (City of Copenhagen, 2019). The effectiveness of these initiatives can be attributed to robust political leadership, active civic participation, and collaborative public-private funding.

In contrast, Madrid places a significant emphasis on social justice and inclusivity. The city has initiated programmes such as participatory budgeting, employment opportunities for at-risk individuals, and investment in the revitalisation of underprivileged neighborhoods (Ayuntamiento de Madrid, 2019; UN-Habitat, 2020). These efforts have led to enhanced access to services and greater equality of opportunities for all residents.

Singapore stands out as a pioneer in the adoption of smart urban technologies. The city has launched a comprehensive Smart Nation strategy that addresses key areas such as mobility, waste management, healthcare, and e-government (Smart Nation Singapore, 2019; OECD, 2018). The success of this approach has been largely driven by strong government leadership, long-term strategic planning, and effective public-private partnerships.

The comparative analysis of urban management strategies in Copenhagen, Madrid, and Singapore, as illustrated in Table 1, offers significant insights into the role of organisational innovation in advancing sustainability objectives. Each city exemplifies a distinctive approach that is deeply rooted in its specific cultural and geographical context, while effectively addressing the shared and urgent challenges posed by urbanisation and climate change. This analysis underscores the importance of contextualised strategies in fostering resilient and sustainable urban environments.

Table 1. Comparative Analysis of Solutions Adopted by Copenhagen, Madrid, and Singapore

City	Smart Management Initiative	Description	Source
Copenhagen	Integrated Transport Systems	Utilises data analytics to optimise public transport routes and schedules, enhancing commuter experiences.	Freudendal-Pedersen, M. (2020). Sustainable urban futures from transportation and planning to networked urban mobilities. Transportation Research Part D: Transport and Environment, 82, 102310.
	Green Infrastructure	Establishes green roofs and urban parks to improve biodiversity and reduce urban heat.	Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. Applied Energy, 115.
	Climate Action Plan	Aims for carbon neutrality by 2025 through various initiatives including cycling infrastructure.	Albert, C., Zimmermann, T., Knieling, J., & von Haaren, C. (2012). Social learning can benefit decision-making in landscape planning: Gartow case study on climate change adaptation, Elbe valley biosphere reserve. Landscape and Urban Planning, 105(4).
Madrid	Smart Waste Management	IoT sensors in waste bins optimise collection routes, reducing emissions and costs.	Chamizo-Gonzalez, J., Cano-Montero, E. I., & Muñoz-Colomina, C. I. (2016). Municipal Solid Waste Management services and its funding in Spain. Resources, Conservation and Recycling, 107.
	Urban Green Spaces	Projects to increase green areas improving air quality and residents' quality of life.	Santo-Tomás Muro R., Rodríguez Romero E. J. (2020). City thresholds. The role of urban green infrastructures in Madrid, ZARCH 14.
	Public Engagement	Participatory budgeting initiatives empower citizens in decision-making regarding urban projects.	Fung, A. (2015). Putting the Public Back into Governance: The Challenges of Citizen Participation and Its Future, Public Administration Review, Vol. 75(4)
Singapore	Smart Urban Solutions	Utilises AI and IoT for traffic management, significantly reducing congestion and enhancing public transport.	Ho, E. (2016). Smart subjects for a Smart Nation? Governing (smart)mentalities in Singapore. Urban Studies, 54(13)

	Sustainability Framework	Focuses on sustainable land use and water management, positioned as a model for urban resilience.	Escobar, R. F., González, H. V. & Gómez-Castillo, H. (2022). Smart and Sustainable Cities in Collaboration with IoT: The Singapore Success Case. Intelligent systems reference library.
	Public Housing Innovations	Implementation of green building designs in public housing developments to enhance energy efficiency.	Kitchin, R. (2016). The ethics of smart cities and urban science. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2083).

Source: own elaboration based on the literature indicated in the table.

Copenhagen's commitment to integrated transport systems presents a compelling framework for decreasing reliance on fossil fuels while simultaneously promoting cycling and public transportation. Furthermore, the establishment of green infrastructure not only enhances climate resilience but also enriches the urban environment's aesthetic and ecological value. The integration of data analytics in transport planning represents an effective utilization of technology in urban management, ultimately leading to improved commuter experiences and a reduction in congestion (Freudendal-Pedersen, 2020).

Madrid's urban strategy, on the other hand, is centred on participatory governance and innovative waste management solutions, particularly through the implementation of Internet of Things (IoT) sensors in waste collection. This approach offers a practical example of how technology can be harnessed to minimize operational costs and mitigate environmental impacts. However, the efficacy of these initiatives hinges significantly on community engagement. The city's participatory budgeting processes empower residents, ensuring that urban development aligns with the community's needs and aspirations. This emphasis on social equity is a vital aspect of Madrid's urban management strategy (Fung, 2015).

Singapore's Smart Nation initiative presents a comprehensive framework for incorporating advanced technologies into urban governance. The application of artificial intelligence (AI) and IoT in traffic management illustrates a progressive approach to addressing urban congestion. Moreover, Singapore's focus on sustainability, particularly regarding land use and water management, positions it as a global frontrunner in urban resilience. Nevertheless, the ethical implications surrounding data privacy and surveillance require careful consideration to uphold public trust in smart city endeavors (Ho, 2016).

4.3. Comparative Analysis of Environmental, Economic, and Social Indicators

A comprehensive comparison of Copenhagen, Madrid, and Singapore across environmental, economic, and social dimensions reveals distinct patterns in their approaches to smart urban management and sustainable development. Copenhagen demonstrates exceptional environmental performance across multiple indicators. The city has achieved significant reductions in carbon emissions through its comprehensive Climate Action Plan, which integrates smart energy management systems, district heating, and renewable energy generation. Copenhagen's smart waste management system, incorporating IoT sensors and real-time data analytics, has enabled it to achieve one of the highest recycling rates globally. Madrid has made substantial progress in improving air quality through its Madrid 360 Environmental Sustainability Strategy, which includes the implementation of low emission zones, smart traffic management, and public transport electrification. However, the city faces challenges in renewable energy deployment and waste management, areas where its performance lags behind that of Copenhagen. Singapore, despite space constraints, has achieved remarkable success in green space coverage through innovative approaches such as vertical gardens, green roofs, and the integration of nature into urban infrastructure. The city-state's smart water management system, which includes real-time monitoring, predictive analytics, and recycled water (NEWater), represents a global best practice in resource efficiency. These findings are summarized in Table 2 below.

Table 2. Environmental Performance Indicators for Selected Cities (2020-2022)

Indicator	Copenhagen	Madrid	Singapore
Carbon Emissions (tCO_2e per capita)	2.5	3.8	4.2
Renewable Energy Share (%)	62	24	8
Air Quality Index (Annual Average)	25(Good)	42 (Moderate)	35 (Moderate)
Waste Recycling Rate (%)	74	38	61
Green Space Coverage (% of city area)	28	22	47

Source: Own elaboration with the help of AI, based on data from C40 Cities (2022), European Environment Agency (2021), and National Environment Agency Singapore (2022).

Regarding economic indicators, results showed that, Singapore leads in economic performance, with the highest GDP per capita and the largest share of digital economy in its overall economic output. The city-state's "Smart Nation" initiative has catalyzed significant investments in digital infrastructure, data analytics capabilities, and innovation ecosystems. Singapore's Economic Development Board has effectively leveraged public-private partnerships to attract global technology companies and nurture local start-ups. Copenhagen demonstrates strong economic performance, with a high innovation index and substantial investments in smart city initiatives. The city's "Copenhagen Solutions Lab" serves as an urban living laboratory, facilitating collaboration between the municipality, businesses, and academic institutions to develop and test innovative solutions for urban challenges.

Madrid shows promising economic indicators but faces challenges in terms of unemployment and digital economy development. The city's "Madrid Digital" strategy aims to address these challenges by enhancing digital skills among residents, supporting technology start-ups, and digitizing public services. These findings are summarized in Table 3 below.

Table 3. Economic Performance Indicators for Selected Cities (2020-2022)

Indicator	Copenhagen	Madrid	Singapore
GDP per Capita (USD)	64.300	43.500	72.800
Smart City Investment (% of Municipal Budget)	8.2	5.5	12.4
Digital Economy Share (% of GDP)	9.5	6.8	16.3
Innovation Index (Score out of 100)	85	76	89
Unemployment Rate (%)	5.2	9.8	3.6

Source: Own elaboration with the help of AI, on data from OECD (2022), European Commission Urban Data Platform (2021), and Singapore Department of Statistics (2022).

Last comparison has been made in taking into account social indicators. According to analysis results Copenhagen very good at in social indicators, particularly in digital inclusion and citizen participation. The city's "Digital Copenhagen" strategy prioritizes universal access to digital services and technologies, with specific initiatives targeting vulnerable populations. Copenhagen's digital participatory budgeting platform enables residents to directly influence municipal spending decisions, fostering a sense of ownership and engagement. Madrid, albeit, has made significant strides in enhancing citizen participation through its "Decide Madrid" platform, which facilitates direct citizen involvement in policy-making and urban planning. However, the city faces challenges in digital inclusion, with disparities in access and skills across different socioeconomic groups. Singapore, similar to others, demonstrates strong performance in quality of life and digital literacy but lags in citizen participation.

The city-state's "Smart Nation" initiative includes comprehensive digital literacy programs and accessible e-government services. However, its top-down governance approach has resulted in lower levels of citizen engagement compared to the European cities. These findings are summarized in Table 4 below.

Table 4. Social Performance Indicators for Selected Cities (2020-2022)

INDICATOR	Copenhagen	Madrid	Singapore
Digital Inclusion Index (Score out of 100)	88	72	81
Citizen Participation Rate (%)	76	65	42
Quality of Life Index (Score out of 100)	92	84	88
Smart Services Satisfaction (%)	85	68	79
Digital Literacy Rate (%)	94	78	87

Source: Own elaboration with the help of AI, based on data from United Nations E-Government Survey (2022), Global Smart City Index (2021), and cities' official reports.

Findings suggest that the effective implementation of smart city initiatives requires a holistic approach that balances technological advancement with governance innovation. The role of institutional capacity and long-term planning emerges as a critical determinant of success.

4.4. Analysis of Successes and Failures - Key Findings

The assessment of the urban transformation initiatives undertaken by Copenhagen, Madrid, and Singapore reveals several critical success factors as well as areas requiring further enhancement:

1. Success factors:
   - effective political leadership coupled with long-term strategic planning (Yigitcanlar & Inkinen, 2019; Nesti, 2018),
   - active citizen engagement and the inclusion of local communities in the decision-making process (Cardullo & Kitchin, 2019; Ojo et al., 2014),
   - innovative financing solutions, which encompass public-private partnerships (Joss et al., 2019; Meijer & Bolívar, 2016),
   - holistic strategies that integrate multiple dimensions of sustainability (Koutitas, 2018; Yigitcanlar et al., 2019).
2. Areas for further improvement:
   - enhancing the monitoring and evaluation processes of implemented solutions (Batty et al., 2012; Ahvenniemi et al., 2017),
   - improving the integration and interoperability of urban technologies (Walravens, 2015; Pereira et al., 2018),
   - adopting a more comprehensive approach to managing organizational and cultural change (Nam & Pardo, 2011; Meijer & Bolívar, 2016),
   - ensuring equitable access to the benefits stemming from urban transformation efforts (Soja, 2010; Anguelovski et al., 2018).

The examination of initiatives implemented by Copenhagen, Madrid, and Singapore reveals several best practices for adapting organizational innovations to achieve urban sustainable development goals. Key factors that have significantly contributed to their success include:

- a comprehensive approach that harmonizes various dimensions of sustainability (environmental, economic, and social) within cohesive urban strategies (Koutitas, 2018; Yigitcanlar et al., 2019),
- strong political leadership, long-term planning, and robust financial models, including public-private partnerships (Joss et al., 2019; Yigitcanlar & Inkinen, 2019),
- active involvement of local communities, fostering citizen participation and inclusivity throughout decision-making processes (Cardullo & Kitchin, 2019; Ojo et al., 2014),

- the integration and interoperability of smart urban technologies designed to support the monitoring, optimization, and enhancement of essential urban systems (Batty et al., 2012; Walravens, 2015).

Simultaneously, the analysis reveals the necessity for further improvements in several key areas:

- adopting a more comprehensive approach to managing organizational and cultural change, which is vital for the successful implementation of innovations (Nam & Pardo, 2011; Meijer & Bolívar, 2016),
- enhancing the monitoring and evaluation processes to assess the effectiveness of implemented solutions, thereby facilitating the continuous improvement of sustainability strategies (Ahvenniemi et al., 2017; Batty et al., 2012),
- ensuring equitable access to the benefits that arise from urban transformation, thus promoting inclusivity and social justice (Soja, 2010; Anguelovski et al., 2018).

In conclusion, the experiences of Copenhagen, Madrid, and Singapore offer valuable insights into best practices and significant challenges associated with aligning organizational innovations with urban sustainable development goals. These findings can serve as essential guidance for other cities striving to enhance intelligence, ecological sustainability, and social responsibility.

5. DISCUSSION

In the analysis of urban transformation through intelligent management and the alignment of organizational innovations with sustainable development goals, Copenhagen, Madrid, and Singapore emerge as exemplary case studies. Each city has adopted distinct strategies that effectively integrate technology, governance, and community engagement, thereby promoting sustainable urban development. This synthesis of elements not only demonstrates the potential for enhanced urban sustainability but also highlights the critical role of local contexts in shaping effective urban policies.

Key discussion points include:

1. Scalability of smart solutions – How can small and mid-sized cities replicate the success of Copenhagen, Madrid, and Singapore?
2. Public-private synergies – Exploring the role of partnerships in financing and implementing smart city initiatives.
3. Ethical and legal considerations – Addressing privacy concerns, data ownership, and equitable access to digital services.

The comparative analysis reveals distinct patterns in the approaches to smart urban management and sustainable development across Copenhagen, Madrid, and Singapore, each reflecting unique contextual factors and strategic priorities. While Copenhagen has embraced a collaborative governance model that facilitates robust partnerships between municipal authorities, business entities, academic institutions, and civil society organisations, creating a multi-stakeholder ecosystem for urban innovation. In contrast, Madrid has developed a participatory governance approach that places significant emphasis on direct citizen engagement and social inclusion mechanisms, democratizing urban development processes. On the other hand, Singapore, employs a more centralized governance structure characterized by strong government leadership and sophisticated inter-agency coordination, enabling rapid and coherent policy implementation.

The technological integration strategies also differ markedly as well. Copenhagen, as the pioneer, prioritizes clean energy technologies and sustainable mobility solutions related with city's environmental objectives; Madrid focuses on developing comprehensive digital platforms that enable citizen inclusion and public service delivery; while Singapore invests heavily in advanced data analytics and artificial intelligence applications that optimize urban management functions. In the context of sustainability frameworks, Copenhagen has initiated a comprehensive strategy focused on attaining carbon neutrality while integrating circular economy principles across its urban systems. This approach reflects a commitment to systematic ecological reform and promotes the interconnection of sustainable practices within the urban landscape. On the other hand, Madrid emphasizes social sustainability dimensions and equitable development across diverse neighborhoods, while Singapore adopts a resource efficiency approach that particularly addresses critical challenges in water management, food security, and land use optimization given its geographical constraints.

Citizen engagement models vary among these cities significantly as well. For instance, Copenhagen and Madrid actively involving residents in co-creating smart city solutions and participatory decision-making processes, whereas Singapore places greater emphasis on ensuring citizen satisfaction with service delivery rather than direct participation in governance structures. The configuration of innovation ecosystems also reflects some distinctions. Copenhagen's ecosystem features heavy public-private-academic partnerships and urban living laboratories for experimentation; Madrid's ecosystem prioritizes social innovation initiatives and community-based approaches to urban challenges; and Singapore's ecosystem is characterized by government-led research and development programmes complemented by strategic international partnerships.

5.1. Guidelines for the Integration of Technology in Socially Responsible Urban Policies

The incorporation of technology within urban policy frameworks necessitates a conscientious approach that prioritises social responsibility. Cities such as Copenhagen, Madrid, and Singapore serve as exemplary models of best practices in this domain. A fundamental guideline involves the adoption of inclusive technological solutions that actively engage all stakeholders, with particular attention to marginalized communities. This objective can be realized through participatory platforms that empower citizens to articulate their needs and concerns, thereby ensuring that technological advancements do not exacerbate pre-existing inequalities (Cardullo & Kitchin, 2019).

Furthermore, it is imperative for cities to establish robust data governance frameworks that safeguard citizen privacy while simultaneously promoting transparency in the utilization of data for urban management. This becomes increasingly salient within the context of smart city initiatives, characterised by extensive data collection procedures. By instituting clear protocols governing data usage, cities can bolster public trust and foster greater community involvement in urban processes (Zuboff, 2019).

5.2. Guidelines The Role of Government, Business, and Civil Society in Promoting Responsible Innovation

The effective transformation of urban environments is contingent upon the collaborative efforts of governments, businesses, and civil society. In Copenhagen, the presence of strong political leadership has proven pivotal in driving sustainable initiatives, exemplified by the city’s ambitious climate action plan that aspires to achieve carbon neutrality by 2025 (City of Copenhagen, 2019). This underscores the significance of governmental commitment in establishing concrete sustainability objectives and allocating requisite resources for their fulfillment.

Businesses play an equally essential role by investing in innovative solutions that resonate with urban sustainability goals. For instance, public-private partnerships in Madrid have facilitated the emergence of smart mobility solutions that enhance urban transport efficiency while mitigating emissions (Ayuntamiento de Madrid, 2019). Moreover, civil society, through grassroots movements and advocacy efforts, acts as a crucial mechanism for holding both governmental and business entities accountable, ensuring that innovations are aligned with the public good and effectively address social challenges (Ojo et al., 2014).

5.3. Future Research Directions in Technology-Driven Urban Responsibility

Future scholarship should concentrate on the long-term implications of technology integration within urban contexts, particularly concerning social equity and environmental sustainability. Research initiatives could examine the efficacy of varied governance models in fostering responsible innovation, enabling comparative analyses across diverse urban landscapes. Additionally, there exists a pressing need to investigate the role of emerging technologies (such as artificial intelligence and blockchain) in enhancing urban resilience and sustainability (Yigitcanlar et al., 2019).

Another salient avenue for future inquiry pertains to the assessment of citizen engagement strategies within smart city initiatives. Understanding the interactions of different demographic groups with technology can yield critical insights for the design of more inclusive urban policies (Albert et al., 2012). Moreover, interdisciplinary approaches that integrate urban studies, technological advancements, and social sciences will be paramount in addressing the multifaceted challenges associated with urban transformation.

The findings presented herein emphasize the paramount significance of context-specific methodologies in smart urban management, which must meticulously consider local priorities, governance traditions, and socio-economic conditions. The varied experiences of cities such as Copenhagen, Madrid, and Singapore compellingly illustrate that a singular universal model for smart urban transformation is untenable. Instead, there exist multiple viable pathways, each intricately shaped by distinct local circumstances and strategic priorities.

6. CONCLUSION

Urban centers globally are confronting a myriad of interconnected challenges, including but not limited to population expansion, resource depletion, environmental degradation, and socioeconomic disparities. Conventional urban management strategies frequently prove inadequate in providing holistic and integrated solutions to these multifaceted problems. Consequently, there is an urgent imperative to explore the strategic utilization of organisational innovation as a means to cultivate sustainable, resilient, and habitable communities. Understanding the mechanisms through which cities can effectively leverage such innovations is essential for developing comprehensive responses to their evolving challenges.

6.1. Key Insights into the Role of Technology in Fostering Socially Responsible Urban Environments

The examination of smart city initiatives in Copenhagen, Madrid, and Singapore elucidates the critical role that technology plays in the development of socially responsible urban environments. Each city exemplifies the capacity of technological integration to enhance urban governance, improve service delivery, and promote sustainability. For instance, Copenhagen’s deployment of data analytics to optimize public transportation systems and mitigate carbon emissions serves as a compelling case study of how technology can contribute directly to environmental sustainability objectives (City of Copenhagen, 2019). In a similar vein, Madrid's adoption of smart mobility solutions underscores the significance of technological innovation in addressing pressing urban mobility challenges while simultaneously enhancing accessibility for all citizens (Ayuntamiento de Madrid, 2019).

Furthermore, Singapore's Smart Nation initiative exemplifies the necessity for a holistic approach that actively incorporates citizen engagement in technological advancements. By prioritizing digital literacy and facilitating public participation, Singapore endeavors to ensure that its smart city solutions are inclusive and equitable (www.gov.sg, 2025). These cases collectively highlight that the application of technology in urban contexts should not be solely driven by efficiency but must also prioritize the enhancement of social equity, thereby ensuring that all members of the community can benefit from urban innovations.

6.2. Summary of Strategies for Further Development

In the pursuit of advancing smart city initiatives, urban centers can adopt several strategic approaches derived from the analysis presented:

1. Strengthening public-private partnerships – the enhancement of collaborative relationships between governmental entities and private sectors is instrumental in accelerating the development and deployment of smart technologies. These partnerships can effectively harness diverse resources, expertise, and innovative capacities to address complex urban challenges (Marx, A., 2019).
2. Enhancing citizen engagement – meaningful citizen involvement in the planning and implementation of smart city projects is imperative for their success. This involvement can be facilitated through participatory platforms that enable feedback and co-creation, ensuring that the developed solutions align with the needs and aspirations of the community (Boulton et al., 2020).
3. Focusing on data governance – the establishment of robust frameworks for data governance is critical in safeguarding citizens’ privacy and fostering trust in smart technologies. By promoting transparency in data utilisation and articulating clear policies regarding data collection, municipalities can enhance public confidence and encourage active participation in smart city initiatives (Zuboff, 2019).
4. Promoting environmental sustainability – incorporating sustainability as a fundamental aspect of smart city strategies is essential for ensuring long-term viability. Initiatives that prioritize renewable

energy, waste reduction, and efficient resource management should be at the forefront of urban planning efforts (Batty et al., 2012).

5. Investing in education and training – to empower all citizens to participate in the digital economy, urban centers must invest in educational programmes that enhance digital literacy and equip the workforce to meet the challenges posed by a technology-driven landscape (Yigitcanlar et al., 2019).

In conclusion, the transformation of urban spaces through the intelligent management of resources and organisational innovation is not only feasible but also essential for achieving sustainable urban development. By adopting a comprehensive approach that prioritizes social responsibility, cities can effectively leverage technology to foster inclusive, resilient, and sustainable urban environments.

In this study, we tried to compare three pioneer cities that engage in application of organizational management approached which emphasized innovative city solutions. The comparisons made according to environmental, economic and social indicators. Although both cities may be called as already smartly developed results demonstrate particular differences. Future studies may involve comparisons with late-smart adapted cities and results may be more divergent.

6.3. Summary of Limitations of the Study

There are several limitations of this study which should be addressed for a more comprehensive analysis and to develop the study further. First of all, there are several methodological constraints of the study. This study relies on secondary data rather than primary ones which relatively limits the depth of insights into some actual implementation challenges and some other organizational dynamics. This, the usage of the case approach, albeit fitting to the purpose of this research, prevented researchers from establishing direct causal relationships between organizational innovations and sustainability outcomes.

Regarding the sample, since three high-performing, well-resourced cities (i.e., Copenhagen, Madrid, and Singapore) were selected, this sample may be assumed to lack representing the diversity of urban contexts globally, particularly those in developing economies. Concerning this, we claim that the research would benefit from more direct engagement with diverse stakeholders, such as citizens, geographically dispersed municipal officials, and business leaders, to capture their lived experiences with smart city initiatives. However, there is limited analysis of how different population segments (such as the elderly, low-income communities, minorities, persons with disabilities, etc.) perceive and interact with smart city technologies. Thus, this point of view could be added for further future research as well.

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THE USE OF AI IN SME's MANAGEMENT IN THE EU COHESION POLICY ON THE EXAMPLE OF POLAND

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ABSTRACT

Purpose: *The aim of the article is to assess the place of artificial intelligence and intelligent management in the assumptions of cohesion policy programs supporting the development of innovation in Poland in 2021-2027.*

Need for the study: *The dimension of innovation evolves with the passage of time and technological progress. In the context of EU programmes, including the tools planned in Poland for 2021-2027, there are still no clear references to artificial intelligence and its clear inclusion in the logic of the designed support instruments.*

Methodology: *The article contains theoretical considerations on the role and nature of innovation in the modern economy, with particular emphasis on artificial intelligence. Next, an analysis was made of the planned support for the sphere R+D+I in Poland in the 2021-2027 budget perspective, with particular emphasis on innovations implemented by the SME sector.*

Findings: *Support for SMEs in the area of R+D+I must assume not only direct assistance to companies, but also complementary support, e.g. for research institutions, and assume complementarity of investments in material resources and human competences. Artificial intelligence is mainly a tool and a carrier of innovation.*

Practical Implications: *Innovations towards Industry 4.0, which are to contribute to increasing the competitiveness of EU companies, must be implemented in a logical and systematic way. Companies will be more willing to reach for aid funds in the area of R+D+I, the greater their knowledge and awareness in this area, and at the same time the greater the effectiveness of the activities of the institutions involved in this process.*

Keywords: artificial intelligence; intelligent management; industry 4.0; innovations; cohesion policy; competitiveness of SMEs; structural funds; European Regional Development Fund

Jel codes: O31; O32; M10

1. INTRODUCTION

Innovation is one of the top priorities of the European Union. Their role is to develop and increase the competitiveness of regions, and probably the most serious beneficiary of support is a group of enterprises from the SME sector. They are the foundation of modern economies, both at the national and regional level.

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The dimension of innovation changes with the passing of the years and technological progress, which is why its nature and main indicators of innovation also change. On the other hand, an important element of innovation is the sphere of research and development R+D, which also evolves along with the development of civilization. Collectively, it can be described as R+D+I.

Recent years have undoubtedly been the time of the realization of the idea of the Industry 4.0 era and, consequently, artificial intelligence, which is increasingly present in the economic and management spheres. It is more and more often appearing as an important element of innovation and the key to the competitiveness of enterprises.

Support for the SME sector has become one of the most important tools for the development and improvement of the competitiveness of EU regions, and the European Regional Development Fund has become the basic instrument for supporting this sector, mainly in the area of investment and innovation.

The article presents how the planned support for the sphere of innovation and research and development is shaped in the 2021-2027 budget perspective on the example of Poland, with particular emphasis on innovations implemented by the SME sector. The article also includes case studies of selected projects that dealt with artificial intelligence and intelligent management.

The background of the analysis is the evaluation of the effects of the Innovative Development Operational Programme, implemented in the 2014-2020 budget perspective.

The article also contains an attempt to answer the question of what is the place of artificial intelligence and intelligent management in the assumptions of programs supporting the development of innovation under the cohesion policy.

2. LITERATURE REVIEW

The development and competitiveness of regions is one of the most important areas of intervention of the European Union's structural funds. In turn, the most important beneficiaries of this intervention are SMEs, which are the backbone of modern economies, both at national and regional level. Increasing the competitiveness of enterprises from the SME sector has become one of the most important priorities mentioned in strategic documents both at the EU level and at the national and regional level. Support for the SME sector has become one of the most important tools for the development and competitiveness of EU regions, and the European Regional Development Fund has become the basic instrument for supporting this sector, mainly in the area of investment and innovation (Poteralski, 2023, p.170).

Regional policy is an important element of Poland's socio-economic policy. The aim of regional policy is to create the competitiveness of regions and to counteract the marginalisation of certain areas in such a way as to foster the long-term economic development of the country, its economic, social and territorial cohesion and integration with the European Union. Regional policy is an increasingly important area of public intervention, and aid for SMEs is part of it. The SME sector is one of the main factors in the competitiveness of regions and their economic growth rate. It is important to include it among the development priorities when planning regional policy activities (Stachowiak & Pyciński S., 2001, p. 7).

In the EU structural policy, in the context of increasing the economic cohesion of the Community regions, their competitiveness is indicated, both in terms of current diagnoses, conditioning the directions of using financial support, as well as in the perspective of expectations as to its image in the future. This competitiveness can be considered both at the national and regional level, as well as at the level of individual institutions or economic entities, including those from the SME sector (Poteralski, 2023, p. 171)

In order to assess the place of Polish in the EU as a country that is supposed to increase its innovativeness, several indicators have been adopted, in the EU considered important from the point of view of the assessment of innovation of EU member states. Out of 9 factors listed by the Innovation European Scoreboard, four can be selected, considered the most important. These include:

- expenditure on research and development (as a relation to the global gross product);
- expenditure on innovative activities, not classified as research and development activities (in relation to GDP);

- share of innovative small and medium-sized enterprises cooperating with other entities in the total number of innovative enterprises;
- export of products with a medium and high level of technology to the total export of a given country (Różański, 2020, p. 19).

The basis for financing the company's development activities is still equity. On the other hand, companies, looking for an additional source of financing, usually reach for an investment loan or try to obtain subsidies from structural funds (Kotowicz, 2008, p.14)

Support for micro, small or medium-sized enterprises refers to the allocation of subsidies to the company, in particular for innovative and investment activities, which in principle should have a positive impact on the development of the company by introducing a new or significantly changed method of production or provision of services (Rydzewska, 2009, p. 122).

It should be emphasized that support for an enterprise under the EU structural funds can take various forms, such as specialist advice, support from business environment institutions, subsidies for starting a business, but undoubtedly the most emotional are those activities under operational programs that are based on direct support for investments undertaken in the SME sector (Poteralski, 2023a, p. 129).

In knowledge-based economies, competitiveness increasingly depends on the ability to apply existing knowledge and technologies to products and production technologies. In order to build its innovation, the segment of small and medium-sized enterprises must use external sources in relation to: information, knowledge, know-how and technology. In order to be able to effectively use the opportunities offered by innovation, it is necessary to create a framework in which innovative activities are modelled and initiated (Kurowska, 2009, p. 199).

It is well known that research and development, new technologies and innovations are the main determinants of the market success of a company. Innovations require large financial outlays to conduct research and development works, which are additionally burdened with a significant degree of risk. Companies from the SME sector have limited possibilities of equipping laboratories, hence their research activity should be carried out in the outsourcing formula. In addition, these companies require the support of the institutional, economic and scientific environment (Szewczuk-Stępień, 2016, p.99).

Innovation and advanced technologies are today the basis for the development of both the largest global economies and individual dynamically developing enterprises. They are often associated with significant capital expenditures and large corporations, but in the modern economy, small and medium-sized enterprises play a huge role in their creation and dissemination. Their undoubted advantages are entrepreneurial dynamism, flexibility and involvement in implemented innovative projects (Kurowska, 2009, p. 198).

Economic theory gives innovation a leading role in creating economic growth. For several years, they have been an increasingly important subject of scientific research, as well as the object of practical activities aimed at their wider use to achieve goals important for societies and enterprises. This increase in interest in innovation is due to its strong impact on the overall economic and social development. Awareness of the role of innovation in solving important global problems also guides activities aimed at better and better organization and management of innovation processes on a macro- and microscale (Pietras & Głodek, 2011, p. 8).

Enterprises from the SME sector, trying to develop, must first of all invest, especially in pro-development activities, which is to allow them to oppose foreign competition. SMEs in Poland have a problem with obtaining funds for the purchase of innovative solutions. Investments of this type are burdened with high risk, so banks, fearing for the result of the project and the repayment of liabilities incurred, are not willing to lend money for them. EU funds are an opportunity, at least partially, to improve the situation in this area. They are to increase the innovativeness of Polish enterprises from the SME sector, and thus increase their competitiveness, which will increase the dynamics of the country's economic development (Jankiewicz, 2009, pp. 610-611).

One of the concepts of the modern economy is the concept of electronic economy, defined by the following 12 features: (1) it is based on knowledge, (2) it is based on cyber technologies, (3) it is characterized by the displacement of analog technologies by digital technologies, which in turn causes the virtualization of physical objects, transactions and, more and more often, economic entities, (4) it is an economy of molecules (molecules), (5) it is a network economy, in which the main communication channel is the Internet, (6) is characterized by the widespread use of computer networks, which eliminates intermediaries and intermediate functions in the processes of economic exchange, (7) is

characterized by a progressive correlation of various, often completely unrelated areas of the economy, (8) is based on innovation, (9) is characterized by the disappearance of the division into producers and consumers, (10) is based on real-time action, which is a key factor determining the possibility of market success (11), is a global economy (12), and operates in a world in which an era of anxiety and threat is dawning (Stawiarska, 2018, pp. 108-109).

One of the most characteristic features of the electronic economy is the disappearance of the barrier between people and machines (replacing people with machines). Digitalization is believed to be the foundation and driving force behind the fourth technological revolution. The name Industry 4.0 first appeared in 2011. It concerns flexible production in the era of knowledge-based economy. Its main idea – smart factory – assumes that in the future, thanks to modern technologies, consumers will be able to receive personalized products from factories, m.in, but this will not increase production costs (Stawiarska, 2018, p. 109).

Industry 4.0 has been hailed as the "fourth industrial revolution" that combines advances in the smart factory with cyber-physical systems that connect people, machines and other devices simultaneously and in real time. According to the European Commission, the fourth revolution involves the physical, digital and biological spheres as well as new technologies related to the entire value chain. The evolution of such technologies related to Industry 4.0 is a real challenge for industrial policy formulation, especially since it implies the reallocation of production factors and new labor force dynamics; It also creates social and economic divisions in regional and international terms. Dynamic technological changes force decision-makers to make decisions aimed at creating conditions for the development of enterprises (Gródek-Szostak, Niemczyk, Niewiadomski & Zamora, 2022, pp. 87-88).

Industry 4.0 is revolutionizing the production and delivery of goods and services through the interconnectedness of products, processes, and consumers. It is characterized by the use of many new technologies, such as: the Internet of Things, artificial intelligence, cloud computing, autonomous robots, sensors. Complementing these technologies, Big Data and Blockchain are being implemented to provide better digital services (Gródek- Szostak, et al., 2022, p. 87).

The digital age requires constant development and innovation. In this context, EU funding for IT opens up new opportunities for the technology industry. These funds are aimed not only at supporting the day-to-day operations of IT companies, but above all at enabling research and implementation of advanced technologies such as artificial intelligence (AI). Thanks to EU funding, companies can accelerate their projects, explore new ideas and pursue ambitious goals that could remain a dream without external financial support (www.innology.pro).

The development of AI is not just the next step in technological evolution – it is a breakthrough that could define the future of many sectors. Grants for the development of AI are a key element of the European Union's strategy to stimulate innovation and increase the competitiveness of the European economy. By funding AI-related projects, the EU wants to encourage companies to experiment and implement solutions that can bring about revolutionary changes in the way they do business, manage data and interact with customers. This gives IT companies the opportunity not only to develop their own products, but also to introduce innovations that can contribute to the sustainable development of society and the economy (www.innology.pro).

It should be emphasized that the introduction and use of modern technologies by small enterprises requires not only technical knowledge. They face great challenges in terms of knowledge of economic, legal, market issues and management competences. In addition, in order to build and maintain their innovation capacity, small and medium-sized enterprises need the right environment in which they can obtain the resources and information they need. An important role in building such an environment is played by the state and support institutions (Kurowska, 2009, p. 198).

Technological transformation has become a requirement of the modern world and a condition for the survival of enterprises and their competitiveness. Companies that want to survive must be ready to adapt to the new digital landscape. The transformation process is not only related to focusing on the technology itself and modernizing the machine park, but is a kind of action strategy consisting in transforming materials, activities and processes into digital versions using, among others, AI. This is also the basis for the transformation of the business model (Bielińska-Dusza, 2022, p. 193).

Business is entering a new "digital normal" where competitive advantages are gained by carefully observing these phenomena, and constantly inventing new connections and building new business models from them using AI. In business, especially those from the SME sector, there is a lack of

knowledge, time and resources for networking with the use of ICT/AI. According to the respondents, the role of the State, the European Commission and international organizations such as the WTO is to create and implement digitization programs. There must be money for this purpose in budgets (Stawiarska, 2018, p. 115).

EU IT subsidies for the development of artificial intelligence are not only a financial injection for enterprises, but also an opportunity to gain a significant competitive advantage. With these funds, companies can invest in research and development, which translates into innovation in products and services. The implementation of AI projects with the use of EU funding allows for the exploration of new technological areas, process automation and personalization of the offer, which directly increases attractiveness and added value for customers.

The introduction of advanced AI solutions allows companies not only to optimize internal processes, but also to open up to new markets and customer segments. Investments in AI with the use of EU subsidies are becoming a catalyst for the creation of unique technologies that are difficult to find on the market, which strengthens the position of the innovation leader. As a result, IT companies gain not only in terms of efficiency and cost savings, but also build a solid brand, associated with modernity and advanced technology (www.innology.pro).

AI systems can support the innovation of activities, which can be important especially in SME companies and reduce waste and costs, and thus increase operational efficiency. The socio-economic and legal aspect will also be important. Certainly, such solutions will limit employment and cause liability for risky activities that is difficult to legally identify. Nevertheless, the fourth technological revolution Industry 4.0 is becoming a fact, in which robotization and automation as well as AI models are taking up more and more areas of activity. Modern business processes, and above all their management, are changing their structural nature using the creativity of AI solutions (Krystian & Zaskórski, 2023, p.136)

Entrepreneurs using European funds to invest in advanced technologies such as artificial intelligence are an excellent example of a strategic allocation of resources that can revolutionise the activities of companies, significantly increasing their innovation potential and competitiveness on an international scale. Funding for technological development, including advanced AI algorithms and IoT applications, not only improves companies' operational processes and products, but also gives them a competitive edge in a rapidly evolving economic environment. Support for European funds can enable companies to overcome technological and financial barriers, leading to the implementation of innovative products that effectively respond to market needs. This allows companies not only to respond effectively to current challenges, but also to actively shape future trends in their industries (Solecki & Kobis, 2024, p. 76).

Modern information and communication technologies, and in particular artificial intelligence, determine the potential of modern organizations and the possibilities of improving business processes. The need to use and implement modern solutions and technologies in areas such as marketing, production, logistics or recruitment processes confirm the legitimacy of using AI technology. The challenge is to connect AI to existing business procedures and systems. This may require an appropriate approach to change management, as well as a lot of time and resources (Krystian & Zaskórski, 2023, pp.149-150)

3. METHODOLOGY

In order to assess the role of artificial intelligence and smart governance in the EU cohesion policy on the example of Polish, the content of strategic and policy documents oriented towards this goal was analysed. For the 2014-2020 budget perspective and its summary, the content of the Smart Growth Operational Programme and the evaluation report assessing the material progress and results of this programme were analysed.

In order to indicate the main priorities of the EU cohesion policy in Poland, focused on supporting smart management and AI in SMEs, an analysis of the Partnership Agreement for 2021-2027 and the content of two key documents was carried out: European Funds for Modern Economy and Detailed Description of the Priorities of the European Funds for Modern Economy Programme.

In order to show the practical aspect and indicate several case studies for projects implemented by SMEs, the database for 947 projects published on the FENG website was analyzed. The database was as of 02.03.2025.

Of the 947 records in the project database, 575 records were analysed that corresponded to the objective of 'Developing and strengthening research and innovation capacities and the use of advanced technologies'. An additional factor determining the selection of projects for the analysis was compliance with the following forms of support: "Research and innovation activities in SMEs, including networking" and "Research and innovation activities in micro-enterprises, including networking (industrial research, experimental development, feasibility studies). There were 270 projects in the first category, and 51 in the second category, which gives a total of 321 projects. The article presents examples of 10 projects, the specificity of which clearly referred to the use of AI tools in business management or in the implementation of its processes.

4. RESULTS

In Poland, since the accession to the EU, support under the structural funds has been implemented in 3 budget perspectives, namely 2004-2006, 2007-2013 and 2014-2020.
Preparations for each of them were accompanied by the development of a number of strategic documents and programs, which included analyses of the most important areas of socio-economic problems, as well as, with the exception of the 2004-2006 perspective, the evaluation of programs implemented in previous periods.

This was also the case during the preparations for the 2021-2027 perspective, when the effectiveness of support instruments from the 2014-2020 period was analyzed.

In the years 2014-2020, the most important operational programmes in which the areas of support were the B+R sphere and investment support for enterprises in the field of innovation were the Smart Growth Operational Programme managed at the national level and 16 Regional Operational Programmes managed and implemented at the voivodeship level.

The diagnosed challenge facing Poland in the 2014-2020 perspective was the low level of innovation in the economy. The related imitative model of development created the risk of slowing down the pace of economic growth and entering the path of development drift related to the phenomenon of the "middle-income trap". In order to further reduce the development gap between Poland and highly developed EU countries, it was necessary to take measures to stimulate the growth of economic innovation, which was to lead to maintaining a high growth rate of labour productivity (Ośka, 2022, pp. 7-8)

The relatively low level of innovation in Poland before the launch of the Smart Growth Operational Programme was indicated by the European Innovation Scoreboard rankings from 2015. Poland has been classified as an emerging innovator along with several other countries in Central and Eastern Europe. Despite a clear upward trend, the indicators related to R+D activities, including expenditures on R+D and employment, were still at a relatively low level. In addition, their structure was unfavorable, with a low share of the private sector in research and development activities. The structure of revenues of industrial enterprises was dominated by low- and medium-technology products, and the share of sales of new and significantly improved products was small. The scope of cooperation between enterprises and scientific units, as well as with other enterprises and business environment institutions in the field of R+D+I was also described as unsatisfactory.

The Smart Growth Operational Programme was divided into 4 main Priority Axes and 2 supplementary Axes, constituting Technical Assistance and support elements increasing the potential of enterprises and preparing for digital transformation in the context of the COVID-19 pandemic. Table 1 presents the characteristics of the Priority Axes of the programme.

Table 1. Priority axes of the Smart Economy Operational Programme in 2014-2020

Priority axis I **Support for R+D work by enterprises**
• Priority axis focused on supporting R+D projects carried out by enterprises. • Only in the case of SMEs (does not apply to large enterprises), in addition to research and development works, the implementation of the results of these works may be an element of the project, while the implementation component must constitute a minority of the total eligible expenditure of the project. • Support is directed only to areas identified as smart specialisations and potential new specialisations resulting from the entrepreneurial discovery process, which is part of the monitoring of the National Smart Specialisation (KIS). • The aim of the axis is to finance R+D projects, from the research phase to the development phase, with particular emphasis on the demonstration phase. The direct effect of the implementation of the axis should be the transfer of the developed innovative solution to business activity, understood in particular as the preparation of new products, services or technologies to the extent enabling the commercialization of the results of research and development works.
Priority Axis II **Support for the environment and potential of enterprises to conduct R+D+I activities (research, development, innovation)**
• The specific objective of the axis formulated as: "Increased potential of enterprises to conduct R+D+I activities" • Support under the axis of projects implemented throughout the country, taking into account specific conditions regarding the development of the environment and the potential of enterprises to conduct innovative activities. • The instruments of the axis are aimed at supporting both services offered by the business environment, conducive to R+D+I activities, and stimulating cooperation between various actors of the national innovation system (enterprises, scientific units, business environment institutions and administration). Therefore, under Axis II, support instruments addressed directly to innovative enterprises, implemented in a competitive mode, as well as systemic instruments, the beneficiaries of which will be public administration units and other entities participating in shaping innovation policy, promoting R+D+I activities and supporting enterprises and scientific units in this area, have been included. • Support is directed only to areas identified as smart specialisations and potential new specialisations resulting from the entrepreneurial discovery process as part of the monitoring of the National Information System. • Financing directed towards the provision of services to enterprises (in particular SMEs) by entities already operating on the market (in accordance with the demand-side support model). In addition, the activities of BEIs should be more subject to competitive mechanisms and enable self-financing of these entities.
Priority axis III **Support for innovation in enterprises**
• The first specific objective of the axis is formulated as "Increased financing of innovative activities of SMEs using risk capital" • Final support addressed to enterprises that implement innovative projects, including those related to the implementation of the results of B+R works. These projects are primarily of an investment nature, as they are related to the commercialization of the results of R+D works. • Within the priority axis, it is assumed that activities aimed at the use of financial instruments, mainly of a shareholding nature, addressed to SMEs (in particular start-ups) will be implemented. • Equity instruments, as a special form of repayable financing, provide an additional element of support, related to access to the investor's network of business contacts, his specialist knowledge and experience, which are particularly important for novice entrepreneurs. Another specific objective of the axis formulated as: "Increased activity of enterprises in the field of conducting innovative activities"; • The support is addressed to enterprises from the SME sector in order to finance the implementation of the results of R+D works, which are a key element of transforming knowledge into new products, services and technologies. Depending on the level of risk occurring in the implementation projects, support will be provided with the use of grants, financial instruments or forms of financing combining financial instruments with grants.
Priority Axis IV **Increasing scientific and research potential**
• Specific objective defined as "Increased level of market exploitation of scientific research results"

- Support targeted only at areas identified as national smart specialisations or regional smart specialisations. The support provided under axis IV of the Smart Growth Operational Programme is focused on research and development projects carried out by scientific units, enterprises and consortia of these entities. These projects are aimed at increasing knowledge resources in areas that are both considered priority for the development of Polish science and important for the Polish economy.
- Projects co-financed under the axis should also serve to consolidate the potential of scientific units, so that as a result of the implementation of the programme, Polish science has stronger, recognizable scientific units in the EU and in the world. Achieving such effects requires investing in scientists - in research teams, in which researchers from foreign centres also participate.

Source: own elaboration based on: Smart Growth Operational Programme for 2014-2020, Ministry of Development Funds and Regional Policy, Warsaw 2022 (version valid from 07.11.2022), pp. 42-138.

As the table shows, the support instruments in the B+R sphere were diverse and covered both enterprises, including SMEs, as well as scientific and research institutions. It is worth noting that there was a strong emphasis on the so-called smart specialisations, which were characterised by a national dimension, but also had a regional reference. From the point of view of the objectives of this article, it is worth analyzing the main areas of research and development work carried out in this period.

Table 2 presents the most important areas of research and development work, taking into account the National Smart Specializations. The analysis concerns the period of implementation of the Smart Growth Operational Programme, implemented in the years 2014-2020.

Table 2. Areas of R+D work carried out, including NSS* in the SG OP** in Poland in 2014-2020

National Smart Specialization	Number of R+D works within the NSS	Percentage share in the NSS
NSS 10: Smart ICT and Geoinformation Networks and Technologies	542	16%
NSS 1: A healthy society	505	15%
NSS 11: Automation and robotics of technological processes	402	12%
NSS 2: Innovative technologies, processes and products of the agri-food and forest-wood sectors	306	9%
NSS 7: Circular economy	293	8%
NSS 6: Environmentally friendly transport solutions	273	8%
NSS 12: Intelligent creative technologies	272	8%
NSS 4: High-efficiency, low-emission and integrated energy generation, storage, transmission and distribution systems	238	7%
NSS 8: Multifunctional materials and composites with advanced properties, including nanoprocesses and nanoproducts	182	5%
NSS 9: Electronica and Photonics	169	5%
NSS 5: Smart and energy-efficient construction	141	4%
NSS 3: Biotechnological and chemical processes, bioproducts and products of specialty chemicals and environmental engineering	89	3%
NSS 13: Innovative maritime technologies in the field of specialized vessels, marine and coastal structures and logistics based on maritime and inland waterway transport	53	2%

* National Smart Specialisations (NSS)
** (projects under Priority Axis I and IV of the Smart Growth Operational Programme)
Source: own elaboration based on: Ośka M., (2022), Evaluation summarizing the material progress and results of the SG OP and assessment of the impact of the SG OP on the innovativeness of the Polish economy, including the impact on the implementation of the objectives of the Europe 2020 Strategy, IDEA, Imapp Consulting, Scientific Foundation Institute for Structural Research, PAG Uniconsult, Serock-Warsaw 2022, pp. 71-73.

The analysis of the data contained in the table shows that the largest share was characterized by scientific and research work within the three National Smart Specializations. These included Smart Networks and ICT, Healthy Society, and Automation and Robotics of Technological Processes.

Based on the above data, it is difficult to clearly indicate which of the specializations directly related to the involvement of artificial intelligence, as it is not directly mentioned in the characteristics of the specialization, but it is possible to indicate a certain distribution of the beneficiaries' interest in specific areas. All of them are susceptible to innovation, including projects related to the involvement and use of artificial intelligence. It is also possible to indicate smart specializations of relatively general importance, as well as industry-oriented ones, for example, on energy distribution, electronics, construction, environmental engineering, or finally innovations in maritime technologies.

Finally, at the threshold of the 2021-2027 perspective, after the implementation of the Smart Growth Operational Programme, the following recommendations were formulated, the main addressee of which was to be the Managing Authority of the European Funds for Modern Economy (FENG):

- launching calls for projects for the implementation of innovations, including the possibility of obtaining support for the initial investment, as part of the FENG;
- research conclusions indicate that the implemented support model was correct, but it must still be continued, but in such a way as to favor financing projects with high innovative potential. Public funds in FENG should be directed towards further increase in innovation. The above means that the previous recommendation cannot overshadow the main challenge (especially in the medium and long term), which is the need for development based on ambitious projects based on high innovation. Such an approach should be fully universalised in instruments where support is transferred on a non-repayable basis. Exceptions to this rule must be applied with great prudence;
- in the continuation of the SG OP Guarantee Fund, provided for in the FENG programme, in the path intended for innovative companies, it is necessary to precisely determine what will be the subjective criteria entitling to apply for a guarantee, interest subsidy and capital surcharge, in such a way that non-repayable instruments are intended (only or primarily) for the most innovative companies (...). Alternatively, you should also consider preferences for the smallest companies (probably micro and small companies);
- within the framework of FENG, as a rule, and unless the economic situation undergoes fundamental, negative changes, special emphasis should be placed on the obligatory creation of new jobs, possibly outside selected projects, with an emphasis on their creation, for example, in the field of research and development (Ośka, 2022, pp. 184-189).

The shape of the recommendations was significantly influenced by adverse external factors, such as the war in Ukraine, the energy crisis, high inflation and the growing risk of economic recession. Especially in the first years of implementation of the European Funds for Modern Economy programme, they may have an adverse impact on the readiness of enterprises to implement investments, including reducing the willingness to engage funds in riskier ventures related to R+D activities and innovation (Ośka, 2022, pp. 32-33).

The course of implementation of operational programs in the 2014-2020 perspective and their evaluation were used to develop strategic assumptions for the years 2021-2027. The most important document conditioning the use of structural funds in Poland in this period is the Partnership Agreement. The document contains a synthesis of analyses of the most important problem areas in the socio-economic area in the country and individual regions and selects instruments to support these areas in the form of operational programmes.

The implementation of the assumptions of the cohesion policy, presented in the Partnership Agreement, will be carried out by means of national and regional programmes. They form a coherent

system of programming documents of the cohesion policy in the 2021-2027 perspective. In these years, Poland will implement activities under all 5 main objectives of the cohesion policy.

The key area of economic modernization, which in the coming decades will determine the possibility of Poland's civilizational breakthrough, is the implementation of solutions identified with the process of the "fourth industrial revolution" (also referred to as "Industry 4.0"), while increasing the quality and potential of human capital to function in the world of modern technologies. Ultimately, it is people – and not even the most intelligent machines – who will determine the success of the necessary restructuring of our economy leading to the building of competitive advantages based on the effective implementation of product and process innovations. (Partnership Agreement, 2022, p.7)

On the threshold of the implementation of the next EU financial perspective, it is crucial from the point of view of the active socio-economic policy of the state to overcome the country's backwardness in terms of the development of high-tech and creative industries, the importance of which will determine the development opportunities of countries and regions in the coming decades. Completion of the construction of broadband network infrastructure, digitization of the economy, administration, services is a condition for further development (Partnership Agreement, 2022, p.8)

Main objectives of cohesion policy for 2021-2027

- PO1: A more competitive and smarter Europe by promoting innovative and smart economic transformation;
- PO2: A greener, low-carbon Europe;
- PO3: A more connected Europe;
- PO4: A Europe with a stronger social dimension;
- PO5: A Europe closer to its citizens;
- PO6: Enable regions and populations to mitigate the social, employment, economic and environmental impacts of the transition towards the Union's 2030 energy and climate targets and towards a climate-neutral Union economy by 2050 based on the Paris Agreement. (Partnership Agreement, 2022, p. 2).

Therefore, the most important objective of cohesion policy in the perspective of this study turns out to be PO1. Its most important assumptions are presented in Table 3.

Table 3. Characteristics of PO1 in 2021-2027

PO1 **A more competitive and smarter Europe by promoting innovative and smart economic transformation**
The main goal in the context of Polish: increasing the productivity of the Polish economy. This process requires parallel action on four complementary levels: • increasing the supply and use of modern technological solutions in all sectors of the economy, with particular emphasis on the development and application of digital and green economy solutions; • modern organization of business activities; • development of competences of employees, management and users, thanks to which physical capital will be properly used; • building and modernising broadband infrastructure to enable the digital transformation of the economy. Technological progress, process and organisational innovation and new business models, growth and updating of competences, and universal access to broadband Internet should complement each other. Three areas: • increasing the importance of research and innovation in the economic structure of the country and the use of advanced technologies; • strengthening the potential of enterprises and public administration for a modern economy; • strengthening digital connectivity. As a rule, the first area will include support for enterprises that already have some potential to conduct innovative activities, while the second area – by supporting production investments, but also the development of competences and supporting business environment services – primarily concerns building the innovative potential of enterprises, in particular those that have not yet conducted innovative activities (or have conducted them to a very limited extent).

Due to the lower productivity of small and medium-sized enterprises compared to large ones, support (especially in the second area) will be focused primarily on SMEs. Supporting the financing of R+D works, implementation of innovation and digitization of SMEs, as well as strengthening competences in the field of modern economy are activities that should contribute to increasing the productivity of SMEs in particular to the greatest extent.
Area two:
The modern economy is associated with the introduction of new business models by entrepreneurs that meet the challenges of digital and green transformation. It will increasingly operate on the basis of digital technologies and new business models in line with the trends described as the 4th industrial revolution, and it is also important to accelerate automation and robotization processes. Global trends related to digitization and a new approach to data, including cybersecurity issues, require a change in the operating model both on the part of enterprises and in the public sector.

Source: own elaboration based on: Partnership Agreement for the Implementation of the Cohesion Policy 2021-2027 in Poland, Ministry of Development Funds and Regional Policy, Warsaw, 30 June 2022, pp. 10-16.

From the perspective of the objectives of this article, the following areas of support for the innovative economy under the 2021-2027 perspective should be included in the following areas under the PO1 objective:

- Increasing the importance of research and innovation in the economic structure of the country and the use of advanced technologies;
- Strengthening the potential of enterprises and public administration for the modern economy.

In the area of "Increasing the importance of research and innovation in the economic structure of the country and the use of advanced technologies", it is necessary to support all stages of innovation creation, in particular in connection with the objectives identified in the smart specialisation strategy.

The key elements of this process include:

- support for conducting R+D activities by enterprises and consortia with their participation;
- support for technology transfer and implementation of R+D results and the supply of ready-to-transfer R+D solutions;
- support for R+D infrastructure, in particular in enterprises;
- support for the development of exports of innovative products.

At the same time, it should be emphasized that complementary Support for innovation of enterprises may be accompanied, depending on the needs, by support for the development of competences of their employees in connection with the objectives of the smart specialization strategy, in particular for the needs of industrial, green and digital transformation, which will allow for the comprehensive implementation of innovation processes. It is important to stress that it is necessary to continue to support the innovation activities of companies of all sizes and at all stages of their development, as each of them plays an important and different role in the innovation ecosystem, both of start-ups (including start-ups), SMEs and large enterprises as leaders of value and production chains in which SME actors are involved. The intervention implemented under PO1 should be comprehensive and adapted to both the needs of the recipient and the rapidly changing economic reality.

Between 2021 and 2027, the assumption is to continue the entrepreneurial discovery process for smart specialization, allowing for the concentration of resources in areas and technologies with potentially the highest social and economic return on investment. At the same time, further efforts are needed to develop effective mechanisms for involvement in the entrepreneurial process of discovering entrepreneurs, coordination of two levels of the process: national and regional, as well as increasing the interdisciplinarity of research and implementation projects (Partnership Agreement, 2022, p. 89-91).

In turn, under the area "Strengthening the potential of enterprises and public administration for the benefit of modern economy", support for the following exemplary types of activities is planned:

- digital transformation of the economy, consisting in particular in the implementation of programs stimulating the introduction of digital solutions in enterprises and the public sector;
- investments in SMEs, in particular to increase their technological advancement, robotisation and capacity to innovate, in particular in the field of Industry 4.0 solutions and green technologies;
- stimulating demand for innovation from businesses, especially SMEs and society;

- increasing the internationalisation of the company in connection with the objectives identified in the smart specialisation strategy, including increasing the ability of enterprises to create products and services with high added value, with high export potential, searching for and acquiring new products and changing the business model;
- support for the development of services for enterprises (including in the field of digitization and Industry 4.0 solutions), development of the potential of selected innovation centers, including Artificial Intelligence Technological Testing and Experimentation Centers, further professionalization and networking of business environment institutions and others;
- development of competences and skills of entrepreneurs, managers and employees necessary for the modern economy, in particular in the field of increasing the technological readiness of R+D projects, commercialization of R+D, new technologies, digital skills and management of innovations and new business models (Partnership Agreement, 2022, pp. 92-93).

Among the above-mentioned areas of support and types of actions taken, the one that concerns the digital transformation of the economy, consisting in particular in the implementation of programs stimulating the introduction of digital solutions in enterprises and the public sector, deserves special attention. In this respect, the following selected objectives can be indicated:

- transformation of Polish enterprises towards Industry 4.0, in particular automation, robotization, the use of the Internet of Things and digitization of enterprises, digitization of export processes;
- development of data-based economy and algorithmic solutions using machine learning and artificial intelligence techniques;
- increasing the supply, quality and usability of public sector e-services (including support for projects in the field of e-government and e-health, among others) while ensuring their integrated nature, interoperability and full online capability;
- digitization and increasing the availability of public data, as well as digital resources with significant potential for re-use, at the disposal of public and private sector entities;
- support for the development of innovative solutions in the area of cybersecurity in various sectors of the economy, development of tools for collecting, analyzing and exchanging information on threats, vulnerabilities and incidents (...), construction and development of the national cybersecurity certification system for products, services and processes;
- support for scalable modern IT and technological solutions as part of cross-sectoral cooperation, including in particular public administration, entrepreneurs and research organizations (Partnership Agreement, 2022, p. 92).

Also in this area, the need for complementary activities relating to the improvement of digital competences of employees of public sector institutions, including employees of local government units, is noticed.

As in the area of increasing importance of research and innovation, the possibility of implementing modular projects, i.e. including both investments and appropriate support for competence creation, taking into account the individual needs of beneficiaries, should be of key importance in the construction of support instruments.

The assumptions of the cohesion policy oriented towards AI tools and their application in business management, presented in strategic and programming documents, must ultimately translate into specific projects and undertakings carried out by entrepreneurs. Their development needs, resulting from the company's strategy and vision, must be in line with the program guidelines and assumptions of the cohesion policy. In the case of such compliance, which is the result of an assessment carried out by experts evaluating applications for funding, specific projects are implemented. Below we will present case studies for projects included in the list of beneficiaries of the European Funds for Modern Economy programme for 2021-2027. Table 4 provides examples of projects implemented by SMEs, while Table 5 contains case studies for micro-enterprises.

Table 4. Examples of projects implemented by SMEs (excluding micro-enterprises)

Specific objective: Developing and strengthening research and innovation capacities and using advanced technologies	
Support Category: Research and innovation activities in SMEs, including networking	
Case 1 (record No 205)	
Project description	The subject of the project is the implementation of R+D work to develop a process innovation to improve and automate the process of preparing influencer marketing campaigns, taking into account the client's brief and optimizing costs through the use of AI. The innovation will enable automatic analysis of data from the client's brief and the selection of influencers in accordance with objective criteria, which will ensure the highest effectiveness of activities compared to the effects of human work. Artificial intelligence (AI) can significantly increase the objectivity of the data analysis process and the selection of influencers.
Project value [PLN]	4 396 354,82
EU support [PLN]	2 947 883,12
Case 2 (record No 449)	
Project description	The project concerns R+D works leading to the design and preparation for the launch of technologies supporting sales in online stores specializing in clothing trade. The developed solutions will respond to the most important needs of the target group, i.e. enabling the ability to try on clothes remotely, in a way that is as close as possible to the experience in a brick-and-mortar store – thanks to the use of generative AI. The project includes industrial research and development work. As part of industrial research, optimal solutions will be sought and new knowledge will be developed to develop innovative technologies and algorithms to bring these functionalities to market. The development work will allow for implementation and integration in practice and validation of the developed solutions in conditions similar to real ones.
Project value [PLN]	3 013 635,00
EU support [PLN]	2 248 150,00
Case 3 (record No 111)	
Project description	The project is carried out in partnership between co.brick and the Institute of Theoretical and Applied Computer Science of the Polish Academy of Sciences in Gliwice. The subject of the project is to develop a technology that will enable the automation of processes related to the technical maintenance of applications and providing customer support, offering, m.in, inference from various data related to the operation and development of the application, incident detection, causal analysis of problems, and natural language interaction with users. The solution will be dedicated to IT startups that create and maintain applications as containerized solutions in the Software as a Service model. The solution addresses a specific market problem. Thanks to the project, startups will be able to focus on innovation and product development, instead of technical and operational problems. The main research challenges of the project include the development of methods for specialized inference from various types of data, analysis of the causality of detected problems, modeling of specific aspects of application behavior and a wide set of issues related to processing and interaction in natural language.
Project value [PLN]	10 142 554,32
EU support [PLN]	7 933 656,20

Case 4 (record No 194)	
Project description	The aim of the project is to develop an innovative platform for active and intelligent management of Contact Millennium business processes on an international market. The product will use advanced machine learning methods to create and optimize business processes, using natural language and a digital twin approach based on assumptions to map real processes. The system will enable the improvement of business processes, from their definition, through modeling, simulations, to the launch of production processes. The product will be addressed in particular to micro, small and medium-sized enterprises.
Project value [PLN]	9 993 987,62
EU support [PLN]	7 511 714,98
Case 5 (record No 120)	
Project description	The aim of the project is to develop an innovative technology for prototyping and manufacturing a new generation of reusable tools for precision forging using an AI-based inference system supported by 3D scanning techniques and virtual reality VR. The proposed solution is an innovation in the business process that will ensure the intelligent and fast production of high-performance, reusable forging tools used on hydraulic breakers. First, the concept assumes increasing the durability of tools, and then designing an innovative system for analyzing wear and prototyping their regeneration operations.
Project value [PLN]	16 062 777,66
EU support [PLN]	11 436 056,05

Source: own elaboration based on: List of projects implemented with FENG 2021-2027. As of 2 March 2025, http:// www.nowoczesnagospodarka.gov.pl (access: 22.04.2025).

The examples of projects presented in the table concern research and development activities in the field of implementation of artificial intelligence instruments, mainly in the area of business management. These are mainly process-based innovations that can be used in many companies, increasing the efficiency of management, as well as their competitiveness on the market. It can be seen that the subject of innovation is the management of customer relationship management processes, data management and sales process improvements. In the latter case, the use of artificial intelligence refers strictly to the production process in the engineering dimension.

Table 5. Examples of projects implemented by micro-enterprises

Specific objective:	
Developing and strengthening research and innovation capacities and using advanced technologies	
Support Category:	
Research and innovation activities in micro-enterprises, including networking (industrial research, experimental development, feasibility studies)	
Case 1 (record No 199)	
Project description	The aim of the project is to develop the Organization Map platform with the PROMOTION ANALYTICS module enabling the prediction of employee promotion based on employment data and information on interactions between employees. As a result of the project, a new, innovative module of this Platform will be developed, which, through the use of artificial intelligence methods, will predict the probability of employee promotion based on employment data and data on cooperation events and interactions. The main element of the solution will be algorithms for automatic and intelligent diagnosis of critical moments in the employee development process, as well as signals indicating the employee's promotion or development (e.g. shifts in the subordinate-supervisor hierarchy and development on the managerial path, changes in the salary level, shifts in the expert hierarchy). The algorithm will be created using the latest graph solutions of artificial intelligence, machine learning and deep learning.

Project value [PLN]	2 331 490,00
EU support [PLN]	1 563 150,00

Case 2 (record No 262)	
Project description	The aim of the project is to create an AI-based tool that will enable automatic and standardized product specifications in online stores of the electronics industry. This will make it easier for companies and consumers to compare products. The standard specification format will include product information, units of measurement, and data format. As part of the project, new data processing methods will be automated, which will allow for the creation of intelligent content. Such content must be structured, semantically categorized, automatically searchable, reusable, reconfigured, and adaptable.
Project value [PLN]	6 823 075,00
EU support [PLN]	4 638 396,00

Case 3 (record No 193)	
Project description	The project aims to develop artificial intelligence (AI) algorithms and software that enable the identification of key words and sentences in the dialogues of competence test participants and their assessment against different competences. The applicant's previous work focused on VR (Virtual Reality) technology for conducting professional, social and psychological competence tests. As part of the project, the new software will be integrated with the IT tool "Salomon", which uses virtual reality technology to research and develop competences. The software will analyse the dialogues of the research participants, identify key words and sentences, and then present them to the assessors along with an assessment proposal.
Project value [PLN]	10 195 724,00
EU support [PLN]	7 033 990,00

Case 4 (record No 139)	
Project description	The aim of the project is to develop a tool – based on artificial intelligence (AI) and machine learning (ML) methods – to monitor and improve the work of the Glivia chatbot, which will contribute to automating this process and reducing its costs. The solution developed as part of the R+D work will have functionalities that are not found in any available tool, such as: the ability to detect incorrect answers given by the chatbot and the ability to suggest additions and corrections in its knowledge base. The recipient of the project results will primarily be the Applicant's company, but since it will result in faster improvement of the Glivia chatbot, the users of this product will also benefit from this innovation. In addition, due to the growing popularity of chatbot technologies, a tool that automates the processes of monitoring and diagnosing chatbot conversations is very desirable on the market and can find a wider audience.
Project value [PLN]	851 586,24
EU support [PLN]	634 863,00

Case 5 (record No 328)	
Project description	The subject of the project is to develop a flexible and universal method for generating text and image data of high quality and reliability for the purpose of building commercial solutions based on machine learning (ML). The product resulting from the project will have the form of a web platform with an API interface and will be implemented for sale by Causality. The solution will be offered in the first place to entities creating software based on artificial intelligence (AI), including ML. It will allow them to expand their customer base and speed up the process of creating this type of software. The universal nature of the product will allow it to be used to create solutions for any industry, but in particular it will be useful in areas requiring very high effectiveness (e.g. medicine, finance, industry) and in the event of problems with the availability/quality of training data.
Project value [PLN]	10 052 632,00

EU support [PLN]	7 223 363,75

Source: own elaboration based on: List of projects implemented with FENG 2021-2027. As of 2 March 2025, http:// www.nowoczesnagospodarka.gov.pl (access: 22.04.2025).

As the table shows, these smallest enterprises also benefit from the support of the EU cohesion policy for projects aimed at developing and implementing AI in business management. Micro-enterprises are also involved in creating tools that support smart management and use artificial intelligence, not only for the needs of specific companies, but also suitable for use by a wider audience. To sum up, it can be said that the scope of projects related to the use of artificial intelligence in management is very wide. Examples of projects presented in the article concerned not only processes closely related to the specificity of a specific industry or supporting processes taking place on the Internet, but also, for example, areas related to human resources management, employee promotion, recruitment, etc.

5. DISCUSSION

Innovations, which have always been the subject of support for the EU cohesion policy, have changed their character, just as the economic reality, dictated by technological and civilizational development, has changed its character. Recent years have marked the era of Industry 4.0 with the increasingly visible and dominant presence of artificial intelligence.

Innovation also plays an extremely important role in shaping the competitiveness of enterprises, regions, countries, and thus has become a permanent element of the European Union's intervention under the cohesion policy.

Since its accession to the EU, Poland has been implementing a policy of increasing the competitiveness of enterprises and regions through innovation. This took place in the following EU budget periods: 2004-2006, 2007-2013, 2014-2020 and currently 2021-2027.

The term "artificial intelligence" does not appear very often in the Partnership Agreement for 2021-2027, which is the most important strategic document conditioning the use of structural funds in Poland in this period. It appears mainly in contexts related to the sphere of research, development and innovation. The sphere of R+D+I is therefore becoming an environment in which it is possible to carry out research and development work, also on artificial intelligence. Its presence in this area is obvious and it can be counted on that projects in this area will be supported by the EU structural funds. In this context, artificial intelligence seems to be not so much an end in itself as a tool and carrier of innovation.

Analyzing the assumptions of strategic documents for the cohesion policy in Poland for 2021-2021 in relation to the competitiveness of the SME sector, innovation and artificial intelligence, the following conclusions can be drawn regarding the directions of support for the economy operating under the Industry 4.0 model with a growing share of artificial intelligence:

- to strive to increase the supply and use of modern technological solutions in all sectors of the economy, while putting emphasis on modern management, the development of employee competences and the construction and modernization of broadband infrastructure enabling the digital transformation of the economy;
- to ensure complementarity between technological progress, process and organisational innovation, new business models, updating competences and universal access to broadband internet;
- research and innovation in the economic fabric and the use of modern technologies must be increased, and support must be given to all stages of innovation;
- business environment services should be supported;
- in the context of SMEs, the financing of R+D, the implementation of innovation and the digitalisation of companies should be supported, but at every stage of their life cycle;
- new business models should meet the challenges of digital and green transformation, accelerate automation and robotization processes;
- the entrepreneurial discovery process for smart specialisations should continue, allowing resources to be concentrated in areas and technologies with potentially the highest social and economic return on investment;

- at the level of national innovation policy objectives, coherence and complementarity of support at national and regional level should be ensured;
- it should be easier for companies to implement investments, in particular those increasing their technological advancement, the level of robotization and the ability to implement innovations;
- the transformation of Polish enterprises should take place towards Industry 4.0, in particular automation, robotization, the use of the Internet of Things and the digitization of enterprises.

6. CONCLUSION

As the presented cases show, entrepreneurs benefit from support for the use of artificial intelligence in company management. The assumptions of the cohesion policy presented in strategic and programme documents are reflected in specific projects implemented by companies from the SME sector, including the smallest entities, i.e. micro-enterprises.

Thanks to the implementation of projects, it is possible to increase the efficiency of management and implementation of processes in the company, which increases the competitiveness of enterprises not only at the national but also at the international level.

Sample projects show that not only tools are created to support the management and implementation of processes at the level of a specific company, but also universal tools that can be adapted to a larger number of enterprises.

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AUTOMATION OF TRANSPORT ANALYSIS USING GEOGRAPHIC INFORMATION SYSTEM (GIS) TOOLS FOR INTELLIGENT LOGISTICS NETWORK MANAGEMENT

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ABSTRACT

Purpose: *This study aims to highlight how GIS can enhance spatial data processing and transport optimization, thereby significantly improving the efficiency of logistics systems. Moreover, it explores the potential of integrating AI to coordinate and automate the use of multiple GIS-based models, supporting intelligent management by enabling transport accessibility analyses.*

Need for the study: *The growing complexity of logistics networks requires intelligent management tools that can process spatial data efficiently and adapt to dynamic transport conditions. There is a need for automated solutions that enhance the speed and accuracy of transport accessibility analyses, especially for intermodal infrastructure planning.*

Methodology: *This paper presents the automation of transport accessibility analysis of intermodal terminals using the Model Builder (MB) tool of ArcGIS Pro software. The study is based on spatial data, including terminal locations and road and rail networks in Poland and Germany. The approach allows for the efficient processing of large data sets and dynamic optimization of transport, considering customizable decision support models.*

Findings: *The results of the research demonstrated the effectiveness of the applied GIS tool in automating the assessment of transport accessibility. The approach allowed faster and more accurate data processing and identification of accessibility to intermodal terminals.*

Practical Implications: *The research can support decision-making processes in developing transport infrastructure and helping improve logistics systems' efficiency. Additionally, the potential integration of AI with GIS enables the creation of more flexible, customized decision-support models.*

Keywords: artificial intelligence (AI); Geographic Information System (GIS); intermodal terminals; intermodal transport; logistics optimization tools; transport accessibility

Jel codes: L91; R41; R42

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1. INTRODUCTION

Standardization and development of combined modes of transport enable the fullest use of individual transport solutions' advantages while minimizing their less favorable elements. The basic example of the aforementioned combined transport is intermodal transport, the importance of which, as indicated by UIRR data, fell in 2023 (-10.57% compared to 2022) to pre-Covid levels (UIRR - International Union for Road-Rail Combined Transport - Annual Reports, n.d.). In studies focusing on the issue of competitiveness and the level of development of intermodal transport, one of the reasons for the small share of this form of transport is, among others, Coverage area in the sense of infrastructure coverage and access to transshipment terminals (Arendt, 2020; Bonk, 2023; Colicchia et al., 2017; Makarova et al., 2020; Rožić et al., 2016; Wichser et al., 2006; Wiśnicki et al., 2017). In more recent publications, in order to address the problems of low use of intermodal transport, some authors are beginning to move away from intermodal models (both in their advanced and basic forms) when planning transport in favor of synchromodal models, in which planning takes place in real-time, as opposed to standard models that assume planning more or less in advance (Zanjirani Farahani et al., 2023). This approach is intended to improve the quality and efficiency of intermodal transport and, in theory, to better counteract uncertainty (Giusti et al., 2019; Tavasszy et al., 2017). However, the multitude of available models and the level of complexity and integration used require specialist knowledge and the ability to match the right solution, which may pose a challenge from the point of view of smaller companies or legislators (Agamez-Arias & Moyano-Fuentes, 2017; Agbo & Zhang, 2017; Fan, 2013; Zanjirani Farahani et al., 2023). At the same time, in practical application in the scope of investments or building transport policy, the advantage of the speed of action is no longer of such high value. Hence, the model selection must be made individually depending on the case being developed. In the case of this article, a customizable model created using GIS based on the transport accessibility of intermodal transshipment terminals was adopted as the basis for a broader model (Horner & Grubesic, 2001; Márton et al., 2019; Pekin et al., 2013; Petrović et al., 2019). The developed model, in accordance with the basic assumptions of models created using GIS tools, is to constitute a decision support model (DDS). At the same time, in the assumption of the authors' concept, the built model can be supported using currently available AI solutions. (Flodén et al., 2017). This type of support can take two forms: coordination of activities or process support. In this case, process support should be understood as the extension of basic component models with AI functions, while coordination should be understood as the performance by the AI expert algorithm of the supervisory function of smaller models based on geographic information, also assuming the function of a link between subsystems and the user.

2. LITERATURE REVIEW

Since the basis of the constructed model is the argument for the accessibility of intermodal transshipment terminals, in the classic literature review, it was decided to focus on the above issue and the approach of various authors to this topic. The issue of optimizing transport and logistics networks, methods of analyzing the accessibility of transshipment terminals, and methods of optimizing and automating this process (accessibility analysis) were taken into account. The Scopus database was adopted as the basic database of texts, the entries: "intermodal terminal" alone and with the additions "GIS", "accessibility" and "transport". The time period between 2020 and 2025 and the languages English and Polish were adopted. 369 articles were selected (with duplicates), and after the selection of titles and keywords, 73 items remained after re-verification, reduced to 54. After assessing the abstracts and the method of accessing the content, 19 articles were selected for the final review and the result is presented in Table 1.

Table 1. A literature review of intermodal terminals accessibility in current studies

References	Approach	Description
(Abbasi et al., 2024)	Model	Focus on disruptions to the transport network. This mainly refers to port terminals and the congestion that occurs there, which negatively affects the operation of international transport. The above indicates the problem of accessibility (bottleneck and optimization).
(Ivankova et al., 2022)	Descriptive, diagrams	Indicates problems with the creation and modernization of infrastructure. It indicates the high necessity of creating transshipment infrastructure near waterways and railways. In summary, the article focuses on increasing accessibility in the form of proximity to road infrastructure and an appropriate layout together with the possibility of expanding the terminal.
(Gnap et al., 2021)	Model	Focus on the accessibility of the infrastructure network. The research was conducted on data obtained from the Sustainable urban mobility plan of Žilina, and the accessibility study was based on the method of finding the shortest path. The negative impact of accidents and congestion on road infrastructure, as well as the importance of locating terminals near the network covered by the European Agreement on Important International Combined Transport Lines and Related Installations (AGTC), were highlighted.
(Gnap et al., 2020)	Classical mathematical methods	The authors point out that the accessibility of terminals is the most important factor from the point of view of the transport service client. The focus of the article is concentrated around the accessibility of Slovak terminals to large transshipment ports in central and southern Europe. The authors analyze the distance and time of transport, pointing out that the presence of two drivers in road transport can be faster than rail transport.
(Taheri & Tamannaei, 2023)	Model	The authors perform a multi-criteria analysis based on the first phase of a genetic algorithm. They pay particular attention to the cost level.
(Badyal et al., 2023)	Model	The developed two-phase stochastic model of the location of intermodal terminals is presented using the Case Study of the South Carolina region (U.S.A.) due to the negative impact of external factors causing disruptions in the functioning of transport terminals. The authors indicate the need to introduce tactical and operational plans to counteract emerging transport disruptions and their negative impact on costs.
(Delgado et al., 2021)	Model	The article focuses on the imbalance in the development and access to road infrastructure and the optimization of the method of selecting locations and transshipment points, taking into account unit transport costs. Portugal and its rail and road infrastructure networks were selected as the Case Study.
(Oudani, 2021)	Model	The focus was on the optimization of the total transport cost and the cost of building the terminal. The optimization of mathematical methods and the use of the CPLEX tool were proposed. The authors indicated the future nature of their work in the field of using other methods with a potential case study.
(Tadic et al., 2021)	Model	Two variants of the presented model (Location-allocation model) were used to check variants for different types of container flows. The focus was on the Southeastern Europe region and Dry-port terminals. The applied model focuses on the cost of cargo transportation and terminal construction and operation.
(Oudani, 2020)	Model	Two fuzzy models of the Intermodal Terminal Location problem are presented. The presented models are distinguished by taking into account the uncertainty of the number of rail links and the number of terminals.

References	Approach	Description
(Stoilova et al., 2020)	Model	The article focuses on the Orient–East Med corridor of the TEN-T network, using multi-criteria decision-making by applying the Sequential Interactive Modeling for Urban Systems (SIMUS). The research takes into account the number and accessibility of terminals, GDP per capita, the length of the rail infrastructure network, and the passenger and freight flows of rail transport.
(Kubáňová et al., 2020)	Descriptive	The article focuses on the advantages and disadvantages of intermodal transport, its evolution, and the role of intermodal transshipment terminals. Cost efficiency and ecological considerations are indicated as advantages, and risk management and coordination are presented as the most important disadvantages.
(Isler et al., 2021)	Case Study, GIS Modelling	The article focuses on the creation of a geo-strategic railway network for freight services in the Santa Catarina region in Brazil. The authors indicate the proximity of terminals to linear infrastructure and production plants as the most important component of building efficient transport networks.
(Jacyna-Gołda et al., 2024)	Graph theory, Mathematical analysis	The authors focused on trade between Poland and Ukraine, while the method used aims to show the possibilities of minimizing the cost of transportation services and time.
(Zanjirani Farahani et al., 2023)	Model	Solutions such as an advanced intermodal service network model (AI-SNM) were proposed to support the development of intermodal (synchromodal) transport networks. The models used are multi-criteria and take into account many variables, which allows for the holistic optimization of the transport process. Service time was given as the factor of the highest importance in relation to the final result of the calculations created. The authors suggest modifying existing intermodal networks in the U.S.A. in order to adapt the concept of synchromodality.
(Nehring et al., 2023)	Mathematical analysis	The Multi-criteria assessment method was used to analyze the efficiency and optimization of transport. The results obtained indicated the most effective variant of carrying out the transport process, assuming the lowest environmental burden for a given Case Study.
(Todorov et al., 2022)	Mathematical analysis	The paper employs a combination of mathematical modeling, numerical algorithms, and cost analysis to determine the optimal placement of intermodal terminals, focusing on energy efficiency and operational costs. The basic conclusions lead to the fact that the optimal placement of terminals increases energy efficiency and reduces the total cost.
(Dai & Yang, 2020)	Model	The focus was on economic and environmental issues, as well as the trade-offs between them in order to optimize the existing transport network. For the purpose of the developed model, the authors adopted the case study of the Yangtze River Economic Belt in China. The authors of the study, based on the achieved results, indicate as an important issue that "there is competition in hybrid intermodal transportation alternatives, rather than the only competition in unimodal and single intermodal options in most intermodal transport research articles" (Dai & Yang, 2020, p.15).
(Batarlienė & Šakalys, 2020)	Mathematical analysis	The article focuses on the issues of accessibility, cooperation, and synchronization within the existing transport network, the East-West Transport Corridor (EWTC), in the southern part of the Baltic Sea Region (BSR) corridor. The authors also draw on the flexibility of the concept of synchromodality, emphasizing the technical and technological factors influencing this concept. The authors indicate the rail transport infrastructure, road transport infrastructure, accessibility to Moscow ports, and accessibility to rail transshipment infrastructure as the most important factors influencing the quality of synchronization within the intermodal transport network.

Source: own elaboration.

The authors agree on the importance of locating transshipment terminals near both road and rail infrastructure as one of the most important determinants of the quality of the transport and logistics network built with the assumption of using intermodal transport. In the case of designating a specific location in a node's network, such as a transshipment terminal, most of the articles accepted for the literature review focus on presenting some type of model that assumes a multi-criteria form. Some authors draw attention to the need to optimize the created system (transport and logistics network) and simultaneously create medium- and long-term plans containing many possible variants of functioning. The above plans and proper optimization of the network are necessary due to the possibility of reducing the negative impact of transport on the environment and social environment (noise, congestion, pollution, etc.) indicated in the articles, the minimization of which is a priority of the current EU transport policy. At the same time, some authors suggest that the elements of optimization and lack of coordination are among the most significant disadvantages of current intermodal transport chains, which even more confirms the importance of these elements in the construction of effective transport and logistics networks. Quite often, in selected literature, the issue of accessibility also appears in relation to the proximity or even direct cooperation of land terminals with existing seaports. This is justified when focusing on freight flows in the scope of transport networks and corridors because large volumes of transport are generated within seaports, which are the gateway for intercontinental transport. Some authors in their studies also try to address the topic of external threats and risk management, which extends the criteria of the developed models to issues related to uncertainty. On the other hand, several articles address the issue of synchromodality, a topic that seems to be a certain emerging trend. Analyzing the available materials, it was decided that in the model presented for the purposes of this article, the most important issue from the point of view of the literature review, i.e. accessibility to road and rail infrastructure, should be addressed.

3. METHODOLOGY

3.1. Overview of the Study Area

Transshipment terminals used in intermodal transport are a key element of an infrastructure hub. In Poland, 42 terminals were active in 2025, of which 6 were container terminals in seaports, and 36 were land terminals serving rail-road connections (Fig. 1). It is worth adding that the terminal in Szczecin also serves inland waterway transport (Urząd Transportu Kolejowego (UTK), 2025).

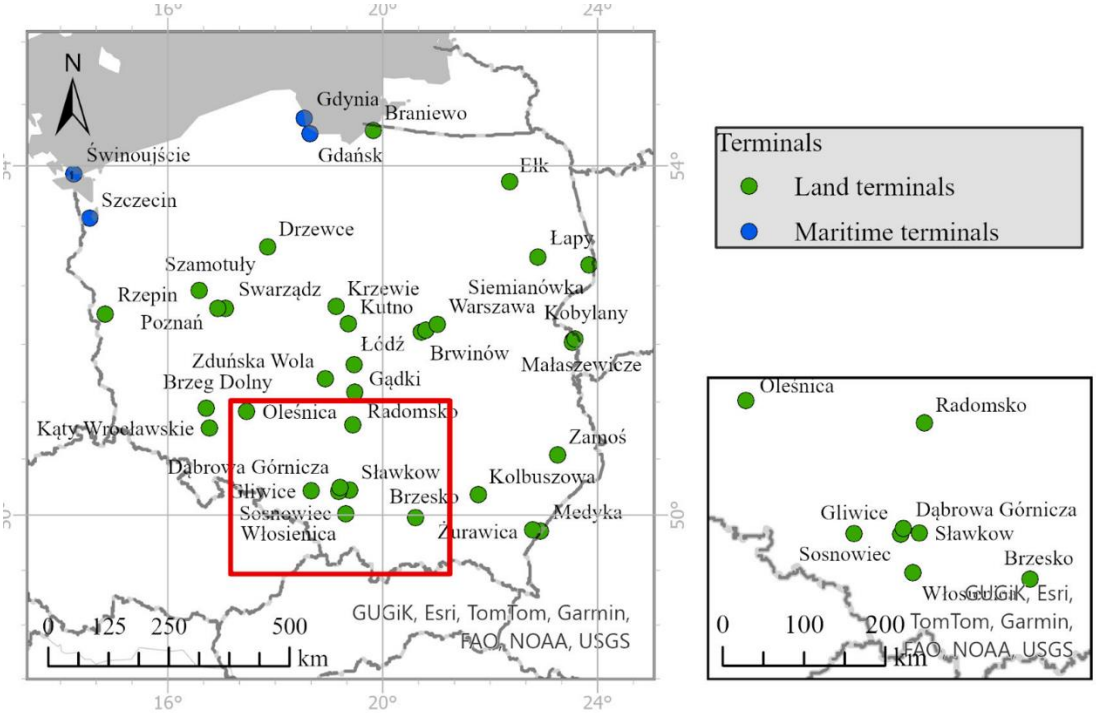


Figure 1. Map of intermodal transport terminals in Poland
Source: own elaboration based on: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html (accessed: 04.03.2025).

Terminal density is a critical factor when considering both accessibility and its impact on the route extension indicator, the value of which influences transport time and cost, particularly in comparison to road-only transport. In Poland, there are 2.23 intermodal terminals for every 1,000 km of railway lines and 1.30 terminals per 10,000 m² of the country's area (see tab. 2). It should be noted, however, that more than one terminal operates in seven locations. Specifically, there are two terminals in six locations (Gdańsk, Gdynia, Warsaw, Łódź, Radomsko, Gliwice) and four terminals in one location (Małaszewicze). Consequently, when considering the number of locations, the terminal density in Poland is 1.76 per 1,000 km of railway lines and 1.02 per 10,000 km² of the country's area. Compared to other EU countries, Poland exhibits a relatively low terminal density, as reflected in the number of terminals per 10,000 km². In one country (Finland), the indicator is below 1, in nine countries (including Poland) it ranges from 1 to 2, in eleven countries it ranges from 2 to 5, and in six countries, it exceeds 5 (International Union of Railways (UIC), 2020).

An uneven distribution characterizes the spatial location of intermodal terminals in Poland. In the northern part of Poland, apart from seaports and the terminal in Braniewo, which was opened in 2017, there are no transshipment terminals. Additionally, there are no terminals in the Kuyavian-Pomeranian, Opole, and Świętokrzyskie Voivodeships, which may significantly limit the potential for socio-economic development of these regions.

Table 1. Number and density of terminals in Poland in 2025 by voivodeship

Voivodeship	Number of terminals	Localities	Terminal density	
			Per 1,000 km of railway lines	Per 10,000 km²
Lower Silesian	3	3	1,76	1,50
Kuyavian-Pomeranian	0	0	0,00	0,00
Lublin	6	3	6,67	2,40
Lubusz	1	1	1,11	0,71
Łódź	6	4	5,45	3,33
Lesser Poland	2	2	2,00	1,33
Masovian	3	2	1,76	0,86
Opole	0	0	0,00	0,00
Subcarpathian	1	1	1,11	0,56
Podlaskie	2	2	2,86	2,86
Pomeranian	4	2	3,33	2,22
Silesian	6	5	3,16	5,00
Świętokrzyskie	0	0	0,00	0,00
Warmian-Masurian	2	2	1,82	0,83
Greater Poland	4	4	2,11	1,33
West Pomeranian	2	2	1,67	0,87
Poland	**42**	**33**	**2,23**	**1,30**

Source: own elaboration based on: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html (accessed: 04.03.2025).

The highest concentration of intermodal terminals is found in the Pomeranian, Silesian, and Lublin Voivodeships. This distribution is primarily influenced by the presence of Poland's largest seaports (Pomeranian), a border crossing serving as a strategic hub for east-west trade (Małaszewicze in the Lublin Voivodeship), and the dense network of the AGTC corridors, alongside the intersection of two TEN-T corridors in the Silesian Voivodeship (Kowalska, 2024).

3.2. Research Methodology

Geographic Information Systems (GIS) serve as a fundamental tool in spatial analysis, enabling the creation, integration, processing, and modeling of geographic data (Attah et al., 2024; Gura et al., 2024; Jebur, 2021; Kłos-Adamkiewicz et al., 2024; Raihan, 2023). In the context of intelligent management and transport accessibility research, the Model Builder (MB) environment within the ArcGIS Pro software (ver. 3.3.2) has been applied.

MB is a visual programming tool for creating geoprocessing workflows, enabling the automation of complex analytical processes. The parameterization of spatial analyses minimizes the risk of human error and optimizes the use of computational resources. The automation of geoprocessing tasks within MB enhances spatial analysis, increases their reproducibility, and supports data-driven decision-making based on geospatial information. The automation of complex spatial analyses is achieved by combining multiple GIS operations into a single data processing sequence. Models are created and presented as diagrams that link sequences of processes and geoprocessing tools, where the output data of one process serves as input data for the subsequent process (Al-Khudhairy et al., 2025; ESRI, 2025).

By utilizing MB, processes related to transport accessibility assessment, road network analysis, and route optimization can be performed iteratively and at a large scale, minimizing time consumption and the risk of manual errors. Such automation enhances the efficiency of transport management by dynamically modeling traffic flows, identifying infrastructure bottlenecks, and analyzing alternatives for the location of new transport hubs. As a result, MB supports strategic decision-making in transport planning, allowing for rapid adaptation of analyses to changing spatial conditions, ultimately impacting stakeholders' decisions in the transport services market (Jiménez-Perálvarez et al., 2009; Zhang, 2012).

Intermodal terminals are key nodes in the logistics supply chain, and their ability to function is determined by access to infrastructure for various modes of transport. Research indicates that the development and operation of intermodal terminals largely depend on high-quality infrastructure, strategic location, and effective integration of different transport modes while also considering the environmental impact and the requirements of stakeholders (Ližbetin, 2019; Sarder, 2020; Tadić et al., 2019).

Given the significant role of road and rail transport in the modal split, this study focuses on the linear infrastructure associated with these two transport sectors. The primary objective was to analyze the accessibility of intermodal terminals in Poland and Germany for road and rail transport. Specifically, the study aimed to assess the spatial reach of terminal services provided by both modes of transport and to evaluate the degree of integration between road and rail infrastructure and the respective transshipment points.

To evaluate road transport accessibility, the study utilized the Network Analyst (NA) tool in ArcGIS software. This tool employs a network-based approach, allowing for supply chain modeling, analysis, and optimization. It enables the assessment of accessibility based on the actual structure of the transport network and applies graph theory algorithms, particularly Dijkstra's algorithm, to determine the shortest or fastest path between points in the network (Audu et al., 2021; Wang et al., 2021). In the context of analyzing the accessibility of intermodal terminals in Poland and Germany, this tool enabled the determination of the spatial coverage of terminal services provided by road transport.

Figure 2 illustrates the structure of the developed model, which depicts the process of determining the areas served by the terminals in the context of the existing transport network, as well as segments of the road and rail transport networks within a 50 km radius of the terminals.

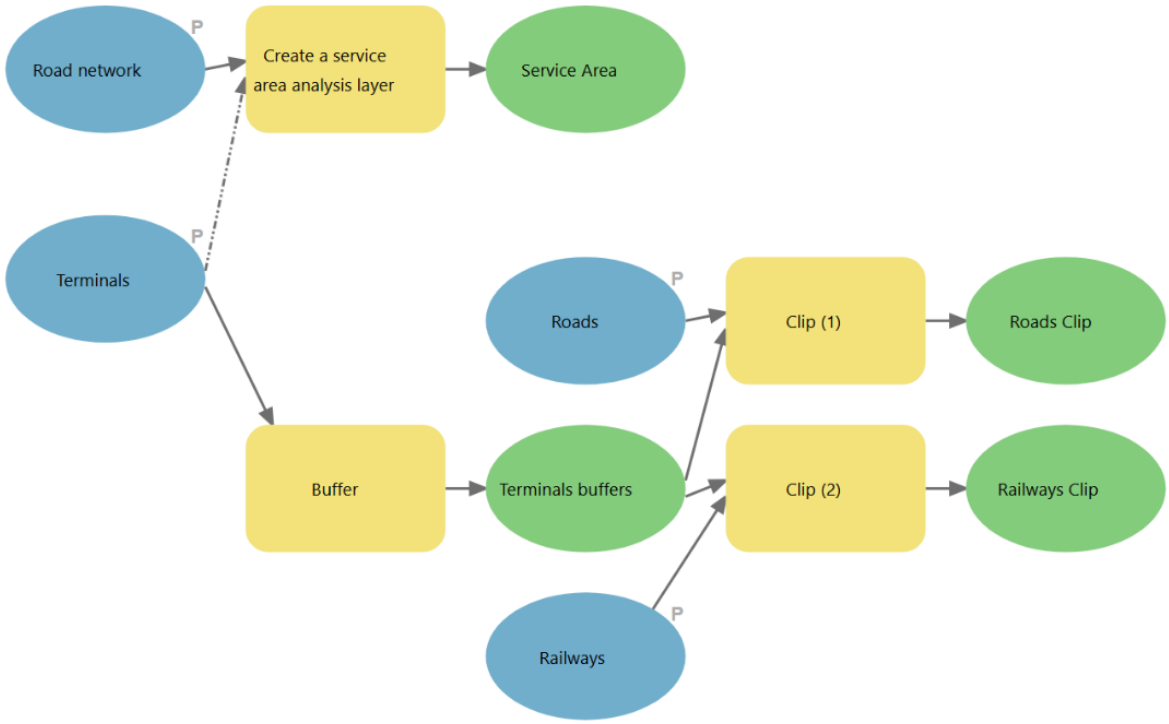


Figure 2. Model builder diagram showing iterative workflow for creating service area analysis layer and road/rail infrastructure network for intermodal terminals
Source: own elaboration developed using ESRI ArcGIS Pro 3.3.2 software.

The figure illustrates the MB diagram representing the iterative workflow employed in analyzing the transport accessibility of intermodal terminals. The model facilitates the generation of service areas at distances of 50 km and 150 km from the terminals, as well as the delineation of road and rail network segments within a 50 km radius of these terminals.

The study was conducted in two primary stages. The first stage involved determining the service areas of the terminals using the NA tool. Accessibility zones were calculated for radius of 50 km and 150 km, specifically for heavy vehicles, thereby enabling the assessment of spatial variations in the reach of road freight transport. The input data for this analysis included the road network layer and the locations of the intermodal terminals. The output of this analysis was a Service Area layer, which represents the areas accessible from the terminals within the specified distance thresholds.

The second stage focused on assessing the density of transport infrastructure in the vicinity of the terminals. To achieve this, a buffer analysis was performed around the terminal points within a 50 km radius, enabling the definition of buffers. Within these zones, geoprocessing operations were conducted using the Clip tool, which allowed for the extraction of road and rail network layers within the boundaries of the defined buffers. This produced layers containing segments of the transport network in close proximity to the terminals. The geoprocessing workflow for this analysis was developed for Poland. Subsequently, the same model was applied in an automated process for conducting the analysis in Germany.

An additional benefit of the model lies in its incorporating parameters, which are instrumental in standardizing the analysis. This parametrization enhances the model's flexibility and its potential for repeated use. By adjusting parameters for elements and variables within the modules, the model can be easily adapted to accommodate different input datasets. This feature is particularly beneficial for batch processing and iterative testing of various scenarios. Consequently, users can modify input data, such as road and rail networks or terminal locations, without requiring modifications to the model's structure. Furthermore, the parametrization facilitates model validation, allowing for the integration of diverse

input data sets, which enables the comparison of results across different scenarios and supports the optimization of the decision-making process (Sunny, 2024).

Due to the implementation of batch processing automation, it could be possible to iteratively test different scenarios and dynamically adjust the model to changing spatial conditions (Cui et al., 2017). This approach enables more precise and efficient decision-making regarding transport management and the integration of various modes of transportation within intelligent spatial management systems, ultimately contributing to the optimization of the supply chain (Tateosian, 2015). For the purposes of this study, the model was constructed for the linear infrastructure of road and rail transport, as well as the network of intermodal terminals in Poland, and tested for Germany without the need for manual modification of its structure.

4. RESULTS

4.1. Spatial Accessibility of Transport Infrastructure to Intermodal Terminals

As a result of the conducted analysis, six maps were developed, which are presented in the form of three compositions. Figure 3 shows the accessibility of road transport to intermodal terminals in Poland and Germany, determined based on road distance for heavy vehicles. The analysis was carried out using maps generated in ArcGIS Pro with the NA tool. The maps display the locations of intermodal terminals and their service areas at 50 km and 150 km distances, which allows for the assessment of the density and distribution of road infrastructure in both countries. The color scheme of the maps illustrates areas covered by road transport accessibility at two distance thresholds, enabling a comparison of the level of integration between terminal infrastructure and the road network.

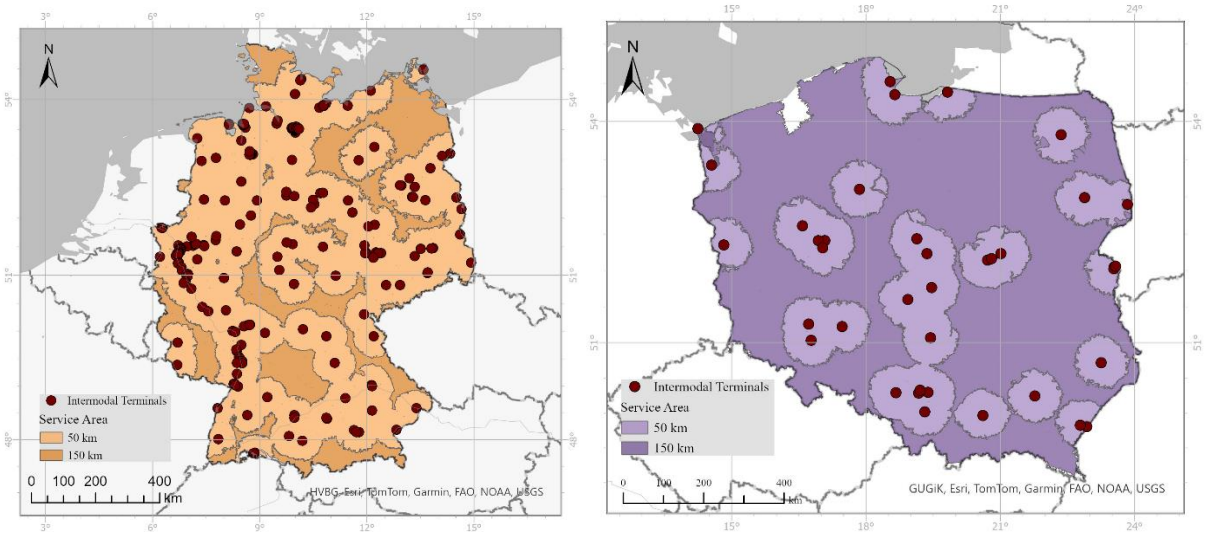


Figure 3. Spatial variation in the accessibility of road transport to intermodal terminals in Germany (left) and Poland (right)

Source: own elaboration based on data provided by: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html (accessed: 05.03.2025), https://www.intermodal-map.com/ (accessed: 04.03.2025), OpenStreetMap.

The spatial analysis highlights significant disparities in the distribution of intermodal terminals between Poland and Germany, which have profound implications for the accessibility of intermodal transport in both countries. In Poland, the density of these facilities is considerably lower than in Germany, with only 1.30 terminals per 10,000 km², compared to 6.51 terminals in Germany. This discrepancy leads to notable differences in accessibility to intermodal transport, particularly in regions distant from major urban centers and key transport corridors.

In Poland, intermodal terminals are predominantly concentrated around major urban hubs and strategic transport routes, resulting in limited accessibility in many areas of the country. This is especially true for the northeastern and central regions, which remain outside the effective reach of intermodal services. Although 98.8% of Poland's territory is located within a 150 km radius of a

terminal, only 35% of the country is within a 50 km radius. Such a distribution indicates a limited availability of intermodal transport at the regional level, which hinders the effective utilization of these services. In contrast, Germany's intermodal terminal network is considerably denser, leading to significantly better accessibility to intermodal transport. The entire territory of Germany is within a 150 km radius of a terminal, and 77% of the country's area is within a 50 km radius. This infrastructure layout fosters the efficient use of combined transport while reducing reliance on road transport over long distances. The high concentration of terminals in Germany reflects better integration of intermodal transport with the national logistics and transportation system, contributing to more sustainable transport development and the reduction of operational costs, thus optimizing the supply chain.

In summary, the analysis indicates a substantially higher level of integration between intermodal infrastructure and the transportation system in Germany compared to Poland. This has a decisive impact on the efficiency of intermodal transport and its role within the logistics systems of both countries.

The following research phase involved identifying the road and rail networks directly adjacent to intermodal terminals. Figure 4 illustrates the road accessibility to intermodal terminals in Poland and Germany, considering the road network and the 50 km radius around these facilities. The purpose of this study was to delineate the roads within the defined zone, allowing for the determination of the density of the road infrastructure in the immediate vicinity of the terminals and highlighting the differences in intermodal transport accessibility between the two countries. This area was selected as a key service zone for terminals, as the 50 km distance is often regarded as economically justified, given the high costs associated with transporting goods between the terminal and the final destination, particularly in relation to road transport costs.

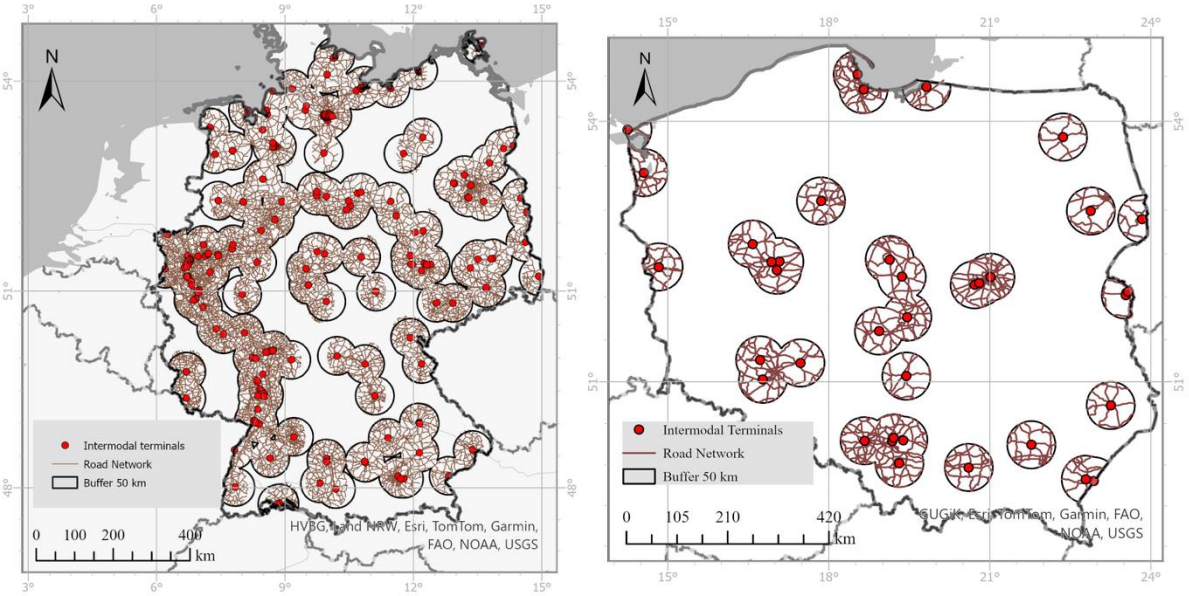


Figure 4. Spatial distribution of road transport infrastructure accessibility to intermodal terminals in Germany (left) and Poland (right)

Source: own elaboration based on data provided by: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html / (accessed on 05.04.2025), https://www.intermodal-map.com/ (accessed on 04.03.2025), Open Street Map.

Poland's spatial coverage of terminals is 22.2% of the country's surface area. The total length of roads within the range of terminals in Poland is 18,510.20 km and constitutes 25.9% of the buffer area, which indicates a relatively small scale of integration of road transport with intermodal infrastructure. The situation is different in Germany - intermodal terminals are much more numerous and evenly distributed, resulting in greater coverage (61.9% of the country's surface area). The length of the road network located within a radius of 50 km from terminals in Germany is 114,675.15 km, which is over six times greater than in Poland and constitutes 51.9% of the buffer area. Therefore, the road density within the terminal in the studied area is twice as high.

The dense road network around terminals in Germany promotes the effective integration of road and intermodal transport. This enables faster cargo movement between terminals and destinations, shortening transport times and reducing logistics costs. Developed road infrastructure also increases the flexibility of the transport system, allowing operators to respond better to changes in demand and minimize the risk of delays and problems with road availability. Developed road infrastructure in Germany allows easier access to terminals for both local carriers and international transport, which strengthens the competitiveness of the German logistics sector. This part of the roads is less exposed to congestion, and additionally, the route extension rate is lower, which shortens the transport time and distance. In the context of intermodal transport, a sufficient road network facilitates the synchronization of individual transport stages, which is crucial for cost optimization and supply chain efficiency. Such a solution increases the competitiveness of the logistics sector, especially in international freight transport, where time and cost are decisive factors in the selection of transport routes.

In Poland, the relatively poorly developed road network around intermodal terminals significantly limits the efficiency of access to these facilities. Low road infrastructure density leads to longer access routes for trucks, resulting in greater traffic congestion on major communication arteries and higher operating costs. In addition, longer travel times to terminals translate into longer total delivery times, which consequently affect the efficiency of the entire supply chain.

The last prepared composition shows the rail network in the area of 50 km from intermodal terminals in Poland and Germany (Fig. 5).

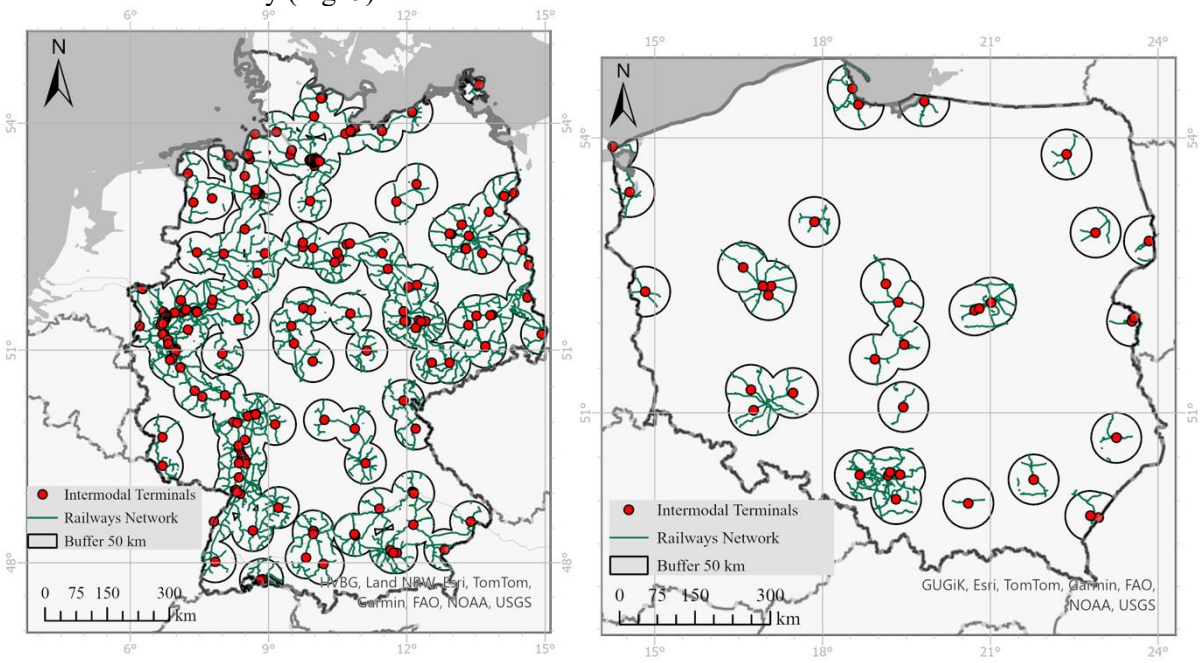


Figure 5. Spatial distribution of rail transport infrastructure accessibility to intermodal terminals in Germany (left) and Poland (right)

Source: own elaboration based on data provided by: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html / (accessed on 05.04.2025), https://www.intermodal-map.com/ (accessed on 04.03.2025), Open Street Map.

The analysis of rail accessibility to intermodal terminals in Poland and Germany reveals significant differences in the involvement of rail transport in intermodal freight and the degree of integration of rail infrastructure with the intermodal transport system in both countries. The total length of the rail network within a 50 km radius of terminals in Poland is 15,952.17 km, which accounts for 22.30% of the buffer zone area. In comparison, in Germany, this length reaches 65,960.07 km, representing 29.85% of the buffer zones. This indicates that the German rail infrastructure in the immediate vicinity of terminals is over four times longer, with a density 7.55% higher than in Poland, reflecting a significantly greater utilization of rail transport and its key role in servicing intermodal terminals.

The differences in rail infrastructure accessibility near intermodal terminals in Poland and Germany primarily result from differing levels of rail network development in both countries. Despite the length of the German rail network near terminals, its density does not differ substantially from the Polish

network, suggesting that both networks exhibit a similar level of integration with the intermodal transport system. Nevertheless, the greater length of the rail network in Germany facilitates better rail transport accessibility within terminal areas, allowing for a higher number of connections and increased flexibility in intermodal transport.

The well-developed rail network in Germany enhances the competitiveness of rail transport in intermodal freight, enabling higher train frequency and the handling of larger volumes of cargo in a shorter period. In Poland, the lower number of rail lines near terminals may lead to limited capacity and longer transport times. Consequently, road transport continues to play a crucial role in accessing intermodal terminals in Poland, while in Germany, rail transport is significantly better integrated into the logistics system.

4.1. Leveraging Geospatial Tools and AI for Optimizing Transport Networks

Having developed a model for determining accessibility zones and their impact on transport efficiency in a given area, it is possible to correlate it with other geoprocessing tools, such as:

- Spatial Join – this tool allows for the integration of spatial data from different layers, enabling a detailed analysis of the relationships between terminal locations and transport infrastructure. This can support a more comprehensive accessibility evaluation by providing a deeper insight into spatial interactions.
- Hot Spot Analysis – a tool for identifying areas with a high intensity of events (e.g., accidents, traffic congestion) that could affect transport accessibility within intermodal terminal areas. This method aids in detecting potential issues related to transport accessibility or safety that may hinder the efficiency of intermodal transport systems.
- Least Cost Path Analysis – a tool that allows for determining the most optimal transport routes, considering various cost factors such as travel time, distance, and terrain conditions. This approach helps identify the most efficient routes to access terminals, thereby improving the overall performance of the transport system.

Alternatively, it could also be compared with models that, while not differing in terms of their functions, focus on different computational variants (as in the case of separate analyses for Germany and Poland, as presented in this article). Having such a set of tools for assessing the parameters of a transport network leads to the problem of needing to update and use each model individually, which prolongs the work process and requires the independent establishment of correlations between the results obtained. Given the current technological state, it would conceptually be possible to combine specialized models based on geographic information system (GIS) analysis systems in order to build individual models coordinated with the help of AI, creating a more broadly applicable method that is easier to use. This basic concept is illustrated in Figure 6.

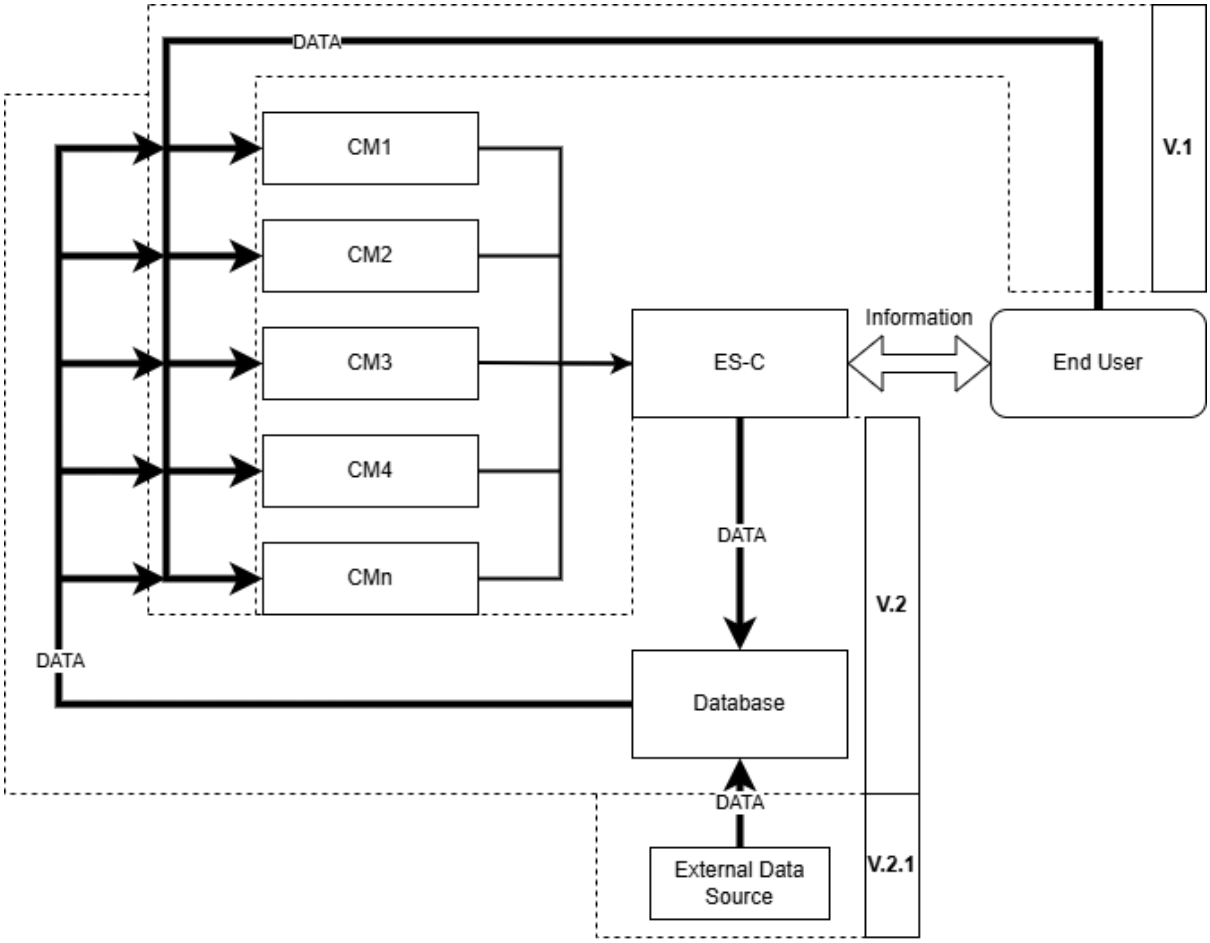


Figure 6. Model of potential AI application for coordinating and extracting results from customizable geographic information models
Source: own elaboration.

The presented graph consists of subsystems with either two or one common point, depending on the assumptions made. The following components of the model have been adopted:

- CM (1,2,3….n) – Custom model GIS, the number of models would be adjusted according to the user's needs (from 2 to n).
- ES-C – Expert system for coordination of specialized customizable geographic information models.
- Database – A database collecting the information needed for the functioning of the created models.
- External Data Source – External data sources, such as statistical offices or geographic information systems.
- End User – The final user.

The advantage of the system utilizing AI (expert system) over standard algorithms is the ability to adjust queries and specify needs without having extensive knowledge of the subsystems (models) applied by the person using the presented potential system. Applying this concept in a business would allow for a reduction in the number of specialized personnel needed exclusively for the construction of subsystems, with less skilled staff managing the overall system. The concept presented includes three variants that further enable the reduction of the qualified workforce. These variants relate to the input of information into the developed subsystems. In version 1 (V. 1), the end-user or the subsystem builder is responsible for delivering output data directly to each of the developed subsystems. This option is the least efficient due to the large number of qualified workers required for task execution and ongoing administration/oversight of the entire system. Therefore, the second version (V. 2) is considered the initial version of the proposed concept. In this case, the main coordinating module, ES-C, would handle the distribution of the provided data, minimizing the need for direct interaction with the subsystems

(individual modules/models). In version 3 (V. 2.1), there is no longer any need for the user to provide output data; instead, the system ES-C would retrieve them from external data sources such as statistical offices or geographic information systems without the need for human supervision. It is important that the AI module (ES-C) does not pull data simultaneously from all subsystems; instead, it first decides which module should be used to respond to the query, thus saving energy and increasing the accuracy of the response.

6. CONCLUSION

The analysis of road and rail transport accessibility in the vicinity of intermodal terminals in Poland and Germany reveals significant differences in the integration of transport infrastructure with the intermodal system in both countries.

Germany, with its denser network of intermodal terminals, demonstrates far better accessibility to intermodal transport. The entire territory of Germany lies within 150 km of a terminal, with 77% of the area within a 50 km radius. This spatial distribution supports the efficient use of combined transport and reduces dependence on long-distance road transport. In contrast, although 98.8% of Poland's territory lies within 150 km of a terminal, only 35% of the country is within a 50 km radius of one. This disparity hampers the efficiency of the intermodal system, especially in regions more distant from major urban areas.

In terms of road transport, Germany has a far more developed network, with 114,675.15 km of road within 50 km of terminals, representing 51.85% of the buffer zone area. In comparison, Poland's road network in this area totals 18,510.20 km, accounting for just 25.86% of the buffer area. This difference contributes to better integration of road transport with intermodal systems in Germany, facilitating faster and more flexible movement of goods. In Poland, although roads are accessible nationwide, the lower density of the road network near terminals leads to higher transportation costs and longer delivery times.

In rail transport, Germany also has a distinct advantage, with more than four times the length of rail infrastructure within 50 km of terminals, enabling better integration of rail transport with the intermodal system. While Poland's rail network is extensive across the country, the relatively limited rail infrastructure near terminals restricts capacity and prolongs transport times. As a result, rail transport in Poland is not yet sufficiently integrated with the intermodal system, whereas in Germany, rail plays a crucial role in the efficient operation of intermodal terminals.

In conclusion, the analysis indicates a much higher level of integration between intermodal transport and the logistics system in Germany, leading to greater efficiency, cost optimization, and enhanced competitiveness in the logistics sector compared to Poland. The development of intermodal terminal infrastructure is essential for improving the efficiency and competitiveness of intermodal transport. Ensuring an optimal distribution and accessibility of terminals is key for seamless logistics operations, as it enables efficient intermodal transfers, optimizes transport time and costs, and reduces reliance on road transport. The lack of even terminal distribution, particularly in underdeveloped regions, hampers the potential for the growth of intermodal transport, emphasizing the need for better spatial accessibility and capacity. Therefore, promoting the use of rail and waterborne transport is critical to achieving a sustainable and integrated transport system.

The theoretical concept introduced in this article—connecting various customizable GIS models into a unified system through an expert coordination model—would significantly enhance operational efficiency for relevant stakeholders (e.g., research centers) by providing results that consider multiple variables, thus offering a more comprehensive interpretation. Moreover, this approach would facilitate users with lower levels of expertise access to the developed models, thereby democratizing the usage of advanced analytical tools in the field.

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In the face of global digital transformation, increasing complexity of socio-economic systems, and mounting sustainability challenges, the integration of artificial intelligence (AI) with intelligent management approaches has become a critical field of inquiry and application. Contemporary organizations, institutions, and cities operate in a reality where data-driven insights, cognitive tools, and algorithmic support are no longer peripheral innovations, but essential components of effective strategy and governance. Against this backdrop, the second Volume of the monograph “Intelligent Management and Artificial Intelligence: Trends, Challenges, and Opportunities” offers a comprehensive continuation of the reflections initiated in Volume I, extending the thematic scope toward applied, interdisciplinary, and future-oriented perspectives.

This publication is part of the official proceedings of the 28th European Conference on Artificial Intelligence (ECAI 2025), held in Bologna, Italy, on October 25–30, 2025. It includes selected papers presented during the InMan – Intelligent Management Workshop, one of the thematic events accompanying the conference. The workshop brought together scholars and practitioners from a wide range of academic and cultural backgrounds, with contributions from authors affiliated with institutions in Poland, Germany, Slovakia, Ukraine, Bulgaria, the Czech Republic, Italy, Greece, Kosovo, and Turkey. This geographic diversity highlights not only the broad relevance of intelligent management as a research area, but also the shared challenges faced by societies and organizations across different regions of Europe and its neighbouring countries. The multidisciplinary nature of the contributions underscores the need for collaborative, context-sensitive approaches to the design and deployment of AI-based management tools and strategies, especially in domains where ethical, economic, and ecological dimensions intersect.

From the Preface

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