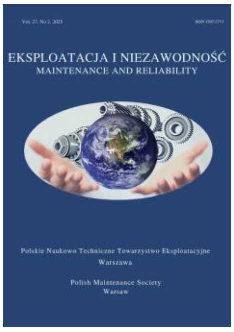

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Reliability and efficiency in technology selection in logistics facilities – multi-criteria decision support using the AHP method

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Highlights

- A Bayesian-based reliability analysis method by fusing prior and test data is proposed.
- The prior data are expanded using neural network in combination with simulation data.
- The mechanism kinematic accuracy reliability is quantified under small-sample condition.
- The key variables affecting the retraction mechanism reliability are identified.

Abstract

Due to intricate operating conditions, including structural clearances and assembly deviations, the acquisition of test data of landing gear retraction mechanism is limited, posing challenges for reliability analysis. To solve the problem, a Bayesian-based reliability analysis method by fusing prior and test data is proposed, focusing on the mechanism kinematic accuracy under small-sample conditions. Firstly, a dynamic simulation model is established to collect prior data, and retraction tests are conducted to obtain test data. Then, based on Bayesian theory, the motion accuracy parameter estimation model integrating prior and test samples is established. To obtain accurate hyper parameters, the prior samples are expanded using neural network. Finally, taking the retraction mechanism as the research object, the kinematic accuracy reliability is quantified, and the impact of uncertainty factors is analysed in depth. The results show that the proposed method is superior to the classical interval estimation method in stability and effectively mitigates the impact of uncertainty factors.

Keywords

Bayesian, small sample, retraction mechanism, kinematic reliability, hyper parameter estimation

1. Introduction

Logistics and supply chain management are areas that have become particularly important in the context of global business in recent decades. Economic change, the dynamic development of technology, as well as changing customer expectations have led to a significant increase in the operational complexity of companies which need to effectively manage the flow of goods from suppliers to end-users 40. In order to remain competitive in the marketplace, today's companies need to ensure that their supply chains are not only efficiently but also flexibly managed. In this context, warehousing processes and technologies used to handle goods play a key role in maintaining operational smooth flow, minimising costs and increasing the efficiency of the entire supply chain.

Logistics facilities such as terminals, transshipment points or warehouses play an important role in the process of supply reliability. For example, today's warehouse is a central operational hub where key logistics processes such as receiving goods, storage, order picking and preparing goods for shipment

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take place 18. Optimising these processes has become a priority for companies seeking to improve operational efficiency. The efficiency with which a company is able to manage its warehousing processes translates directly into lead times, customer satisfaction and the company's bottom line 3. In an era of globalisation, where competition on the market is steadily increasing and customers' expectations of reliability and delivery efficiency are becoming higher and higher, warehouse management is taking on a new dimension and companies are faced with a wide range of demands. Response times to orders, flexibility to adapt to changing market needs and minimisation of operating costs are becoming key determinants of success 1638. Therefore, the optimisation of warehouse processes, while ensuring a high level of customer service, is becoming not only a necessity but also a strategic objective for the company.

In the aspect of the foregoing, the authors of the paper undertook the study, analysis and evaluation of the selection of technology in warehouses in view of the efficiency and reliability of processes throughout the supply chain. The operation and maintenance of the equipment of a particular storage technology is becoming one of the important aspects of warehouse management. Decisions on the choice of storage systems, automation technologies or ways to manage the flow of goods have long-term implications for operational efficiency 34. Technology that maximises operational efficiency can at the same time generate significant capital costs, which in turn can affect the profitability of the overall project.

The decision-making process of assessing the effectiveness of technology selection for a given type of storage facility requires the consideration of a number of indicators (criteria) that are often in conflict with each other 42. For example, technology that can significantly increase the operational efficiency of a warehouse can, at the same time, require high investment outlays. Similarly, storage systems that are more flexible and scalable may involve higher operating costs or greater complexity in implementation 2. In such a situation, it is essential to use tools that allow a thorough evaluation of all available options and the selection of the optimal solution to meet the specific needs of the company. Multi-Criteria Decision Making (MCDM) methods offer a set of tools that can significantly facilitate the decision-making process in the context of warehouse facility management. The methods allow different decision criteria, both quantitative and qualitative, to be taken into account and their relative importance to be assessed.

The paper explores the application of the Analytic Hierarchy Process (AHP) in the field of logistics, particularly focusing on decision-making for warehouse management and handling technology selection. This comprehensive study includes a literature review, a structured procedure for evaluating cargo movement technologies, and a practical application of the AHP method to the problem under analysis. The findings are accompanied by practical conclusions and recommendations, offering a holistic perspective on the process of selecting warehouse technologies. The structured approach provides both theoretical and methodological insights, as well as actionable guidance for logistics practitioners.

The primary aim of the article is to analyse and evaluate decision-making processes related to the selection of warehouse technologies, emphasizing the efficiency and reliability of logistics processes. It highlights the application of the AHP method as a robust tool for supporting decisions in a multi-criteria environment. Through the conducted research, the paper seeks to identify technological solutions that not only maximize operational efficiency but also ensure stability and reliability in a rapidly evolving logistics landscape.

Additionally, the article aims to demonstrate the exceptional utility of the AHP method in addressing this type of analytical challenge. By integrating both quantitative and qualitative decision-making criteria, the AHP method enables a comprehensive and transparent assessment of available technological options. Its hierarchical structure facilitates the prioritization of diverse criteria, ensuring that decision-makers can select the most advantageous solutions. This capability significantly contributes to strategic decision-making in logistics, offering a reliable framework for evaluating and implementing warehouse technologies to meet both current and future operational demands.

2. Literature analysis

2.1. Decision-making issues in infrastructure projects in terms of efficiency and reliability of implementation

The efficiency of cargo movement processes through a logistics facility is a key aspect of any logistics facility's operations, affecting service quality, operating costs and lead times. Challenges involved include optimising the layout of storage space, synchronising staff work and equipment operation and minimising downtime 41. The efficiency of cargo movement processes through a logistics facility is a key element of logistics management, especially in the context of increasing market demands and pressure for speed of delivery 9.

In the literature, efficiency is defined in different ways, taking into account the specifics of a given system and the context in which it operates. In general terms, efficiency is understood as the ability of a system to achieve its objectives or tasks, treating it as an assessment of the correctness of the performance in the context of the objectives set. Efficiency can also be understood as a measure of economic rationality. In this case, efficiency refers to interactions within an organisation and its environment, where the focus is on optimising the relationship between outputs, objectives and inputs, particularly in terms of economic 32. In the paper 4 the author identifies efficiency in supply chain terms. Here, it is defined as a measure of the degree to which objectives are met in the supply chain, based on the optimal use of the resources available. Thus, the efficiency defined in 7 expresses the extent to which the supply chain 32 achieves better results with fixed inputs. Given these definitions and the necessary aspects of efficiency in logistics facilities to consider, in the works 4051 authors classify efficiency into organisational (the ability of the system to adapt and use resources productively), economic (an assessment of the relationship between effects and inputs) technical (measured by production efficiency and cost minimisation) and qualitative (the competitiveness of the facility in relation to similar facilities, where market share or resource utilisation rates are measures). An important issue in the rationalisation of supply chains is the efficiency of logistics facilities, as examined in the paper 43. The author of the paper concluded that the efficiency of logistics facilities such as warehouses is now becoming a competence centre or strategic weapon that many organisations are using to improve their position in the market. As recently as the 20^{th} century, warehousing was seen as a stable branch supporting other functional areas of the supply chain, but it is now considered a strategic industry in itself 12.

The efficiency of the cargo movement through the warehouse facility plays an important role in the decision-making process for shaping the facility in technical, technological and organisational terms. Decisions made in logistics facilities, such as warehouses or distribution centres, are usually geared towards optimising resources, minimising costs and improving customer service. Thus, the decision-making process at both operational and strategic levels requires an evaluation of effectiveness. In the paper 19 the authors conclude that measures for assessing the efficiency of a storage facility can be divided into those relating to operational efficiency and storage efficiency. The main objective of operational measures is to analyse the efficiency of material handling operations in the warehouse, whether they are performed by humans, automatically or semi-automatically. At the same time, the author of the work 21, notes that warehouse efficiency is also a set of measures that primarily measure the capacity of the storage space. Furthermore, the authors of the work 1921 conclude that the efficiency of a warehouse facility can be evaluated on the basis of the following aspects: the ability to track the movement of cargo units in the warehouse, the facilitation of inventory taking in the warehouse, more efficient use of available storage space, greater accuracy of inventory data, or aI reduction in theft of goods.

Warehouse efficiency is closely linked to warehouse reliability, as any downtime or error in warehouse operations can lead to delays, additional costs and a reduction in customer service. The concept of reliability in warehousing refers to a number of key technical, technological and organisational areas that together affect the smooth flow and efficiency of warehouse operations. Thus, the reliability of a warehouse facility is understood as the ability to operate as required and in a timely manner 14. In the literature, the reliability of warehouse facilities is a well-known issue, although it has not been given much attention. In works such as 35, 6 the authors have presented considerations on the reliability of logistics systems and complex supply chains at a general level. In the paper 35 the author broadly states that system reliability boils down to securing a timely and uninterrupted delivery process to meet the demands of the end customer. These publications provide some basis for defining the reliability of elements of logistics systems, including storage systems. The reliability of storage facilities in the literature is also considered from the point of view of the place and role of these facilities in supply chains. For example, in the work 36 considering warehouse reliability in the supply chain, the authors point out that it is crucial to ensure reliable storage and distribution of products. In their work, by including warehouse reliability in the model, the authors minimised disruptions and delays in the supply chain. The issue of reliability of storage facilities was addressed in a broader context in the work of the 26. The authors define a reliability framework for storage facilities that can be useful for assessing their performance. This work also defines the OTIFEF (on-time, in-full, error-free) indicator which can be used in the evaluation of the entire facility or its individual functional elements. In addition to the study of reliability, the literature also develops various methods for increasing reliability. Thus, in the work 8 the authors developed a genetic algorithm to maximise service reliability in a distribution centre. The developed algorithm was used to solve the problem of locating materials in a distribution centre, allocating resources to tasks and routing internal transport means to increase the reliability of cargo movement through the warehouse. In turn, in 10 authors, using multi-criteria methods and fuzzy logic, undertake an assessment of the reliability of AGV systems in a warehouse. A different approach to investigating the reliability of storage facilities is presented in paper 48, where the authors investigated the reliability of AGVs using Failure Modes Effects and Criticality Analysis and Fault Tree Analysis (FTA) to identify the causes of damage 12.

Literature studies carried out on the reliability of warehouse facilities indicate that the efficiency of a warehouse is directly related to its reliability, as any interruption or error leading to delays and additional costs negatively affects the quality of customer service. Reliability encompasses many technical, technological and organisational aspects that together affect the operational efficiency of warehouses. In the literature, the reliability of warehouses and logistics systems is mainly analysed in general terms, but is an important topic in the context of ensuring the smooth operation of supply chains. Developed indicators, such as OTIFEF, allow a comprehensive assessment of warehouse performance, while various methods, such as genetic algorithms or FTA analyses, help to improve the reliability of processes and systems, such as when localising goods, routing internal transport or assessing AGV systems.

2.2. AHP method and its application areas

One of the most common applications of the AHP method in warehouse management is the selection of warehouse locations. The study conducted by the authors 38 presents a novel decision support system (DSS) for the evaluation and selection of green warehouses, which integrates criteria such as energy efficiency, CO_2 emissions and waste management. This system, based on the AHP method, allows companies to make the optimal choice of warehouse locations in a way that supports sustainable development goals. Also in 9, using multi-criteria decision support methods, the authors investigate how decisions regarding the location of factories, warehouses and other elements of the supply chain can affect transport costs and efficiency. The study 4 analyzed different locations of warehouse facilities in terms of criteria such as infrastructure availability, transport costs, access to labor and proximity to the target market. The selection of the optimal location requires taking into account many factors that have a significant impact on the efficiency of the entire supply chain. The authors 30 conducted research on the selection of the optimal location of warehouses, using the AHP method to evaluate various factors such as the availability of transport infrastructure, land costs, access to labor and proximity to customers. The results showed that the location of the warehouse has a key impact on the operating costs of the entire supply chain. Optimal locations allow for the reduction of transport costs and shortening of delivery times, which has a direct impact on the level of customer satisfaction. The research showed that AHP enables a comprehensive assessment of warehouse locations, taking into account both quantitative criteria (e.g. costs) and qualitative criteria (e.g. access to infrastructure).

Another important area is the optimization of warehouse processes, such as inventory management, selection of warehouse systems or assessment of warehouse technologies. An example is the use of AHP to select a warehouse management system (WMS). The assessment criteria include implementation costs, functionality, ease of integration with existing ERP systems and availability of technical support 15. Taking into account the aforementioned method, it is possible to precisely determine preferences and choose the best-suited technological solution.

A key element of supply chain management is the selection of suppliers and outsourcing strategies. The authors 41 presented an integrated AHP-PROMETHEE II model, which enables a comprehensive assessment of logistics service providers, taking into account various criteria such as costs, quality of services, operational flexibility and risks related to outsourcing. Such a model supports companies in making more sustainable and strategic decisions regarding supply chain management. The authors' study 20 used the AHP method to benchmark the location of logistics centers in the context of sustainable development. The authors used AHP to evaluate locations in terms of criteria such as CO_2 emissions, energy consumption, availability of transport infrastructure and impact on local communities. The results of the analysis allowed for the creation of a location ranking, which is crucial for optimizing supply chain strategies in dynamically developing markets. In the research conducted in 50, the use of the AHP method helped to evaluate warehouse technologies in terms of their compliance with sustainable development goals. The research showed that automated warehouse systems such as AS/RS can significantly contribute to reducing energy consumption and CO_2 emissions. In addition, sustainable warehouse technologies were assessed as more expensive in the implementation phase, but the research showed that they generate savings in the long term due to lower operating costs and greater energy efficiency. The results of the study suggest that companies that invest in green technologies can count on a return on investment through reduced operating costs and a positive impact on the environment.

An important aspect of supply chain optimization is risk management. The article 29 concerns the application of multi-criteria methods (MCDM) for the selection of vehicles for the transport of oversized loads. The authors discuss the challenges related to the transport of goods with unusual dimensions and weight and present decision support tools in this area. This work provides practical tools for risk management in the supply chain. The use of MCDM methods allows for effective assessment and minimization of risks in transport. Also the publication 22 provides a review of the applications of multi-criteria decision support methods in risk management in warehouses. The authors 51 analyzed warehouse safety from the perspective of operational risk, using the AHP method to evaluate various safety systems. The studies showed that warehouse technologies that have integrated monitoring systems (e.g. sensors, alarm systems) significantly reduce the risk of accidents and damage to goods. Automatic warehouse systems were assessed as safer compared to traditional solutions, which is due to the lower involvement of employees in the storage and picking processes. The research results indicate that systems with a high level of automation can improve operational safety, which in turn translates into lower losses resulting from accidents.

In the context of urban transport, AHP is widely used for planning and optimization of transport systems. In 50 one can find the application of the AHP method to the selection of urban transport modes based on criteria such as costs, availability, travel time and environmental impact. The results of the analysis provided the basis for developing a transport strategy that is consistent with the goals of sustainable development and responds to the needs of residents. The authors 3 analyzed the priorities of stakeholders of urban transport systems in the context of crowd logistics. The AHP method enabled the assessment of various scenarios for the implementation of social logistics, which is important for the development of sustainable transport systems in cities. In the article 13, the authors focused on the location of urban consolidation micro-centers supporting last-mile deliveries using cargo bikes. The use of the discussed methods allowed for the optimization of the centers' location based on demand data and specific city features.

The literature analysis shows that multi-criteria decision support methods play a key role in warehouse management and supply chain optimization. Their versatility allows them to be used in various aspects of logistics, from the selection of warehouse locations, through the optimization of warehouse processes, risk management in the supply chain, to the planning and optimization of urban transport and sustainable development. The literature review confirms that the integration of these methods in logistics and supply chain management leads to more informed, strategic and sustainable decisions, which is crucial for modern enterprises operating in a dynamically changing environment. Despite the wide range of applications of the AHP method in various aspects of management and logistics, the analysis of the literature indicates that it has not yet been fully utilized for the optimal selection of warehouse technologies. There is a lack of examples that would concern the use of AHP in the context of comparison and selection between traditional pallet racks, automated high-bay systems, integrated AS/RS systems, semi-automatic warehouse systems, automated systems using AGV and advanced warehouse management systems using drones. The results of the search of available sources indicate that the potential of AHP application in this area remains not fully untapped. Therefore, the authors decided to discuss in their article an example that shows that the selection of appropriate warehouse equipment using the AHP method is crucial for operational efficiency, cost reduction and achieving competitive advantage.

2.3. Methods to support decision-making by efficiency

Efficiency and reliability are key criteria in the selection of technologies for the movement of cargo through logistics facilities such as warehouses or distribution centres. Efficient technology supports the efficient and cost-effective movement of goods, which reduces operational time and logistics handling costs. Reliability influences process stability, minimising the risk of downtime and failures that could disrupt the supply chain and increase costs associated with repairs and downtime 1530. The right decision support tools, such as multi-criteria decision support methods (MCDM), enable detailed analysis and evaluation of technologies, leading to the selection of appropriate solutions. The frequently used MCDM methods include ELECTRE 24, PROMETHEE 1, AHP 47, the scoring method 49 or TOPSIS 28. Each of these methods offers a unique approach to evaluating technology alternatives, allowing the decision-making process to be better tailored to the specific characteristics and needs of the organisation 45. AHP is a hierarchical method that allows decision-makers to break down a problem into individual levels, such as the decision objective, criteria and alternatives. Each level is scored in pairs, allowing prioritisation and weighting of different criteria, including efficiency and reliability. AHP is particularly useful when decision-makers have to choose between different cargo flow technologies, taking into account both performance and stability of operation. The authors 49, applied AHP to evaluate warehouse management systems in logistics centres. The results indicate that the AHP allows a clear prioritisation of criteria related to energy efficiency and operational sustainability. The paper 27 presents an analysis of the choice of handling technology in seaports. The study proves that the method is effective in prioritising the time efficiency and reliability of cargo flow systems. The publication 46 explores different warehouse automation technologies, using AHP to analyse cost criteria and reliability indicators. AHP has proved particularly useful in identifying technologies that require less maintenance while maintaining high efficiency.

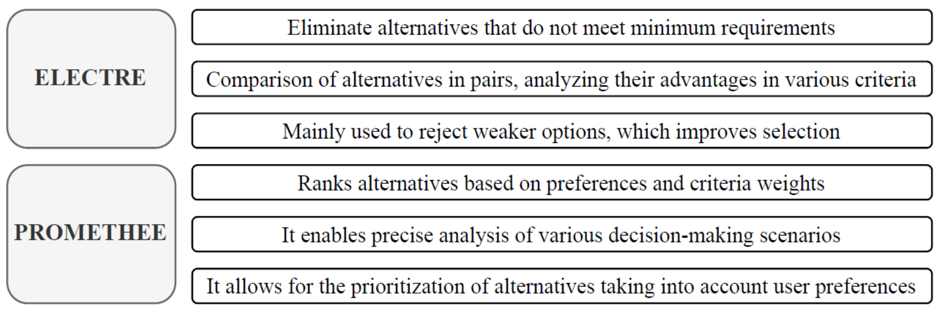
Another method of multi-criteria decision support is the ELECRE method, which allows the comparison of alternatives and the elimination of those that do not meet the selected criteria. In the case of technologies for the movement of cargo through logistics facilities, the ELECTRE method is used to quickly reject options that do not meet minimum operational and environmental requirements. The authors of the paper 11 applied the method to the selection of material handling systems, focusing on minimising downtime and maximising operational stability. In turn 5 uses the ELECTRE method to analyse goods flow systems in warehouses, taking into account reliability and efficiency criteria. Their studies have shown that ELECTRE allows the rapid elimination of low-stability technologies, simplifying the decision-making process. In the literature, in the context of this topic, this method is also used to study cargo flow systems in ports 24where key criteria include reducing the risk of breakdowns or for analysing internal transport systems in distribution centres, focusing on minimising maintenance costs and high energy efficiency 3.

The PROMETHEE method of multi-criteria decision support in logistics is also widely used. Unlike the ELECTRE method, PROMETHEE allows full rankings of alternatives based on the assigned preferences and weightings for each criterion. The authors 31 indicated that PROMETHEE is particularly useful in the logistics technology selection process, as it allows preferences to be analysed at different levels of detail, allowing decisions to be fine-tuned to the specific requirements of the organisation. PROMETHEE is also appreciated for its ability to deal with uncertainty and the diverse priorities of decision-makers, making it a very versatile tool. Its application in logistics allows a more precise assessment of the long-term consequences of technology selection, which is crucial for strategic planning. In 23 research was carried out into the selection of e-commerce flow technology, using PROMETHEE to assess flexibility and reliability. The method has been shown to accommodate the specific preferences of decision-makers. The publication 44 addresses the reliability analysis of logistics technologies for urban transport in order to minimise the risk of failure. The scoring method, although simpler compared to ELECTRE and PROMETHEE, is an effective tool for evaluating alternatives, especially when the number of criteria is limited and their weighting can be easily determined. The scoring method consists of assigning points to each alternative in relation to the established criteria and then multiplying them by the assigned weightings. The paper 22 used a scoring method to evaluate logistics technologies, particularly in the context of smaller facilities, where the number of criteria considered was limited to criteria such as operating costs, reliability and response time. In their study, the authors noted that the scoring method is particularly effective in small and medium-sized logistics companies, where decisions need to be made quickly and without the need for more sophisticated analytical tools. The method is easy to implement even in less advanced organisations. Its flexibility allows it to adapt quickly to changing conditions, making it an attractive choice in dynamic business environments.

The next method i.e. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a method that selects the alternative that is closest to the ideal solution and at the same time furthest from the anti-ideal solution. The publication 28 conducted a study on the choice of handling technologies in distribution centres using TOPSIS, evaluating the alternatives in terms of efficiency, scalability, environmental compliance and operating costs. TOPSIS proved to be extremely effective, as it made it possible to quickly compare alternatives and identify the one that best suited the organisation's needs. The TOPSIS method is also valued for its simplicity and intuitiveness in application, making it easy to implement in a wide variety of decision-making contexts. Thanks to its structure, it allows a quick comparison of alternatives, even in the case of a large number of criteria, which makes it particularly useful in a dynamically changing logistics environment.

A paper 33, which describes the application of various MCDM methods in logistics, pointing out their strengths and limitations, complements the aforementioned studies. The authors emphasise that the choice of an appropriate method depends largely on the characteristics of the decision problem and the number of criteria and alternatives. In contrast, studies 25 focus on the application of complex MCDM methods, such as ELECTRE and PROMETHEE, in large logistics centres where multiple criteria need to be analysed simultaneously, requiring a sophisticated analytical approach. Thus, multi-criteria methods are becoming an indispensable part of decision-making in logistics, enabling more informed and tailored decisions for the organisation. In addition, these studies point to the growing importance of MCDM tools in supply chain management, especially in the context of the increasing complexity of logistics operations. The use of such methods allows a flexible response to changing market conditions, which is key to maintaining the competitiveness and operational efficiency of companies 11.

Multi-criteria decision support methods play a key role in warehouse management and supply chain optimisation. Their versatility allows them to be applied to various aspects of logistics, from the selection of warehouse locations, the optimisation of warehouse processes, supply chain risk management to urban transport planning and optimisation and sustainability. The integration of these methods in logistics and supply chain management leads to more informed, strategic and sustainable decisions, which is crucial for today’s businesses operating in a rapidly changing environment. The diagram summarises the decision support methods described above.



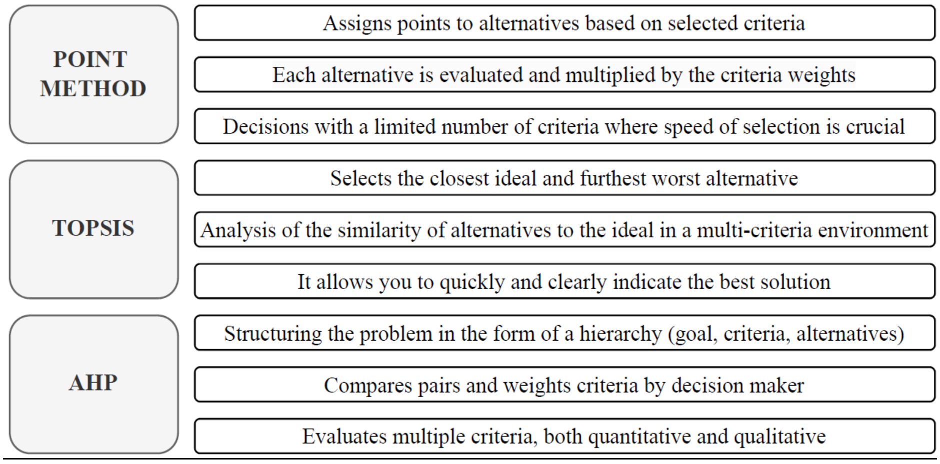


Figure 1. Selected decision support methods Source: own study based on 231.

3. The research problem of evaluating the choice of technology for cargo movement through logistics facilities

3.1. General assumptions – load on the logistics facility

It is assumed that warehouse facilities that mediate the flow of goods between suppliers and receivers of cargo are the subject of the study m, whereas $m \in \boldsymbol{M}$ where $\boldsymbol{M}$ is a set of objects, while each warehouse m belongs to a certain type t, whereas $t \in \boldsymbol{T}$, where $\boldsymbol{T}$ is the set of types of warehouses. Different groups of goods are stored in the facilities gt, whereas $gt \in \boldsymbol{GT}$ is a set of commodity groups. The size of each commodity group is defined as q, whereas $q \in Q$ where $\boldsymbol{Q}$ is the set of volumes of each commodity group. In addition, the capacity of the m-th warehouse type t is defined as $\boldsymbol{P}_{t(m)}$, where $t(m)$ is the type of the m-th warehouse. The number of commodity groups stored gt depends on the load of the warehouse $\boldsymbol{L}_{m}$, which represents the intensity of the warehouse operations m, i.e. the number of cargo or operations handled in a given period of time. The load depends on the number of commodity groups stored gt, their size $\boldsymbol{Q}_{gt,m}$ and the frequency of goods movements. Accordingly, the load on the warehouse L_m is expressed as:

$$L_m = \sum_{gt \in GT} Q_{gt,m} \cdot o_{gt,m} \tag{1}$$

where: $o_{gt,m}$ – turnover rate for $gt - th$ commodity group in $m - th$ the warehouse.

It was assumed that the volume of logistics tasks identified in the area would be mapped using a supply matrix $\boldsymbol{A}_{GT}$ (quantity of supplied goods) and the demand matrix $\boldsymbol{B}_{GT}$ (volume of demand declared). The volumes $a_{gt,m}$ are the volume of supply, while $b_{gt,m}$ the volume of demand declared by the warehouse facilities in question $(m \in M)$ of goods from the following commodity groups $(gt \in GT)$. The structure of the matrix is shown below. They serve to identify asymmetries between supply and demand, which is key to optimising logistics processes. It is also possible to prioritise deliveries, taking into account the reported needs of warehouses.

$$\boldsymbol{A}_{GT} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,M} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ a_{GT,1} & a_{GT,2} & \cdots & a_{GT,M} \end{bmatrix} \boldsymbol{B}_{GT} = \begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,M} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ b_{GT,1} & b_{GT,2} & \cdots & b_{GT,M} \end{bmatrix} \tag{2}$$

In order to carry out the study and the analysis of the effectiveness of applying an appropriate technology to the $t(m)$-th type of warehouse, a set of $\boldsymbol{V}$ of warehousing technologies that can be used, whereas: the $v \in \boldsymbol{V}$ (v-th variant of storage technology). For the unambiguousness of further analysis, the notation is adopted: $V = \{v \equiv v_i: \ i = 1, \dots, N\}$. For the purposes of the study, it is assumed that the set $\boldsymbol{V(m)}$ will be a set of warehousing technology options:

$$V(m) = \{v(m): \ v \in V\}, \ m \in M \tag{3}$$

Binary decision variables are also introduced into the analysis $\boldsymbol{X} = \left[\boldsymbol{x}_{v(m)}\right]_{\boldsymbol{VxM}} \in \{0,1\}$:

$$x_{v(m)} = \begin{cases} 1, \text{if technology v is applied in } m-th \text{ warehouse facility; } m\epsilon M, \\ 0, \text{otherwise.} \end{cases}$$

3.2. Indicators for assessing the efficiency and reliability of process implementation using different technologies

Choosing the right warehousing technology, taking into account the reliability and efficiency of the systems, is a key element of the operational strategy of any company managing a warehouse facility. To make the best choice, it is important to focus on a few key criteria $\boldsymbol{K}$ that have the greatest impact on the company's efficiency, costs and future growth. Each technology $v-th$ is assessed against a number of key sub-criteria k that make up a set of $K = \{f_k: k = 1, \dots, K\}$.

These criteria reflect the most important aspects that are relevant when deciding on the choice of warehousing technology. In particular, operational efficiency and the reliability of technology are key to ensuring the smooth execution of logistics processes. Other criteria that are relevant and should be taken into account in the assessment include: investment cost, cargo access time, safety, operational costs.

Each of the criteria k depends on $c(k)$ factors, which can be written in a vector $\boldsymbol{Y_k}$ of the form:

$$Y_k = [y^{kc(k)}:\ c(k) = \overline{1, \dots, C(k)}], k = 1, \dots, K;\ f_k \in K \quad (4)$$

where: $y^{kc(k)}$ – denotes the value of $c(k)$-th factor affecting the criterion k.

Factors are of key importance, defining precisely which aspects of each warehousing technology directly affect the rating in the context of a given criterion, allowing the technology to be more precisely tailored to the specific requirements and operational needs of a given business. For example, factors influencing investment costs include the unit investment cost per unit of capacity P_m, the cost of installation and configuration of the warehouse, the cost of adapting the warehouse or the cost of staff training. Operational efficiency, on the other hand, is influenced by, among other things, the number of operations per hour, the level of automation, the unit time of operations, etc.

Safety, on the other hand, is determined by minimising accidents through the use of fire protection systems, process automation, process monitoring, risk management, schedules or the introduction of safety procedures and staff training, among other things. Similarly, the criterion of cargo access time will be influenced by factors such as the speed of warehouse operations, the efficiency of goods distribution or the degree of automation of the system.

As mentioned, one important criterion for evaluating a technology is its reliability. The reliability of the technology is influenced by many aspects, such as the number of human errors, system overload, the amount of delay caused by a single failure, the cost and time to restore the system to full capacity after a failure, and the quality of the system components. In the case of operating costs, the following should be mentioned: energy consumption, maintenance costs, technology operating costs, etc. Each v_i-th technology is assessed against each k-th criterion. With this in mind, the influence of factors on a given evaluation criterion can be illustrated as in Figure 2.

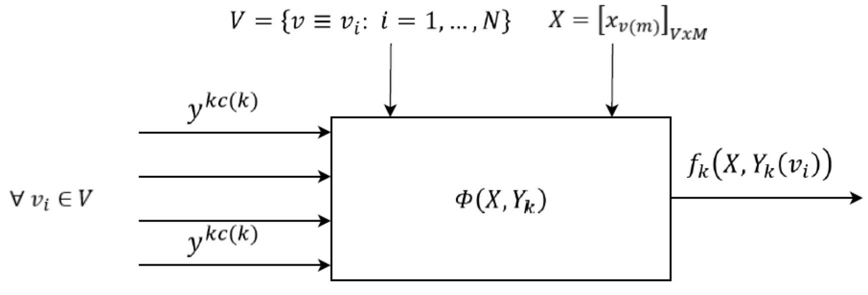


Figure 2. Evaluation of warehousing technologies in terms of efficiency and reliability based on criteria and factors affecting them.

Source: own study

As a result, for the v_i-th variant, a score is obtained for the *k-th* criterion, written with the function $\boldsymbol{\Phi(X, Y_k)}$ of the form:

$$\forall\, k \in K \quad \Phi(X, Y_k) = f_k(X, Y_k(v_i)) \to extreme \quad (5)$$

Given the above ratings of the options from the point of view of the sub-criteria, a rating matrix of the form can be written:

$$OV(m) = [o_{vk}: o_{vk} \equiv f_k(v_i) \in R^+, v_i \in V \wedge f_k \in K; i = 1, \dots, N; k = 1, \dots, K]\ \forall\, m \in M \quad (6)$$

$$f_k(X, Y_k(v_i)) = \sum_{c=1}^{C(k)} y^{kc} \cdot x_{v(m)} \to extreme \quad (7)$$

The objective function in the process of evaluating the efficiency and reliability of technology selection in a warehouse facility is expressed as a vector $F(X,Y)$, which consists of individual sub-functions corresponding to the evaluation criteria. Each partial function $f_k(X)$ describes the influence of factors Y_k on the assessment of the technology v used in the warehouse facility m. As a whole, this enables a comprehensive assessment and identification of a favourable technology option for the facility:

$$F(X,Y) =< f_1(X, Y_1(v_1)), \dots, f_k(X, Y_k(v_i)), \dots, f_K(X, Y_k(v_n)) > \quad (8)$$

4. Evaluation of cargo flow technology through warehouse facilities in terms of efficiency and reliability

4.1. Efficiency and reliability evaluation process in terms of equipment selection

Analysing and evaluating the selection of warehousing technologies in terms of their efficiency and reliability requires interdisciplinary knowledge not only of the operation of warehouse facilities and the implementation of processes in them, but also of database construction, cost determination and decision-making from multiple, often conflicting, viewpoints. The general procedure can be written in several steps, as shown in Figure 3.

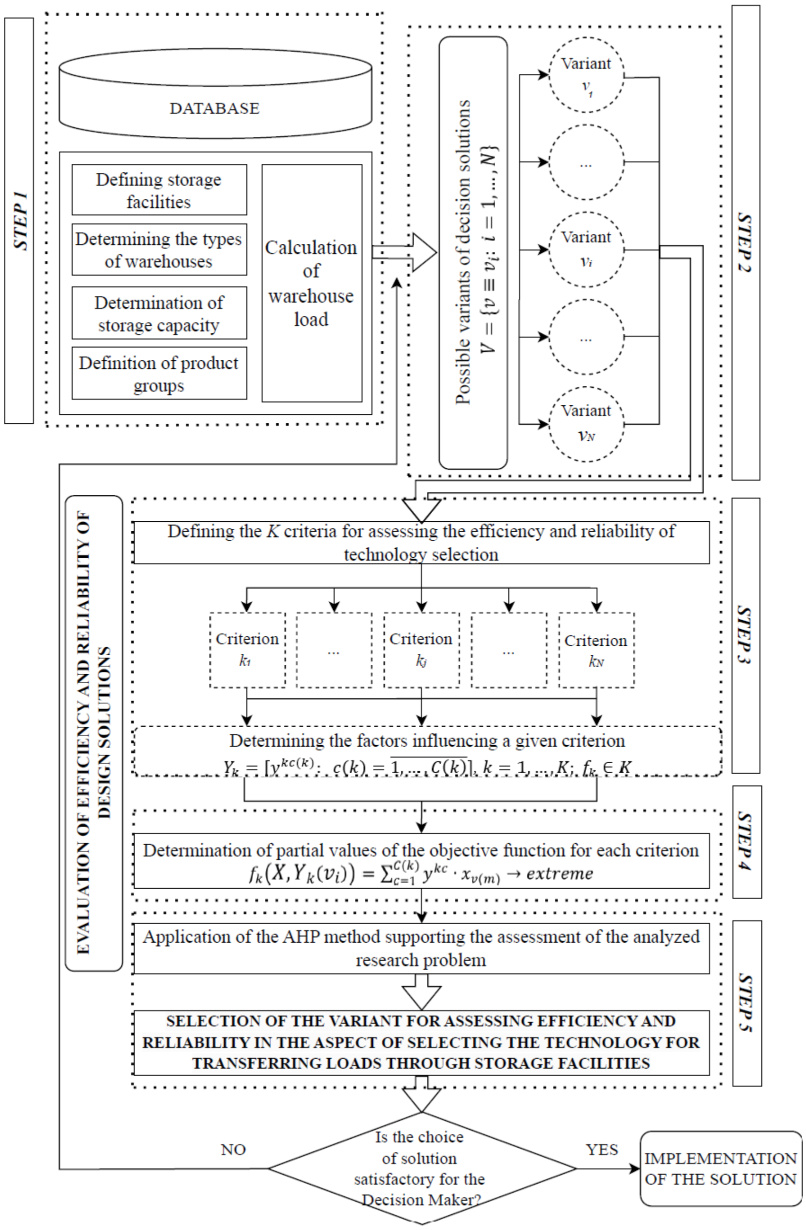


Figure 3. Diagram for assessing efficiency and reliability in terms of equipment selection in warehouse facilities.
Source: own study

Step 1: define the basic assumptions about the type of facilities, their parameters, storage capacity, commodity groups, determination of warehouse load. The load depends on the number of commodity groups stored, their size and the frequency of goods turnover.

Step 2: Establishing a set of options of V warehousing technologies. Each technology option v represents different approaches to the implementation of storage processes. A set of options $V(m)$ assigns permissible technologies for the *m-th* object.

Step 3: establishing a set of K criteria for evaluating the storage technologies used and determining the factors that affect each criterion. For each f_k criterion, a vector of factors is defined Y_k which directly influence the value of a given criterion. Factors make it possible to determine the impact of the technologies in question on the implementation of storage processes.

Step 4: estimation/determination of the partial values of the objective function for each criterion. The values of the objective function are calculated as: $f_k(X, Y_k(v_i)) = \sum_{c=1}^{C(k)} y^{kc} \cdot x_{v(m)} \rightarrow extreme$ for each option. The result is a matrix of ratings $OV(m)$ for each type of warehouse from the point of view of the established criteria and the identified technology options.

Step 5: application of the AHP method for selecting the best technology option in terms of efficiency and reliability of process implementation. Based on the results of the AHP analysis, the best variant of storage technology is selected that meets the adopted criteria for efficiency, reliability and cost. Using AHP enables a logical and transparent transition from the defined assumptions to the selection of the most advantageous storage technology.

4.2. Algorithm of the AHP method

In order to carry out a multi-criteria analysis of technology selection, a diagram was developed to illustrate the mechanism of the AHP method, which includes steps leading to the construction of a ranking and selection of an option to assess the efficiency and reliability of the technology. Figure 4 shows the successive steps of the decision-making process, from identifying the objective and defining the criteria, to the calculations leading to the selection of a favourable technology option.

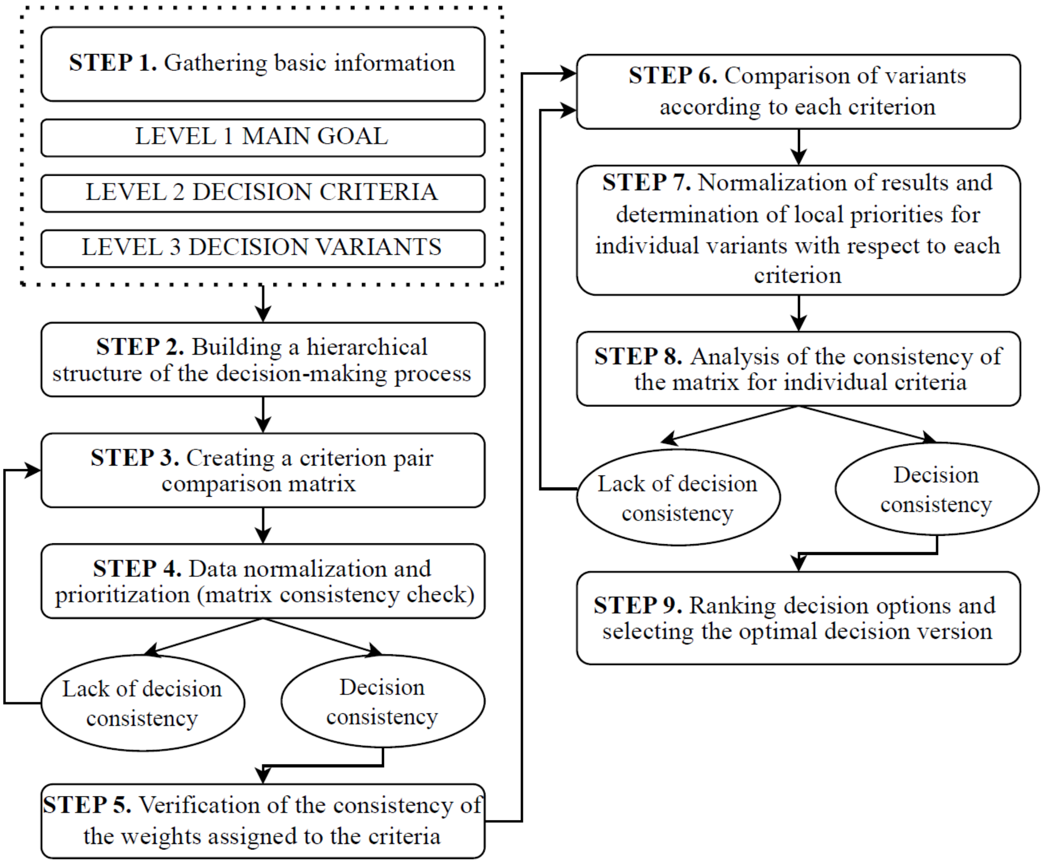


Figure 4. Algorithm for the implementation of calculations in the AHP method Source: own study based on 17.

In the first step of the assessment, the input information must be defined. Subsequent calculations for assessing efficiency and reliability in terms of equipment selection in warehouse facilities depend on their quality. The second step concerns the creation of a hierarchical structure for the decision problem, which sets out three levels (study objective, criteria, decision options). Step 3 is related to the creation of a pair of criteria comparison matrix. The assessments were carried out according to Saaty's 9-point scale and the results of the individual expert assessments were aggregated using a geometric mean. The Saaty's scale, allows values to be assigned by comparing criteria, with the weighting of a criterion numbered k against criterion numbered k' amounting to $\omega_{k'k}$ will take the value $\frac{1}{\omega_{k'k}}$, when evaluating criterion numbered k' against criterion number k.. Importantly, the values are compensatory, ensuring that comparisons between pairs of criteria are consistent. Therefore, the weighting value for criterion numbered k with a lower weighting over criterion k' in a given pair of criteria is the reciprocal of the value attributed to the element with the higher weighting: $\omega_{k'k} = \frac{1}{\omega_{k'k}}$, where $\omega_{k'k}$ is an assessment of the superiority of k-th criterion over k'-th one. This maintains proportionality between assessments and minimises the impact of extreme values. In case of significant discrepancies in the assessments, additional consultations were held, during which the experts discussed their decisions, clarified doubts and jointly agreed on the final values.

The next step 4 is to set global priorities and rank the importance of criteria 51. Subsequent elements of the matrix were normalised according to the relationship: $\omega'_{kk'} = \frac{\omega_{kk'}}{\sum_{k^n=1}^{K}\omega_{k^n k'}}$, where $k, k' = 1, \dots, K$. The calculation of the values allowed the criteria to be prioritised (weightings) according to the formula: $g_k = \frac{1}{K}\sum_{k'=1}^{K}\omega'_{kk'}$, whereas $k = 1, \dots, K$.

At step 5, each comparison matrix is verified for consistency using the CR indicator. 17, which takes values less than 0.1 and is calculated from the relationship: $\Omega W = C = [c_k]_{Kx1}$; $\lambda = \frac{1}{K}\sum_{k=1}^{K}\frac{c_k}{g_k}$; $CI = \frac{\lambda - K}{K-1}$; $CR = \frac{CI}{RI}$, where: K – the number of criteria being compared, while RI – consistency index.

The individual decision options are then analysed for each criterion in step 6. According to the procedure of the AHP method for K criteria, a K of comparison matrix is created, on the basis of which local priorities are determined, creating a ranking. Each comparison matrix was checked for consistency. The priorities for k-th criterion form a matrix $V_k = [v_{ik}]_{Nx1}$, where $i = 1, \dots, N$ is the option number, while $k = 1, \dots, K$ is the criterion number.

$$V = [V_1 \dots V_k \dots V_K] = \begin{bmatrix} v_{11} & \cdots & v_{1k} & \cdots & v_{1K} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ v_{i1} & \cdots & v_{ik} & \cdots & v_{iK} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ v_{N1} & \cdots & v_{Nk} & \cdots & v_{NK} \end{bmatrix}_{NxK} \quad (9)$$

In situations where consistency would be compromised, additional expert meetings should be organised to revisit contentious issues. Particular attention should be paid to the criteria with the highest weighting, such as operational efficiency or operating costs. The diversity of experts' competences allowed the practical constraints of technology implementation to be taken into account, the potential risks to be assessed and the real benefits to be understood.

Step 7 involves the normalisation of the results and the determination of local priorities for the options in relation to each criterion. In order to establish local priorities, all the ratings in a given row must be added up and then divided by the number of those ratings, which in practice means calculating the arithmetic mean of the normalised ratings for a given option.

The next step 8 is to analyse the consistency of the matrix for each criterion. The product of each matrix containing pairwise comparisons of the criteria and the columns labelled "priority" in the normalised matrices with priorities for the criterion was calculated. The results of these products were then divided by the priorities for each criterion and, after calculating the mean of the values obtained, the indices of λ, CI and CR were determined.

The last step 9 is related to the creation of the final ranking and requires the determination of the product of the matrix that emerged from the local priorities $VW = A = [a_i]_{Nx1}$. The option with the highest score indicates the most favourable solution.

5. Case study

5.1. Determination of input data, decision options and evaluation criteria

The input data are a key element of the multi-criteria analysis process, as it is on the basis of these data that technological alternatives are evaluated. In the context of selecting the optimal technology, the data include the values of the individual evaluation criteria for the alternatives under consideration, allowing an accurate comparison of their efficiency and costs. The data are then normalised to allow comparison on standardised scales and then processed using the AHP method. **The data for the analysis relate to a high-bay warehouse facility (area 36,750 m^2) with a daily cargo flow of 9,000 - 12,000 pallet load units (PLU).** When comparing different warehousing technologies for a large high-bay warehouse acting as a distribution centre for food and consumer goods, it is necessary to use data based on benchmarking and available industry sources, such as operational reports. For as yet unimplemented technologies, estimates are derived from benchmarking of other facilities with similar characteristics, the results of operational simulations, and specifications and tests provided by system manufacturers. These data were supplemented with analyses of the life-cycle costs of the technologies to better understand their long-term financial implications. The impact of integrating the technology with existing warehouse systems was also considered, which is important to minimise disruption to the facility.

The multi-criteria analysis process using the AHP method applied the knowledge and experience of a group of experts to ensure the reliability of the assessments and the validity of the results. The group of experts was selected to include the diverse perspectives and competencies needed to assess the effectiveness of warehousing technologies. It included logistics and warehouse facility managers, warehouse technology specialists, logistics consultants and health and safety experts. Each of these individuals brought unique experience in the practical aspects of technology implementations, cost analysis, operational efficiency and safety. The experts assessed the criteria and decision options individually, thus avoiding group influence on the preliminary results.

Investment and operating costs were obtained from market bids, cost analyses, and consultations with companies using the technologies under consideration, allowing an accurate estimate of the financial outlay associated with each option. Operational efficiency and cargo access times were determined using data from actual warehouse operations and performance reports, as well as information from the websites that produce the technologies under study. This made it possible to take into account actual operating conditions.

Safety indicators were established by analysing historical accident data, safety audit reports and prevention procedures used at other facilities with a similar profile. System reliability indicators were assessed on the basis of an analysis of historical data, the results of operational simulations and technical specifications provided by warehousing technology manufacturers. Key factors such as failure rate, repair time and cost, and system resilience to overload were assessed with expert opinion. This process made it possible to precisely determine the impact of individual technologies on operational reliability under real-world operating conditions. The process of determining the data took into account the opinions of experts, which ensures that the data are in line with actual operational conditions and can be used for a sound analysis using the chosen multi-criteria decision support method.

Six options differing in the technology used were defined for the analysis of efficiency and reliability assessment in terms of equipment selection in a high-bay warehouse facility:

- $v_1 -$ an option using traditional pallet racks,
- $v_2 -$ the use of automated high-rack systems,
- $v_3 -$ implementation of the integrated AS/RS system,
- $v_4 -$ implementation of a semi-automated storage system,
- $v_5 -$ an option using the AGV system to manage warehouse processes,
- $v_6 -$ introduction of drones for efficient management of storage space.

Table 2 shows the inputs for assessing equipment efficiency and reliability.

Table 1. Input data for efficiency and reliability assessment in terms of equipment selection in a high-bay warehouse facility.

K \ V	v_1	v_2	v_3	v_4	v_5	v_6
Investment cost [PLN]	600.000	1.600.000	2.500.00	1.200.000	900.000	2.100.000
Operational efficiency [operations/h]	90	150	200	120	160	250
Cargo access time [s]	100	40	35	60	50	30
Safety [number of accidents/year]	3	4	2	3	3	1
Reliability of the technology [number of failures/year]	3	5	4	6	6	7
Operating costs [PLN/year]	150.000	100.000	130.000	110.000	140.000	120.000

Source: own study based on 52- 61

5.2. Hierarchical structure of the decision-making process for evaluating efficiency and reliability in terms of equipment selection

Figure 5 shows the hierarchical structure of the decision problem, which delineates three levels. The first one is the purpose of the studies, i.e. the selection of warehousing technology in terms of the efficiency and reliability of the entire supply chain. The second level is criteria and the final level is decision options.

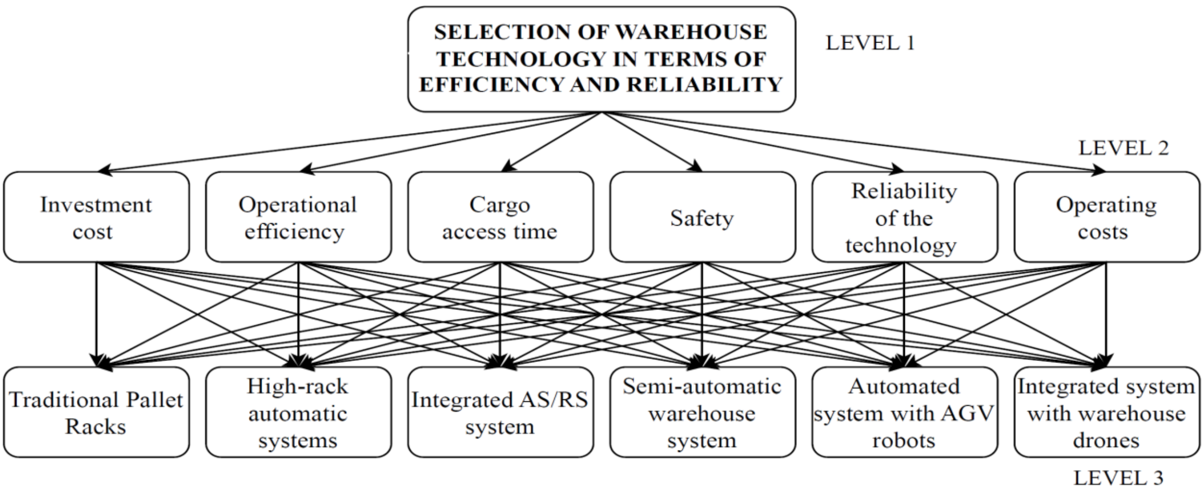


Figure 5. Hierarchical structure of the decision-making problem under study.

Source: own study

5.3. Construction of a criteria pair comparison matrix, prioritisation and verification of consistency of criteria weightings

Collaborating with a group of experts, for the assessment of the decision-making situation under analysis, was crucial in order to obtain consistent and reliable analysis results that reflected both technical and operational aspects of the warehousing technology assessment. This ensured that the decision-making process was based on a solid foundation, taking into account different perspectives and ensuring the reliability of the final results.

Table 3 shows the criteria pair comparison matrix for the decision situation analysed. Table 4, on the other hand, shows the normalised matrix with priority for each criterion. It also includes a global priority column which can be written in a vector of $G = [g_k]_{Kx1}$. Consistency analysis was performed by calculating the λ, CI and CR ratios.

Table 2. Criteria pair comparison matrix.

K	k_1	k_2	k_3	k_4	k_5	k_6
k_1	1.00	0.33	0.25	0.20	0.33	0.25
k_2	3.00	1.00	0.33	0.25	0.50	0.33
k_3	4.00	3.00	1.00	0.50	2.00	1.00
k_4	5.00	4.00	2.00	1.00	3.00	2.00
k_5	3.00	2.00	0.50	0.33	1.00	0.50
k_6	4.00	3.00	1.00	0.50	2.00	1.00
Total	20.00	13.33	5.08	2.78	8.83	5.08

Source: own study

Table 3. Standardised input data and determination of global priority.

K	k_1	k_2	k_3	k_4	k_5	k_6	Global priority
k_1	0.05	0.02	0.05	0.07	0.04	0.05	0.05
k_2	0.15	0.08	0.06	0.09	0.06	0.06	0.08
k_3	0.20	0.23	0.20	0.18	0.23	0.20	0.21
k_4	0.25	0.30	0.39	0.36	0.34	0.39	0.34
k_5	0.15	0.15	0.10	0.12	0.11	0.10	0.12
k_6	0.20	0.23	0.20	0.18	0.23	0.20	0.21

Source: own study

For the case under analysis: $\lambda = 6{,}27$; $CI = 0{,}05$; $CR = 0{,}04$. The values of the coefficient RI determined from the computer simulation are summarised in Table 5 17.

Table 4. The values of the coefficient RI determined on the basis of computer simulation.

n	2	3	4	5	6	7	8	9
Value	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45

Source: own study based on 3717

The results of the above calculations showed that the CR index is less than 0.1, which means that the assessments regarding the importance of the criteria are in compliance.

5.4. Comparison of options against each criterion

The sum of the scores for each option under each criterion was calculated. The collected assessments were used in the next step, namely the normalisation of the results. The results of comparing the options against each criterion are shown below

Table 5. Comparison of options in relation to the investment cost criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	0.33	0.20	0.50	0.25	0.50
v_2	3.00	1.00	0.50	1.00	0.50	1.00
v_3	5.00	2.00	1.00	3.00	1.00	2.00
v_4	2.00	1.00	0.33	1.00	0.50	1.00
v_5	4.00	2.00	1.00	2.00	1.00	2.00
v_6	2.00	1.00	0.50	1.00	0.50	1.00
Total	17.00	7.33	3.53	8.50	3.75	7.50

Source: own study

Table 6. Comparison of options in relation to the operational efficiency criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	0.33	0.25	0.33	0.20	0.17
v_2	3.00	1.00	3.00	2.00	1.00	0.20
v_3	4.00	0.33	1.00	3.00	0.33	0.17
v_4	3.00	0.50	0.33	1.00	0.50	0.25
v_5	5.00	1.00	3.00	2.00	1.00	0.20
v_6	6.00	5.00	6.00	4.00	5.00	1.00
Total	22.00	8.16	13.58	12.33	8.03	1.99

Source: own study

Table 7. Comparison of options in relation to the cargo access time criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	0.25	0.20	0.33	0.50	0.33
v_2	4.00	1.00	2.00	3.00	4.00	2.00
v_3	5.00	0.50	1.00	4.00	5.00	3.00
v_4	3.00	0.33	0.25	1.00	2.00	1.00
v_5	2.00	0.25	0.20	0.50	1.00	0.33
v_6	3.00	0.50	0.33	1.00	3.00	1.00
Total	18.00	2.83	3.98	9.83	15.50	7.67

Source: own study

Table 8. Comparison of options in relation to the safety criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	2.00	3.00	2.00	2.00	1.00
v_2	0.50	1.00	0.50	1.00	1.00	0.50
v_3	0.33	2.00	1.00	0.50	1.00	1.00
v_4	0.50	1.00	2.00	1.00	1.00	0.50
v_5	0.50	1.00	1.00	1.00	1.00	1.00
v_6	1.00	2.00	1.00	2.00	1.00	1.00
Total	6.50	6.33	6.50	12.00	6.50	8.00

Source: own study

Table 9. Comparison of options in relation to the scalability criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	0.50	1.00	2.00	1.00	1.00
v_2	2.00	1.00	2.00	3.00	3.00	3.00
v_3	1.00	0.50	1.00	2.00	1.00	1.00
v_4	0.50	0.33	0.50	1.00	0.50	1.00
v_5	1.00	0.33	1.00	2.00	1.00	3.00
v_6	1.00	0.33	1.00	1.00	0.33	1.00
Total	6.50	2.99	6.50	11.0	6.83	10.00

Source: own study

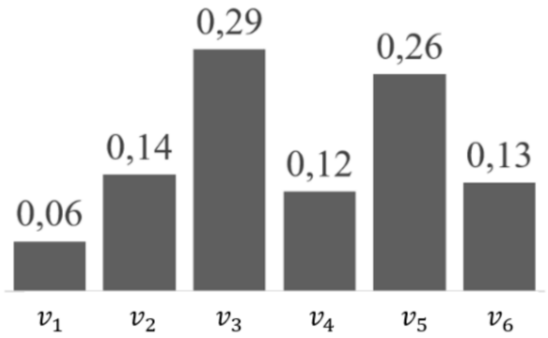
Table 10. Comparison of options in relation to the operating costs criterion.

Option v_i	v_1	v_2	v_3	v_4	v_5	v_6
v_1	1.00	0.33	0.50	1.00	0.50	2.00
v_2	3.00	1.00	2.00	2.00	1.00	3.00
v_3	2.00	0.50	1.00	1.00	0.50	2.00
v_4	1.00	0.50	1.00	1.00	1.00	1.00
v_5	2.00	1.00	2.00	1.00	1.00	2.00
v_6	0.50	0.33	0.50	1.00	0.50	1.00
Total	9.50	3.67	7.00	7.00	4.50	11.00

Source: own study

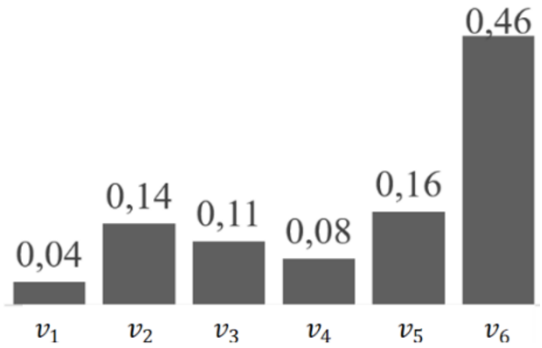
5.5. Normalization of the results and determination of local priorities for the options for each criterion

The identification of local priorities for the options against each criterion allowed a ranking of the options to be created in the form of a matrix. Normalisation was performed so that comparable values could be obtained, allowing a consistent ranking to be determined and identifying the option with the best overall rating. In order to establish local priorities, all the ratings in a given row were added up and then divided by the number of those ratings, which in practice means calculating the arithmetic mean of the normalised ratings for a given option. The following figures 11-16 show the value of local priority for the alternatives against the criterion analysed.



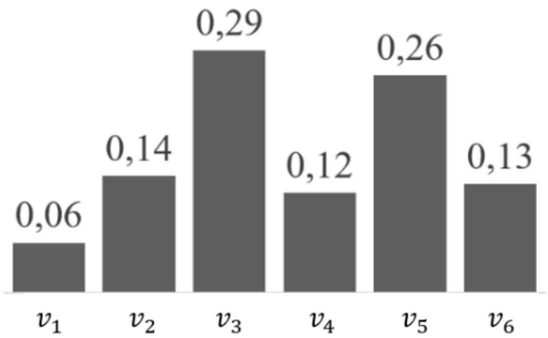
Source: own study

Figure 11. Local priority value of the options against the investment cost criterion.



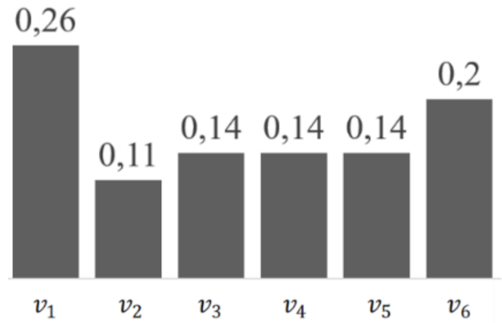
Source: own study

Figure 12. Local priority value of the options against the operational efficiency criterion.



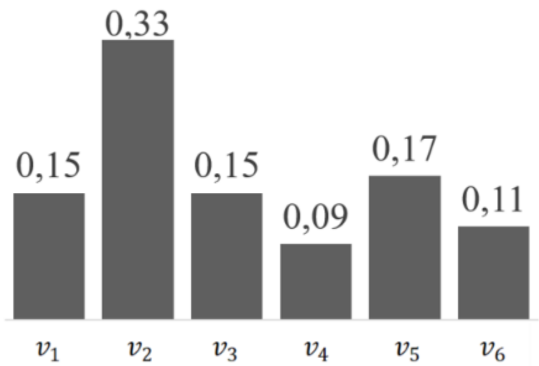
Source: own study

Figure 13. Local priority value of the options against the cargo access time criterion.



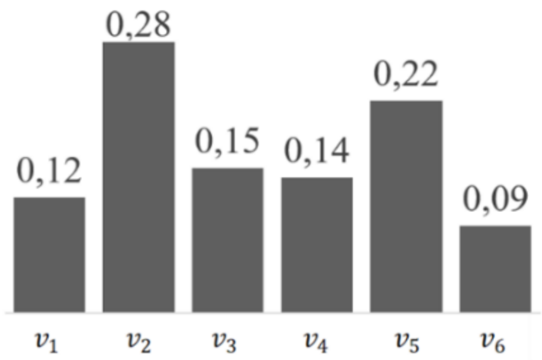
Source: own study

Figure 14. Local priority value of the options against the safety criterion.



Source: own study

Figure 15. Local priority value of the options against the investment cost criterion.



Source: own study

Figure 16. Local priority value of the options against the operating costs criterion.

5.6. Analysis of the consistency of the matrix for each criterion and determination of the best decision option

The final stage of the analysis is to perform a matrix consistency analysis for the criteria studied. For each criterion, indicators were determined in accordance with the AHP evaluation algorithm λ, CI and CR.

Table 17. Results of the matrix consistency analysis for the investigated criteria.

	k_1	k_2	k_3	k_4	k_5	k_6
λ	6.0320	6.5950	6.2440	6.2560	6.1740	6.1870
CI	0.0064	0.1190	0.0489	0.0512	0.0350	0.0373
CR	0.0052	0.0960	0.0394	0.0413	0.028	0.0301

Source: own study

The final step is to develop a final ranking and determine the product of the matrix, formed on the basis of local priorities (comparing the options against each criterion): $VW = A = [a_i]_{Nx1}$. The option with the highest score indicates the most favourable solution, as shown below:

$$\begin{bmatrix} 0,06 & 0,04 & 0,05 & 0,26 & 0,15 & 0,12 \\ 0,14 & 0,14 & 0,32 & 0,11 & 0,33 & 0,28 \\ 0,29 & 0,11 & 0,30 & 0,14 & 0,15 & 0,15 \\ 0,12 & 0,08 & 0,12 & 0,14 & 0,09 & 0,14 \\ 0,26 & 0,16 & 0,07 & 0,14 & 0,17 & 0,22 \\ 0,13 & 0,46 & 0,14 & 0,20 & 0,11 & 0,09 \end{bmatrix} \text{x} \begin{bmatrix} 0,05 \\ 0,08 \\ 0,21 \\ 0,34 \\ 0,12 \\ 0,21 \end{bmatrix} = \begin{bmatrix} 0,15 \\ 0,22 \\ 0,18 \\ 0,13 \\ 0,15 \\ 0,17 \end{bmatrix}$$

The matrix presents the final results of the multi-criteria analysis performed using the AHP method, the aim of which was to compare different options of warehouse technologies in terms of their efficiency and reliability. Each column in the matrix represents local priorities of technological options in relation to individual criteria. The final result of the analysis is a vector containing the total scores for each option, calculated as the product of the local priority matrix and the weights assigned to individual criteria. The result of 0.22 indicates the technology that received the highest score, which means that it best meets the assumed criteria and is the most beneficial solution in a given logistics context. In the analysed case, it was the technology of the automatic high-rack system, which turned out to be the most efficient, reliable and adapted to operational requirements.

6. Summary

This paper examines the process of evaluating and selecting, using the AHP method, warehousing technologies for the efficiency and reliability of process execution. Six different technology options were considered in the decision-making process, including traditional pallet racks, automated high-rack systems, an integrated AS/RS system, semi-automated warehouse systems, automated systems with AGVs and advanced integrated drone warehouse management systems. Investment cost, operational efficiency, cargo access time, safety, technology reliability and operational costs were considered as key criteria for assessing the efficiency and reliability of the technologies used.

Studies have shown that an automatic high-rack system (option v_2) is the most efficient solution. The chosen technology, although initially generating higher investment costs, has proven to be not only efficient but also reliable in the context of varying operational requirements, providing the long-term stability and flexibility needed in a rapidly changing logistics environment.

A key criterion for the analysis was operational efficiency, i.e. the warehouse's ability to manage the flow of goods quickly and smoothly. The automated high-rack system proved unrivalled, completing up to 150 operations per hour – a result that significantly exceeds the performance of technologies such as traditional pallet racking or semi-automated warehouse systems. This level of operability makes it possible to significantly increase the throughput of the warehouse and thus the efficiency of warehouse processes. In addition, the low cargo access time of 40 sec on average contributes to streamlining the entire process of picking and preparing orders for dispatch, which is key to improving customer service.

Choosing an automated high-rack system is also about ensuring operational stability, which minimises the risk of interruptions to warehouse operations and, therefore, the reliability of the entire supply chain. The system has a lower failure rate compared to other advanced technologies, such as storage drones or AGV systems, which, while highly innovative, often generate higher maintenance costs and require a more complex supporting infrastructure.

The chosen solution also has a bearing on operating costs – the estimated annual maintenance costs of PLN 100,000 are relatively low compared to the potential costs associated with operating more complex systems. The choice of high-rack technology also ensures a high level of flexibility and scalability. The ability to expand the system as operational demand increases means that the technology can meet future market challenges without the high cost of infrastructure modifications. When market dynamics force an increase in the volume of operations, the system can be adapted, which is crucial in terms of operational and cost stability. In addition, the scalability of this solution makes it possible to adapt warehouse operations to seasonal fluctuations in demand, further increasing its value for companies with intensive logistics operations.

To conclude, the analysis indicates that the choice of automated high-rack systems brings benefits from an operational angle. The solution provides high performance, flexibility while minimising the risk of failure. The final choice of this technology was made with a long-term operational strategy in mind, including cost optimisation, operational efficiency and reliability, which are key to remaining competitive and stable in a dynamic logistics environment.

The studies carried out indicate that the AHP method can be an effective tool for decision support in situations where the problem under analysis requires the consideration of multiple criteria with varying degrees of importance. Because of its hierarchical structure and its ability to take into account both quantifiable and non-quantifiable aspects, AHP is ideally suited to the processes of evaluating technologies used in logistics facilities that must meet high standards of reliability and operational efficiency.

Based on the results presented in this article, several key directions for further research can be identified that will allow for deepening knowledge and improving decision-making processes in the field of warehouse technology selection. Future research will focus on integrating the AHP method with the advanced simulation tool FlexSim. This will allow for dynamic verification of selected technologies in various operational scenarios, which will increase the reliability of the decision-making process. Another direction of further research is to conduct comparative studies combining the AHP method with other multi-criteria decision support methods, such as PROMETHEE or TOPSIS. This could provide new information on the consistency and variability of results obtained in different analytical frameworks. The implementation of these research directions will contribute to the further development of decision support methods and the introduction of innovations in logistics and supply chain management.

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