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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

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.

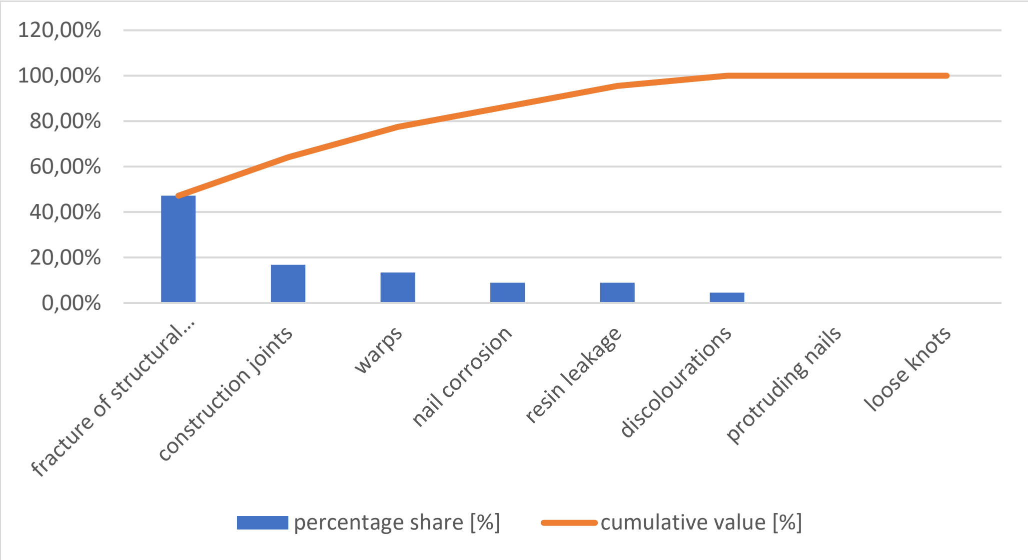

Figure 8. Pareto-Lorenz chart of identified defects in EPAL pallets made of dry components
Source: own elaboration.

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.

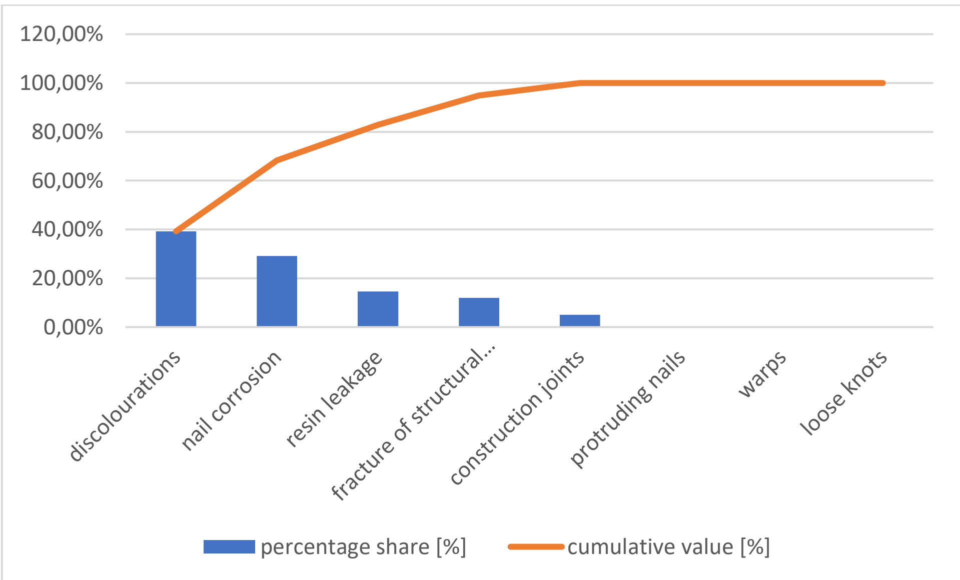

Figure 9. Pareto-Lorenz chart of identified defects in EPAL pallets from wet components
Source: own elaboration.

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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