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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

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).

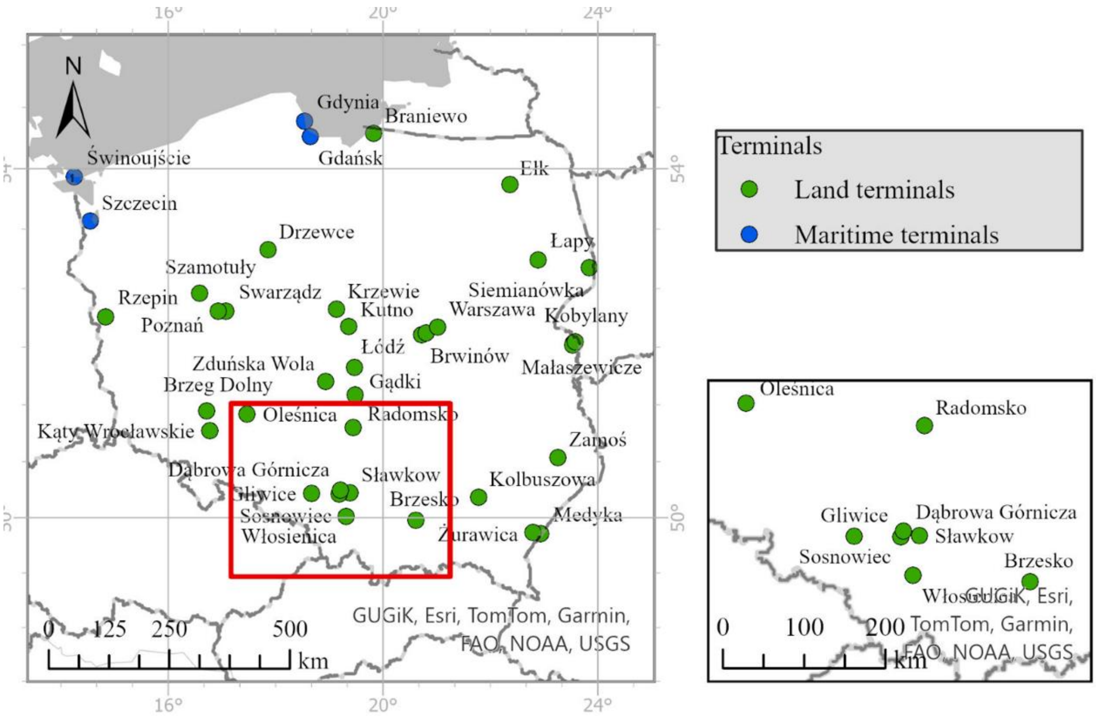

Figure 1. Map of intermodal transport terminals in Poland
Source: own elaboration based on: www.dane.utk.gov.pl/sts/transport-intermodalny/mapa-terminali/18573,Dane-o-terminalach-intermodalnych.html (accessed: 04.03.2025).

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 km^2
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.

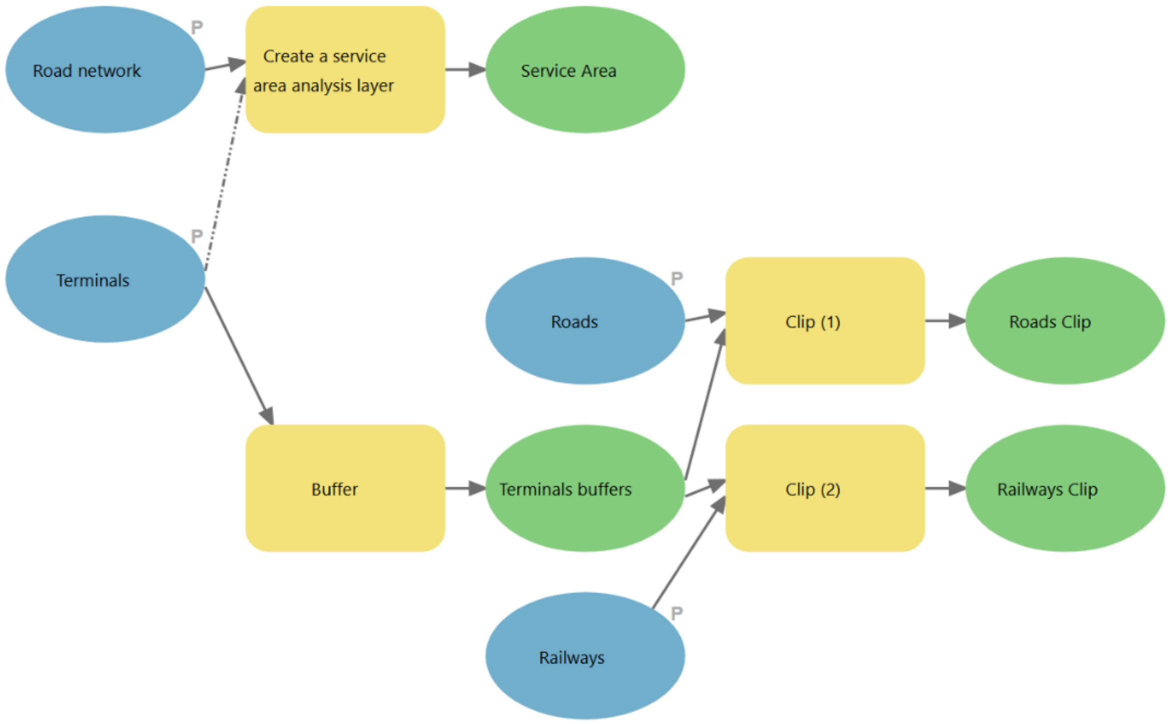

Figure 2. Model builder diagram showing iterative workflow for creating service area analysis layer and road/rail infrastructure network for intermodal terminals
Source: own elaboration developed using ESRI ArcGIS Pro 3.3.2 software.

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.

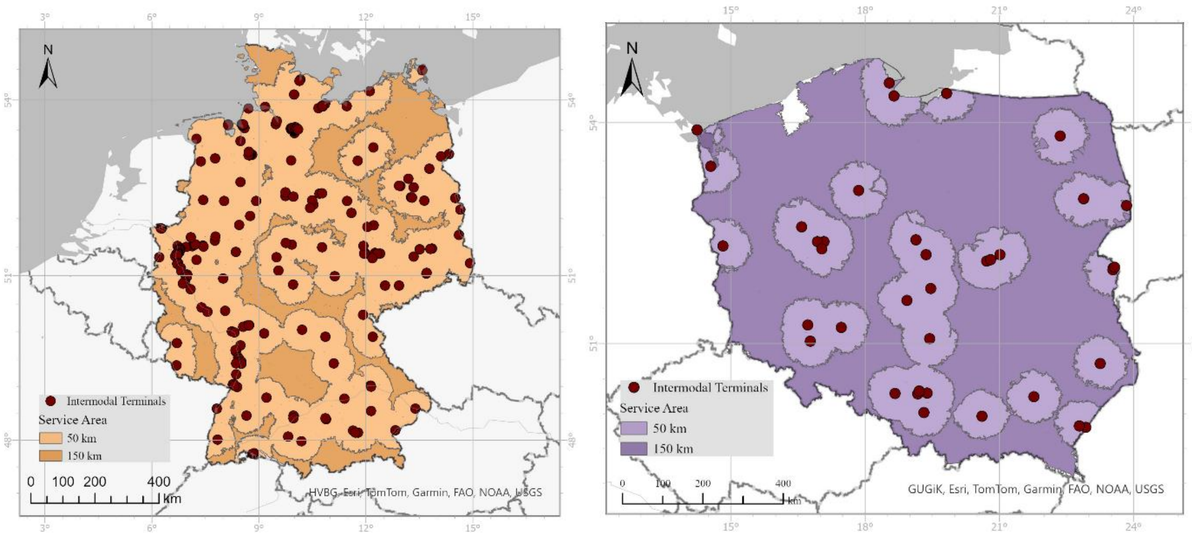

Figure 3. Spatial variation in the accessibility of road transport to intermodal terminals in Germany (left) and Poland (right)

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.

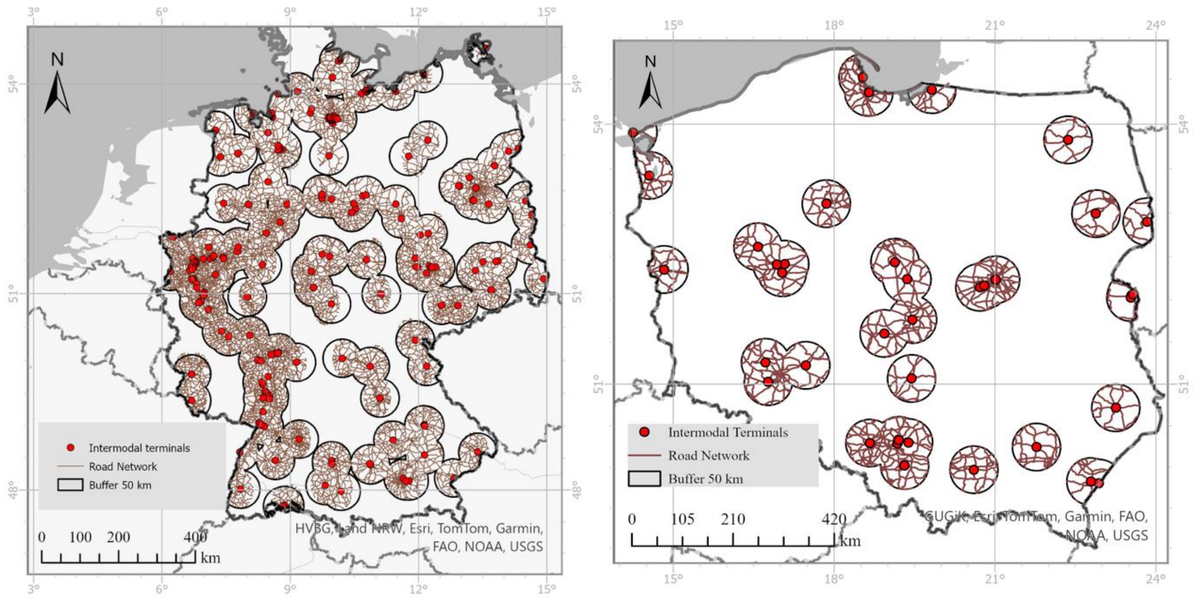

Figure 4. Spatial distribution of road transport infrastructure accessibility to intermodal terminals in Germany (left) and Poland (right)

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).

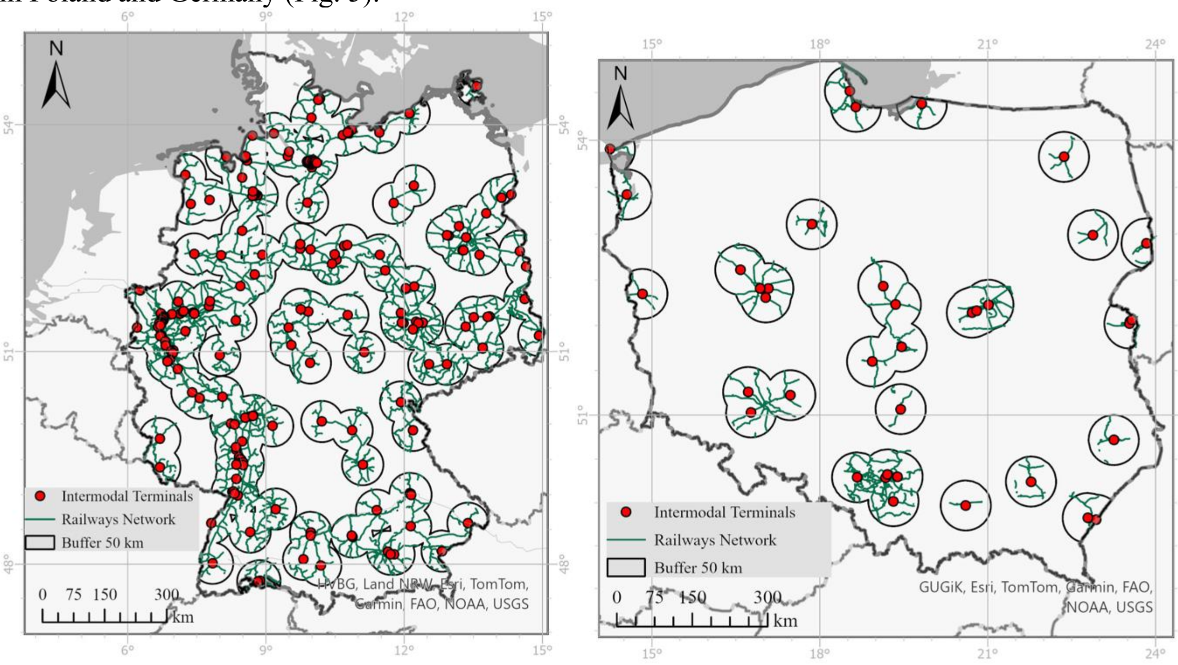

Figure 5. Spatial distribution of rail transport infrastructure accessibility to intermodal terminals in Germany (left) and Poland (right)

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.

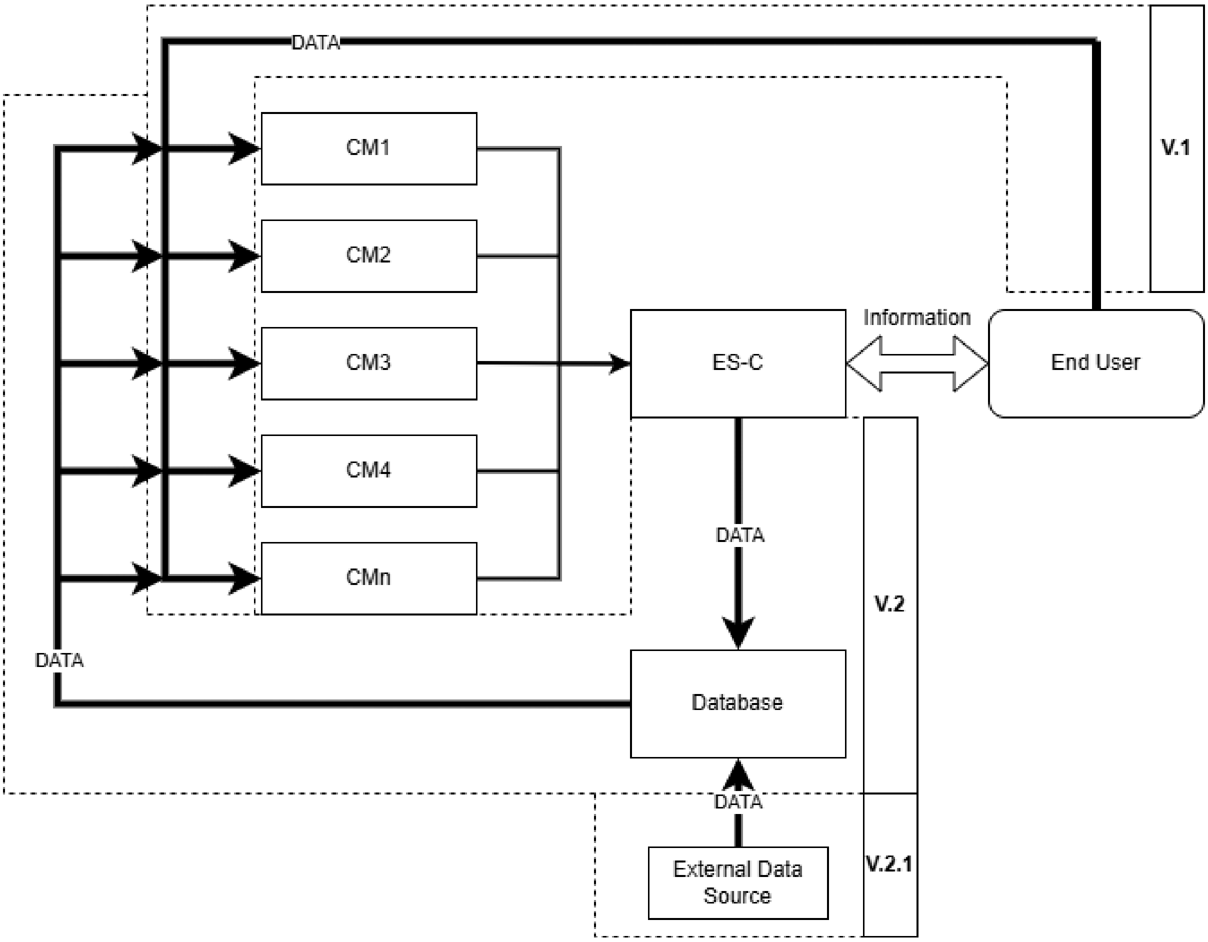

Figure 6. Model of potential AI application for coordinating and extracting results from customizable geographic information models
Source: own elaboration.

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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