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A Multi-Criteria Decision Making for Automated Storage System Selection in the Warehousing Industry Using AHP-TOPSIS

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ABSTRACT
The growing demand for customized products and shorter delivery times has intensified the pressure on logistics and warehouse operations to become more efficient, flexible, and responsive. In this context, selecting an appropriate automated storage and retrieval system (AS/RS) is a complex multi-criteria decision-making (MCDM) problem that requires a systematic, quantitative evaluation approach. This study proposes an integrated decision-making framework that combines the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to determine the most suitable automated storage technology for warehousing operations. Four key criteria were identified—Throughput, Accuracy, Ergonomics, and Space Utilization—and three alternatives were evaluated: Miniload, Vertical Carousel, and Vertical Lift. The AHP method was used to derive the relative importance of the criteria, producing consistent weights with a CR value of 8.28%. These weights were subsequently applied in the TOPSIS analysis to rank the alternatives based on their closeness to the ideal solution. The results indicate that Vertical Lift emerged as the optimal choice (CC = 0.6657), followed by Vertical Carousel (CC = 0.4657) and Miniload (CC = 0.3688). Sensitivity analysis, conducted through both One-at-a-Time (OAT) and scenario-based approaches, confirmed the robustness of the decision model under varying preference scenarios. This research contributes to the body of knowledge on warehouse automation decision-making by providing a transparent, quantitative, and adaptable framework that supports managers in enhancing operational performance and optimizing resource utilization.

Keywords: Warehouse Automation, Automated Storage and Retrieval System, AHP, TOPSIS, Multi-Criteria Decision-Making (MCDM).

I. Introduction

Supply chain management has emerged as a crucial factor influencing organizational competitiveness amid globalization and digital transformation. Companies now compete not only on product quality or price but also on their ability to deliver items more swiftly, accurately, and at lower operational costs. As global marketplaces grow increasingly turbulent and client demand becomes more tailored, supply chain efficiency is crucial for maintaining corporate sustainability and fostering long-term success (Ivanov & Dolgui, 2020). In the supply chain, warehousing serves as a pivotal hub that directly affects inventory precision, order fulfillment speed, and overall service level performance. The swift progression of digital technologies, including automation, artificial intelligence, and cyber-physical systems, has expedited the evolution of warehouse operations. Organizations are increasingly implementing automated storage and retrieval systems (AS/RS) to mitigate operational issues arising from labor shortages, human error, spatial constraints, and escalating consumer demands (Boysen, de Koster, & Weidinger, 2019; Zhang et al., 2021). Automated storage solutions offer significant advantages, including increased throughput, greater picking precision, enhanced team member safety, and optimized use of warehouse space. The installation of warehouse automation entails substantial investment expenditures and long-term strategic considerations, rendering technology selection a complex managerial decision. Choosing a suitable automated storage system is a complex endeavor, since decision-makers must assess numerous, frequently contradictory criteria. A system characterized by high throughput may necessitate increased spatial requirements or sacrifice ergonomic conditions, whereas a system with superior accuracy may not consistently deliver ideal processing speed. Recent studies underscore that decisions about warehouse automation should not be based exclusively on cost factors, but rather on a comprehensive assessment of technological, operational, and human-centric variables (Azadeh et al., 2021; Liu et al., 2022). As a result, selecting warehouse automation has become a multi-criteria decision-making (MCDM) challenge, requiring rigorous, transparent, and quantitative assessment methodologies.

Prior studies have extensively utilized MCDM approaches to facilitate decision-making in logistics and supply chain environments. Methods including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR, and ELECTRE have been utilized to assess suppliers, logistics service providers, warehouse sites, and automation technologies. (Pamucar et al., 2020; Stević et al., 2021). AHP is notably proficient at organizing complex decision-making problems and determining the relative importance of assessment criteria via pairwise comparisons. In contrast, TOPSIS is adept at ranking options based on their proximity to an optimal solution and their distance from the least favorable outcome. Recent research highlights the growing interest in hybrid MCDM models that combine AHP with TOPSIS to enhance decision robustness. Chen et al. (2020) employed an AHP–TOPSIS framework to assess intelligent logistics systems, emphasizing its capacity to reconcile quantitative and qualitative criteria. Rashidi and Cullinane (2021) demonstrated that hybrid MCDM techniques yield more lucid decision insights than single-method models, especially in intricate logistical contexts. Notwithstanding these developments, the prevailing research predominantly emphasizes supplier selection, transportation mode selection, or robotic system assessment, whereas empirical investigations explicitly concerning automated storage system selection are scarce.

Moreover, current research frequently prioritizes technological and cost-related factors while comparatively neglecting ergonomic and space-use considerations, which are becoming increasingly vital in contemporary warehousing. Ergonomics is essential for alleviating operator fatigue, reducing workplace injuries, and enhancing overall productivity, particularly in semi-automated settings where human-machine contact is inevitable. (Longo et al., 2020). Likewise, effective space utilization has emerged as a strategic issue owing to escalating land costs and the growing preference for urban, high-density warehouses. (Accorsi, Manzini, & Maranesi, 2022). The inadequate incorporation of these criteria in previous studies reveals a distinct research gap in the formulation of a more holistic evaluation framework for automated storage systems. A significant deficiency is the lack of robustness analysis in several MCDM-based warehouse automation projects. Although much research provides ranking results, few investigate the impact of alterations in decision-maker preferences on the outcomes. Sensitivity analysis is crucial to confirm that the proposed alternative remains robust amidst fluctuating strategic priorities. (Liu & Xu, 2020). In the absence of such analysis, decision-makers may encounter doubt concerning the reliability of the suggested solution, especially in dynamic operational contexts.

This study addresses the lack of an organized, transparent, and robust decision-support framework for selecting automated storage systems that concurrently evaluate operational performance, human factors, and spatial efficiency. Warehouse managers frequently rely on subjective assessments or single-criterion evaluations, which can lead to suboptimal investment decisions and enduring operational inefficiencies. The main aim of this project is to create and implement an integrated AHP–TOPSIS framework to facilitate the selection of automated storage systems in the warehouse sector. This research specifically aims to (1) identify and prioritize essential evaluation criteria for the selection of automated storage systems, encompassing throughput, accuracy, ergonomics, and space utilization; (2) evaluate and rank alternative storage technologies—Miniload, Vertical Carousel, and Vertical Lift—according to their overall performance; and (3) assess the robustness of the decision model through thorough sensitivity analysis.

This work offers both theoretical and practical contributions. This research enhances the literature on warehouse automation decision-making by offering a comprehensive evaluation model that incorporates operational, ergonomic, and spatial factors within a hybrid MCDM framework. The suggested technique provides decision-makers with a systematic, flexible tool to support investment decisions in warehouse automation, mitigate decision uncertainty, and improve supply chain performance. Furthermore, the paradigm can be expanded and applied to other industries with analogous automation decision dilemmas, thereby enhancing its applicability and significance across other operational contexts.

II. Literature Review and Hypothesis Development

2.1. Warehouse Automation and Emerging Technologies in Logistics

The swift expansion of international trade and e-commerce has significantly increased the complexity of logistics and warehousing operations. Warehouses have transformed from basic storage units into sophisticated logistics centers that facilitate inventory management, order processing, and value-added services. Consequently, warehouse automation has evolved into a strategic imperative rather than a technological indulgence. (Zhong et al., 2020). Automation technologies empower firms to adapt to variable demand, mitigate operational risks, and improve service reliability in intensely competitive marketplaces.

Mattummal (2024) examined the obstacles and remedies related to warehouse automation developments within the logistics sector. The research highlighted that, while the acknowledged advantages of automation exist, its implementation is progressing slowly, even within prominent logistics firms. This postponement is frequently attributed to substantial investment costs, technological uncertainty, and the challenges of integrating new technologies with existing infrastructure. The research found numerous significant automation developments, including robotic process automation, artificial intelligence, Internet of Things (IoT) connectivity, autonomous cars, voice-directed picking, and automated sorting systems. These technologies collectively aim to enhance operational efficiency, precision, adaptability, and safety in warehouse settings.

Recent studies emphasize that the adoption of automation is significantly affected by operational environment, warehouse configuration, and product attributes. Zhang et al. (2021) assert that automation systems effective in high-volume, standardized settings may be inadequate for warehouses characterized by extensive product variation and frequent order modifications. This underscores the need to choose automation technologies that align with organizational requirements rather than implementing generic solutions. Furthermore, human-machine interaction is a significant concern, as numerous warehouses function in semi-automated settings where human operators and automated systems coexist. (Longo et al., 2020). Automated storage and retrieval systems (AS/RS), such as Miniload systems, Vertical Carousels, and Vertical Lift Modules, constitute a prevalent category of warehouse automation. These systems aim to enhance picking precision, minimize travel time, and optimize vertical space utilization. (Accorsi et al., 2022). Each system, however, demonstrates distinct performance attributes, cost frameworks, and ergonomic considerations. Thus, choosing the optimal automated storage system necessitates a thorough assessment of several technological and operational factors.

2.2. Multi-Criteria Decision-Making (MCDM) Approaches in Logistics and Supply Chain

Decision-making in logistics and supply chain management is inherently intricate due to various conflicting criteria, unpredictability, and varied stakeholder preferences. Multi-Criteria Decision-Making (MCDM) techniques have been widely used to manage complexity by providing systematic, transparent evaluation frameworks. (Pamucar et al., 2020). These strategies enable decision-makers to evaluate alternatives using quantitative and qualitative criteria systematically. Alastal et al. (2025) performed an exhaustive analysis of MCDM methodologies utilized in sustainable supplier selection across multiple industries, such as manufacturing, healthcare, and supply chain management. Their research used bibliometric and content analysis of Scopus-indexed papers to identify research trends, predominant approaches, and emerging themes. The results indicated an increasing inclination towards hybrid MCDM models that use methodologies such as AHP, TOPSIS, fuzzy logic, and entropy-based weighting to improve evaluation accuracy. While the study primarily focused on supplier selection, the methodological insights are highly relevant to logistics and warehousing decision-making. Numerous recent studies have broadened the applications of MCDM to warehouse decision-making. Stević et al. (2021) established that MCDM approaches are proficient in assessing logistics service providers by reconciling cost, reliability, flexibility, and sustainability criteria. Liu et al. (2022) employed MCDM methodologies to support automation investment decisions in smart warehouses, highlighting the need to align technology selections with strategic goals. These studies repeatedly demonstrate that MCDM frameworks improve decision quality by diminishing subjectivity and augmenting analytical rigor. Nonetheless, several MCDM studies in logistics emphasize strategic-level decisions, such as supplier selection or network design. In contrast, operational-level decisions, such as automated storage system selection, receive relatively less attention. Moreover, much research predominantly uses singular MCDM approaches, thereby compromising robustness in complex decision-making contexts. This underscores the need for integrated methodologies that combine the strengths of various MCDM techniques.

2.3. Integration of AHP–TOPSIS and Advanced Hybrid Models

The amalgamation of the Analytic Hierarchy Process (AHP) with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has gained increased appeal in recent years owing to their methodological complementarity. AHP is notably proficient in establishing criterion weights via pairwise comparisons, whereas TOPSIS is superior at ranking alternatives according to their proximity to ideal solutions Ishizaka & Labib, (2020). Collectively, these methodologies offer an extensive framework for tackling multi-criteria decision-making challenges. Costa et al. (2023) introduced a methodology for choosing business processes for automation by combining AHP and TOPSIS within a Design Science Research Methodology (DSRM). Their methodology illustrated how hybrid MCDM models can facilitate automation-related decisions by systematically assessing process attributes and organizational priorities. The research emphasized that integrating AHP and TOPSIS enhances decision-making transparency and increases the likelihood of effective automation deployment.

Tran et al. (2024) proposed a combined Fuzzy AHP–TOPSIS model for selecting industrial robots. The work used fuzzy logic to address uncertainty and ambiguity in expert assessments, a challenge prevalent in real-world decision-making contexts. The findings indicated that hybrid models surpass conventional crisp MCDM techniques in managing ambiguous criteria and subjective evaluations. The findings indicate that integrated MCDM frameworks are highly appropriate for intricate technology selection challenges in industrial and logistical environments. Yildirim et al. (2023) advanced this field of study by evaluating mobile robot systems in warehouses using a multi-criteria evaluation method. Their research delineated essential evaluation criteria through literature analysis and expert consultation, employing both the Equal Weight and

Full Consistency Method (FUCOM) to evaluate system performance. The study revealed that consistency in the weighting criteria substantially influences ranking results, underscoring the need for effective weighting systems. Notwithstanding these developments, current research frequently emphasizes robotics or process automation rather than directly addressing automated storage systems. Furthermore, scant research clearly incorporates ergonomics and space utilization as fundamental criteria alongside throughput and accuracy. This gap highlights the need for a customized AHP–TOPSIS framework tailored to the specific attributes of automated storage system selection.

2.4. Research Gap and Hypothesis Development

Upon reviewing the literature, several research gaps emerge. Despite extensive discourse on warehouse automation, empirical research concentrating on the systematic selection of automated storage systems is limited. Numerous studies examine automation conceptually or technologically, yet fail to offer structured decision-support frameworks for practitioners. Secondly, current MCDM-based research frequently prioritizes cost and performance measures, while inadequately addressing human-centered and spatial factors, such as ergonomics and space usage, which are becoming increasingly vital in contemporary warehouses. Third, although hybrid MCDM methodologies such as AHP–TOPSIS have been effectively applied in supplier selection and robotics assessment, their application in automated storage system selection remains constrained. Moreover, robustness analysis, especially sensitivity analysis, is often neglected, diminishing trust in the stability of decision outcomes amid fluctuating preferences. (Liu & Xu, 2020).

This study presents an integrated AHP–TOPSIS framework to select automated storage solutions for the warehouse sector and address existing gaps. This project seeks to develop a resilient and flexible decision-support tool by integrating many evaluation criteria and performing extensive sensitivity analysis. Based on the literature review, the following hypotheses are formulated:

H1: Throughput has a significant influence on the selection of automated storage systems in warehouse operations.
H2: Accuracy significantly affects the preference ranking of automated storage system alternatives.
H3: Ergonomics is a critical criterion influencing automated storage system selection
H4: Space utilization significantly contributes to the overall performance evaluation of automated storage systems.
H5: The integrated AHP–TOPSIS model provides a robust and consistent ranking of automated storage system alternatives under varying decision-maker preferences.

These hypotheses provide a theoretical foundation for the proposed methodology and guide the subsequent analysis and discussion of results.

III. Research Method

Selecting the appropriate automated storage is a fundamental aspect. This study begins with the identification of the problem statement, followed by data collection through observation, expert interviews, and a literature review. These methods provide the necessary input to establish assessment criteria and identify alternative automated storage systems. (Boysen et al., 2021). AHP is used to assign criterion weights because it can handle the complexity of decision-making involving many criteria. TOPSIS was chosen because it allows automated storage systems to be assessed by comparing the best and worst system alternatives, providing a clear perspective for decision-making based on automated systems' performance against specified criteria. The integration of AHP and TOPSIS methodologies is then applied within a Multi-Criteria Decision-Making (MCDM) framework to evaluate these alternatives. Finally, sensitivity analysis is conducted to assess the robustness of the results. (Govindan et al., 2020). By adopting this systematic approach, the study aims to pinpoint comprehensive automated systems evaluation criteria, establish a structured evaluation framework, and incorporate the AHP-TOPSIS techniques into decision-making processes. This initiative is poised to mitigate risks effectively, enhance supply chain reliability, and increase the organization's overall value.

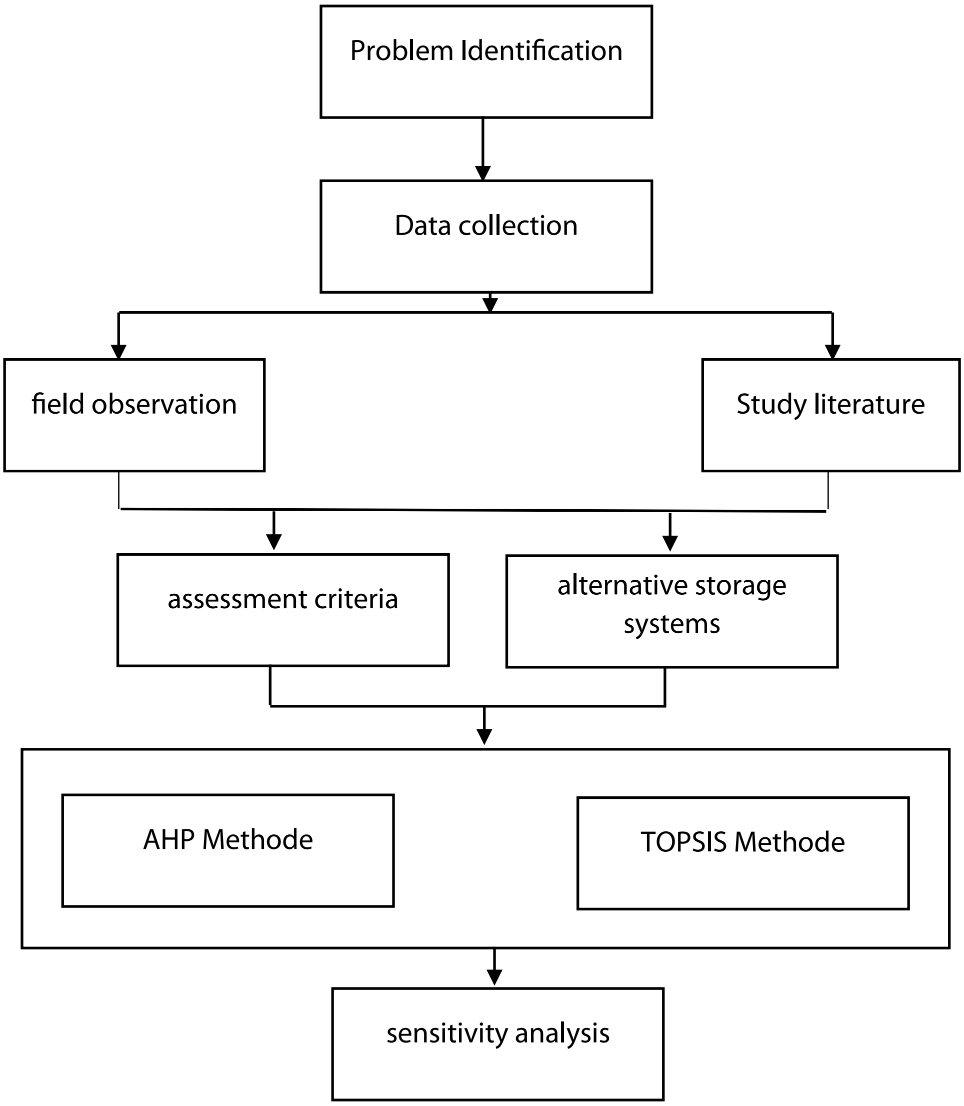

Figure 1. Research Flow

Figure 1 illustrates the overall research framework adopted in this study. The process begins with problem identification and data collection through field observation, expert interviews, and literature review. Subsequently, AHP is applied to determine the criteria weights, followed by TOPSIS to rank the alternative storage systems. The framework concludes with a sensitivity analysis to assess the decision model's robustness.

3.1. Analytical Hierarchy Process

The AHP method, developed by Thomas L. Saaty around 1970, serves as a framework for effective decision-making on complex problems. AHP employs a more precise pairwise comparison than traditional scoring methods (Kamble et al., 2020). As one of the most widely used multi-criteria decision-making (MCDM) methodologies, the Analytic Hierarchy Process (AHP) is conventionally used to determine the weights of criteria based on pairwise comparisons of both alternatives and criteria, thereby computing the relative importance of alternatives, ranking them, and selecting the best alternative. (Marccuci et al., 2021). Below is a description of the AHP method stages:

1. Generating the hierarchical structure model from observation, interview with an expert, and literature review, four important criteria and four alternative vendors were hierarchically modeled.

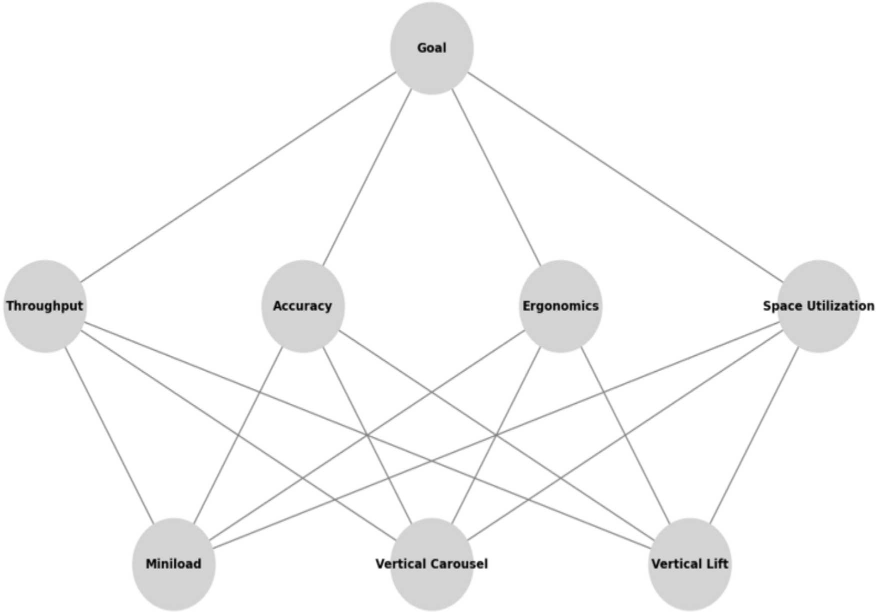

Figure 2. Hierarchical Structure of the Problem

Figure 2 depicts the hierarchical structure of the AHP model used in this research. The structure consists of three levels: the overall goal at the top, the evaluation criteria in the middle, and the alternative storage systems at the bottom. This hierarchical decomposition simplifies the complex decision-making problem and enables systematic pairwise comparisons.

2. Generating pairwise comparison matrix

$$A = [aij]$$

$$aij = \frac{1}{aij}$$

$$aii = 1$$

3. Determining the eigen vector

$$aij = \frac{aij}{\sum_{i=1}^{n} aij}$$

Weight calculation of each criterion

$$wi = \frac{1}{n} \sum_{j=1}^{n} aij$$

4. Calculating the eigen vector's consistency with the formula

$$CI = \frac{\lambda \max - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

3.2. Technique for Order Performance of Similarity to Ideal Solution (TOPSIS)

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is a multi-criteria decision-making (MCDM) approach developed by Hwang and Yoon (1981). It is based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). In essence, TOPSIS evaluates and ranks alternatives by comparing their relative closeness to an ideal solution. TOPSIS is widely used because it is logical, simple, and effective for solving real-world decision problems involving multiple, often conflicting, criteria (Behzadian et al., 2012).

1. Begins by constructing a decision matrix

$$X = [xij]$$

where:

- $i = 1,2,...,m\rightarrow$ number of alternatives
- $j = 1,2,...,n\rightarrow$ number of criteria
- $x_{ij}\rightarrow$ performance value of the alternative $i$under criterion j

$$X = \begin{vmatrix} x_{11} & x_{12} \cdots & x_{1n} \\ x_{21} & x_{22} \cdots & x_{2n} \\ x_{m1} & x_{m2} \cdots & x_{mn} \end{vmatrix}$$

2. Normalization of the Decision Matrix

$$rij = \frac{xij}{\sqrt{\sum_{i=1}^{m} x^2 ij}}$$

3. Weighted Normalized Decision Matrix

Each criterion is assigned a weight (w_j) representing its importance

$$v_{ij} = w_j \text{ x } r_{ij}$$

The resulting weighted normalized matrix is

$$V = [\, v_{ij} \,]$$

4. Determination of Positive and Negative Ideal Solutions
The method defines two reference points:
    - Positive Ideal Solution (PIS):

$$A^+ = \{\, v_1^+ , v_2^+ , \dots , v_n^+ \,\}$$

Where:

$$v_j^+ = \max(v_{ij}) \; for \; benefit \; criteria$$
$$v_j^+ = \min(v_{ij}) \; for \; cost \; criteria$$

- Negative Ideal Solution (NIS):

$$A^- = \{\, v_1^- , v_2^- , \dots , v_n^- \,\}$$

Where:

$$v_j^- = \min(v_{ij}) \; for \; benefit \; criteria$$
$$v_j^- = \max(v_{ij}) \; for \; cost \; criteria$$

5. Distance from the Ideal Solutions
    - Distance from the positive ideal:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)}^{2}$$

    - Distance from the negative ideal:

$$D_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)}^{2}$$

6. Closeness Coefficient (CC)

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

$$\text{Where } 0 \leq C_i \leq 1$$

A higher C_i indicates that the alternative is closer to the ideal solution and thus more preferable.

$$C_i \text{ (higher) } \Rightarrow \text{better alternative}$$

IV. Results and Discussion

4.1. Analytical Hierarchy Process (AHP)

Table 1. Pairwise Comparison Matrix of Criteria

Criteria	Throughput	Accuracy	Ergonomics	Space Utilization
Throughput	1	3	5	4
Accuracy	0.333	1	0.50	2
Ergonomics	0.20	2	1	3
Space Utilization	0.25	0.5	0.333	1
Total	1.783	6.50	6.833	10

Table 1 presents the pairwise comparison matrix for the evaluation criteria used in the AHP analysis: Throughput, Accuracy, Ergonomics, and Space Utilization. The matrix reflects expert judgments regarding the relative importance of each criterion using Saaty's fundamental scale. Throughput is consistently rated as more important than the other criteria, indicating its dominant role in automated storage system selection. The reciprocal values ensure logical consistency in comparisons and form the basis for subsequent normalization and weight calculation.

Table 2. Normalized Matrix of Criteria

Criteria	Throughput	Accuracy	Ergonomics	Space Utilization
Throughput	0.561	0.462	0.732	0.400
Accuracy	0.187	0.154	0.073	0.200
Ergonomics	0.112	0.308	0.146	0.300
Space Utilization	0.140	0.077	0.049	0.100
Total	1	1	1	1

Table 2 shows the normalized pairwise comparison matrix derived from Table 1. Each value represents the relative contribution of a criterion compared to others after normalization. The normalization process ensures that the sum of values in each column equals 1, enabling an objective comparison of criterion importance. The results highlight Throughput as the most influential criterion, followed by Ergonomics, Accuracy, and Space Utilization.

Table 3. Weight & Consistency Ratio of Criteria

Criteria	Weight	P. Vector	Eigen		
Throughput	0.5385	2.4475	3.250	4.2235	λ
Accuracy	0.1535	0.6243	0.958	0.0745	CI

Criteria	Weight	P. Vector	Eigen		
Ergonomics	0.2165	0.9057	1.550	0.9000	RI
Space Utilization	0.0915	0.3750	0.521	0.0828	CR

Table 3 summarizes the final weights for each criterion and the AHP model's consistency metrics. The calculated weights confirm that Throughput holds the highest priority, while Space Utilization has the lowest relative importance. The consistency ratio (CR) value of 8.28% is below the acceptable threshold of 10%, indicating that the expert judgments are consistent and reliable for decision-making.

Table 4. Pairwise Comparison Matrix of Alternatives

Based on Throughput			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	1	0.250	0.333
Vertical Carousel	4	1	0.500
Vertical Lift	3	2	1
Total	8	3.250	1.833

Based on Picking Accuracy			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	1	3	3
Vertical Carousel	0.333	1	1
Vertical Lift	0.333	1	1
Total	1.667	5	5

Based on Ergonomics			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	1	4	3
Vertical Carousel	0.250	1	0.5
Vertical Lift	0.333	2	1
Total	1.583	7	4.5

Based on Space Utilization			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	1	0.50	0.50
Vertical Carousel	2	1	2
Vertical Lift	2	0.50	1
Total	5	2	3.50

Table 4 presents the pairwise comparison matrices of the alternative storage systems—Miniload, Vertical Carousel, and Vertical Lift—under each evaluation criterion. These matrices capture expert preferences for the relative performance of each alternative across throughput, picking accuracy, ergonomics, and space utilization. The results show that Vertical Lift generally outperforms the other alternatives in most criteria, particularly in throughput and ergonomics.

Table 5. Normalize the Matrix of Alternatives

Based on Throughput			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	0.125	0.077	0.182
Vertical Carousel	0.500	0.308	0.273
Vertical Lift	0.375	0.615	0.545
Total	1	1	1

Based on Picking Accuracy			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	0.600	0.600	0.600
Vertical Carousel	0.200	0.200	0.200
Vertical Lift	0.200	0.200	0.200
Total	1	1	1

Based on Ergonomics			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	0.632	0.571	0.667
Vertical Carousel	0.158	0.143	0.111
Vertical Lift	0.210	0.286	0.222
Total	1	1	1

Based on Space Utilization			
	Miniload	**Vertical Carousel**	**Vertical Lift**
Miniload	0.200	0.250	0.143
Vertical Carousel	0.400	0.500	0.571
Vertical Lift	0.400	0.250	0.286
Total	1	1	1

Table 5 displays the normalized matrices for the alternative storage systems under each criterion. The normalization process converts subjective judgments into comparable numerical values, ensuring that each column's sum equals 1. These normalized scores represent the relative performance contribution of each alternative, providing a quantitative foundation for calculating preference vectors and final rankings.

Table 6. Consistency Ratio

Based on Throughput			
P.Vector	**Eigen**		
1.583	0.528	3.1087	λ
5.500	1.833	0.0543	CI
6.000	2.000	0.58	RI
		0.0937	CR

Based on Picking Accuracy			
P.Vector	**Eigen**		
7.000	2.333	3	λ
2.333	0.778	0	CI
2.333	0.778	0.58	RI
		0	CR

Based on Ergonomics			
P.Vector	**Eigen**		
8.000	2.667	3.018	λ
1.750	0.583	0.009	CI
3.333	1.111	0.58	RI
		0.016	CR

Based on Space Utilization			
P.Vector	**Eigen**		
2.000	0.667	3.050	λ
5.000	1.667	0.027	CI
3.500	1.667	0.58	RI
		0.046	CR

Table 6 reports the consistency ratios for each pairwise comparison matrix of alternatives. All CR values are below the acceptable limit of 10%, indicating a high level of consistency in expert judgments across all criteria. This confirms the validity of the pairwise comparison process and supports the reliability of the derived priority vectors.

Table 7. Final Result

	CC	Rank
Miniload	0.3140	2
Vertical Carousel	0.2992	3
Vertical Lift	0.3867	1

Table 7 presents the final AHP-based ranking of the automated storage system alternatives. The results indicate that Vertical Lift achieves the highest closeness coefficient, followed by Miniload and Vertical Carousel. This ranking suggests that Vertical Lift delivers the most balanced performance across all evaluated criteria when their relative weights are taken into account.

4.2. AHP - TOPSIS

Table 8. Decision Matrix

Criteria	Throughput	Accuracy	Ergonomics	Space Utilization
Miniload	0.1279	0.6000	0.6232	0.1976
Vertical Carousel	0.3601	0.2000	0.1373	0.4905
Vertical Lift	0.5119	0.2000	0.2395	0.3119

Table 8 shows the decision matrix used in the TOPSIS analysis. The matrix contains the aggregated performance scores of each alternative across all criteria, derived from the AHP results. These values serve as the initial input to the TOPSIS procedure, capturing the relative performance of each automated storage system.

Table 9. Weighted Matrix

Criteria	Throughput	Accuracy	Ergonomics	Space Utilization
Miniload	0.0689	0.0921	0.1349	0.0181
Vertical Carousel	0.1939	0.0307	0.0297	0.0449
Vertical Lift	0.2757	0.0307	0.0519	0.0285

Table 9 presents the weighted normalized decision matrix, obtained by multiplying the normalized decision matrix by the corresponding criterion weights. This step incorporates the relative importance of each criterion into the evaluation process. The weighted values reflect the overall contribution of each alternative under each criterion.

Table 10. Preference value

Criteria	D+ (to A+)	D- (to A-)	CC (Vi)	Rank
Miniload	0.2085	0.1218	0.3688	3
Vertical Carousel	0.1467	0.1279	0.4657	2
Vertical Lift	0.1046	0.2082	0.6657	1

Table 10 summarizes the TOPSIS results, including the distance from the positive ideal solution (D+), the distance from the negative ideal solution (D–), and the closeness coefficient (CC) for each alternative. Vertical Lift achieves the highest CC value, indicating that it is the closest to the ideal solution and therefore the most preferred alternative.

4.3. Sensitivity Analysis

To evaluate the robustness of the AHP–TOPSIS decision model, two types of sensitivity analysis were conducted, namely the *One-at-a-Time (OAT)* method and the *Scenario-based* method. Both approaches aim to test the stability of the final ranking of alternatives when the criterion weights are varied. However, they differ in the nature and extent of those variations.

4.3.1. One-at-a-Time (OAT) sensitivity

One-at-a-Time (OAT) sensitivity analysis is a method for examining the effect of changing a single input variable on the outcome while holding the other variables constant. In the context of your research (AHP–TOPSIS):

Input variables = criterion weights (Throughput, Accuracy, Ergonomics, Space Utilization).
Outcome = closeness coefficient (CC) value for each alternative.

With OAT, you will choose one criterion.

Table 11. OAT Sensitivity Analysis Results

Criteria	Throughput -10%	Throughput +10%	Accuracy -10%	Accuracy +10%	Ergonomics -10%	Ergonomics +10%	Space Utilization -10%	Space Utilization +10%	Initial
Miniload	0.379	0.334	0.349	0.362	0.338	0.372	0.356	0.355	0.355
Vertical Carousel	0.459	0.490	0.480	0.471	0.488	0.464	0.475	0.477	0.476
Vertical Lift	0.654	0.697	0.685	0.670	0.690	0.664	0.678	0.677	0.677

The following are the results of a One-at-a-Time (OAT) sensitivity simulation and a scenario involving changing criterion weights. Table 11 shows the effect of a ±10% change in each criterion on the Closeness Coefficient (CC) value. From the graph, it can be seen that Vertical Lift remains superior in most weight variations, indicating high robustness to changes in preferences between criteria. The results show that the CC values for all alternatives varied only slightly, and the ranking order remained unchanged (Vertical Lift > Vertical Carousel > Miniload).

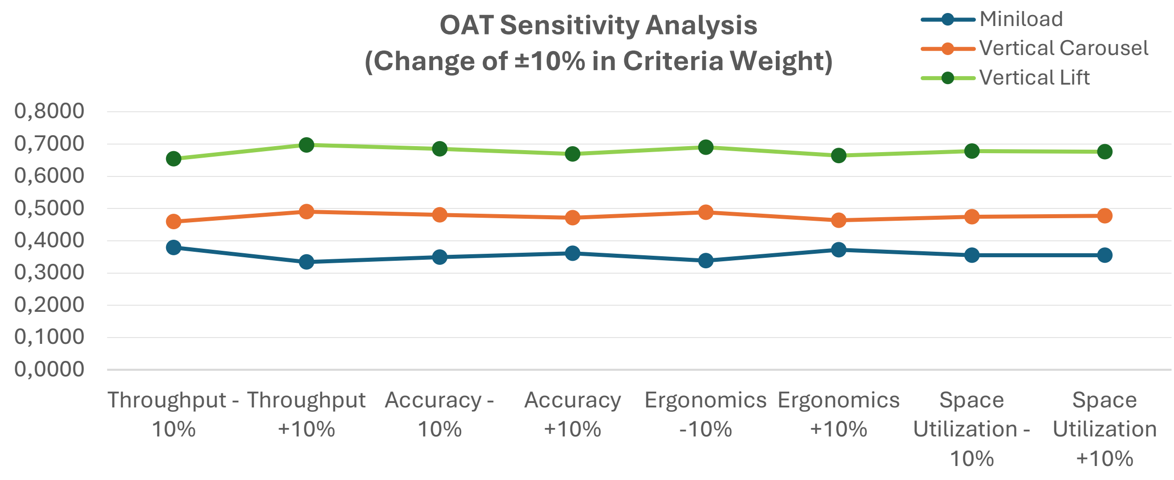

Figure 3. Graph of OAT Sensitivity Analysis Results

Figure 3 visually illustrates the results of the OAT sensitivity analysis. The graph shows that Vertical Lift consistently maintains the highest CC value across all weight variation scenarios. This visual representation reinforces the numerical findings and highlights the stability of the ranking results. As an academic writer, I understand the critical role that the results and discussion section plays in a research paper. This section presents the study's key findings and interprets their meaning and significance (Şanlı et al., 2014; Ghasemi et al., 2019).

The results and discussion section typically begins with a concise restatement of the main findings. This provides the reader with a clear and focused overview of the study's results. Next, the discussion section delves into interpreting the meaning and implications of the results. This is where the researcher explains the meaning of the findings and how they relate to the existing body of research in the field. The discussion should go beyond simply restating the results and instead focus on evaluating the significance and broader context of the findings. (Ghasemi et al., 2019)

Importantly, the discussion section should compare the study's results to those of other relevant research. This allows the researcher to situate their work within the broader scientific landscape and identify areas of agreement or disagreement with prior studies. Additionally, the discussion should address the implications of the findings, explaining why the results matter and how they might be applied or built upon in future research. Finally, the discussion section should acknowledge the study's limitations and highlight any unresolved questions or areas for future investigation. By carefully addressing these key elements, the results and discussion section helps to elevate the research paper, providing a comprehensive and insightful analysis of the study's significance and contribution to the field (Busse & August, 2020) (Şanlı et al., 2014) (Ghasemi et al., 2019).

4.3.2 Scenario-based Sensitivity Analysis

The scenario-based analysis simultaneously alters all criteria weights to represent different strategic perspectives — for instance, Throughput-focused, Accuracy-focused, and Balanced scenarios. This method tests the global robustness of the decision under significantly different decision-making priorities.

Table 12. Scenario-based Sensitivity Analysis Results

Criteria	Throughput	Accuracy	Balanced
Miniload	0.2256	0.6603	0.5489
Vertical Carousel	0.5528	0.2474	0.3837
Vertical Lift	0.8009	0.3434	0.4251

Table 12 presents the results of the scenario-based sensitivity analysis, in which all criterion weights are simultaneously adjusted to reflect different strategic priorities. The results indicate that the preferred alternative varies depending on the decision-making focus. Vertical Lift dominates in throughput-focused scenarios, while Miniload performs better in accuracy-focused and balanced scenarios, demonstrating the model's adaptability across different strategic contexts. The results reveal that the preferred alternative shifts depending on the scenario:

- Under a Throughput-focused scenario, Vertical Lift achieved the highest CC value, indicating its superior performance when efficiency and speed are prioritized.
- Under an Accuracy-focused scenario, Miniload became the best alternative, showing its advantage in precision-oriented contexts.

In the Balanced scenario, Miniload slightly outperformed the others, suggesting a trade-off between efficiency and accuracy.

4.4. Discussion

This study sought to assess and identify the optimal automated storage system for warehouse operations by integrating the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The discourse centers on analyzing empirical results, evaluating the support for the proposed hypotheses, juxtaposing the findings with prior research, and delineating the theoretical and practical ramifications of the study. The AHP analysis results indicate that Throughput is the most significant criterion in selecting automated storage systems, followed by Ergonomics, Accuracy, and Space Utilization. This discovery suggests that operational efficiency, especially the capacity to handle a substantial volume of items within a specified timeframe, remains the primary focus for warehouse managers. Thus, Hypothesis H1, asserting that throughput significantly affects the selection of automated storage systems, is accepted. This outcome aligns with prior studies highlighting throughput as a vital performance metric in automated warehouses, particularly in high-demand contexts influenced by e-commerce and just-in-time delivery systems. (Zhong et al., 2020; Liu et al., 2022) . The significance of throughput also underscores the growing need for warehouses to minimize order cycle times while ensuring service reliability. Automated storage systems that effectively manage peak demand periods provide strategic benefits in sustaining customer happiness and competitiveness. Accorsi et al. 2022) revealed analogous findings, emphasizing that throughput-related criteria frequently take precedence over cost considerations when firms assess long-term automation expenditures.

Accuracy was recognized as the second most significant criterion influencing alternative rankings, albeit with a smaller relative weight than throughput and ergonomics. The TOPSIS results demonstrate that systems exhibiting superior picking accuracy enhance the overall closeness coefficient, especially in contexts where order precision is essential. Consequently, Hypothesis H2, which asserts that accuracy substantially influences the preference ranking of automated storage systems, is accepted. This study corroborates previous research highlighting precision as a critical factor in warehouse performance, as inaccuracies in picking and inventory management can lead to higher returns, customer dissatisfaction, and increased operating expenses. (Stević et al., 2021; Zhang et al., 2021) .

Nonetheless, the findings indicate that precision alone does not guarantee the highest overall rating. For example, although Miniload systems performed better in accuracy-centric situations, they were surpassed by Vertical Lift systems in the comprehensive assessment. This reinforces the assertion that decisions about warehouse automation should include numerous variables instead of depending on a singular predominant component, as emphasized by Pamucar et al. (2020). Ergonomics appeared as a significant factor, ranking second in the AHP weighting outcomes. This affirms that human-centered factors are becoming progressively significant in decisions regarding warehouse automation. In semi-automated warehouses where human operators interact with automated equipment, ergonomic design significantly influences worker safety, fatigue, and productivity. Consequently, Hypothesis H3, asserting that ergonomics is a pivotal factor in the selection of automated storage systems, is affirmed.

This outcome aligns with the human-centered manufacturing viewpoint articulated by Longo et al. (2021) who contended that automation should augment, rather than supplant, human capacities. Vertical Lift systems, which limit operator movement and alleviate physical strain, excelled in the ergonomics category, significantly improving their overall ranking. This underscores the notion that ergonomic improvements can yield concrete operational gains, including less absenteeism and enhanced workforce productivity. Although Space Utilization was allocated the lowest weight among the four criteria, it nonetheless significantly contributed to distinguishing between options. Automated storage solutions that maximize vertical space are especially advantageous in urban or high-density warehouse settings, where floor space is limited and expensive. The findings demonstrate that Vertical Carousel and Vertical Lift systems surpass Miniload systems in space efficiency, thereby improving their rankings. Thus, Hypothesis H4, positing that space usage substantially influences total performance assessment, is accepted; however, it exerts a comparatively lesser impact than other criteria. (Tavana et al., 2021).

This discovery corroborates other studies that emphasize the strategic significance of spatial efficiency in contemporary warehousing, especially as enterprises endeavor to optimize storage capacity without expanding physical infrastructure. (Accorsi et al., 2022) . While space utilization did not solely dictate the highest-ranked alternative, it functioned as a significant supplementary criterion that enhanced the overall efficacy of vertically oriented systems.

The integrated AHP–TOPSIS analysis determined Vertical Lift as the most favored automated storage solution, attaining the highest proximity coefficient. This outcome demonstrates its equitable performance in throughput, ergonomics, accuracy, and spatial efficiency. The reliability of this ranking was further validated through a sensitivity analysis using both One-at-a-Time (OAT) and scenario-based methodologies. In the majority of weight variation scenarios, Vertical Lift retained its leading position, signifying robust stability of the decision model. Consequently, Hypothesis H5, which asserts that the combined AHP–TOPSIS model yields a reliable and consistent ranking across diverse decision-maker preferences, is affirmed.

These findings align with previous research highlighting the benefits of mixed MCDM models in intricate decision-making scenarios. Costa et al., (2023) illustrated that the amalgamation of AHP and TOPSIS improves transparency and dependability in automation-related decision-making, whilst Tran et al., (2024) evidenced that hybrid models surpass single-method approaches in managing conflicting criteria. This study enhances existing knowledge by applying the integrated framework to automated storage system selection and confirming its robustness through a thorough sensitivity analysis. The scenario-based sensitivity analysis provides greater insight into how strategic priorities affect decision outcomes. In throughput-oriented scenarios, Vertical Lift consistently outperformed other options, underscoring its suitability for high-volume operations. Conversely, in accuracy-oriented and balanced conditions, Miniload systems exhibited competitive efficacy. These findings highlight the necessity of synchronizing automation decisions with corporate strategy and operational environment, rather than implementing a universally optimal solution.

This study theoretically enhances the literature by broadening the applicability of AHP–TOPSIS integration within automated storage systems. This research targets a distinct and underexplored choice problem within warehouse automation, in contrast to many previous studies that concentrate on supplier selection or robotic systems. Moreover, by integrating ergonomics and space utilization as fundamental evaluation criteria, the study promotes a comprehensive perspective on warehouse automation decision-making that encompasses technical, operational, and human-centered aspects.

The results provide essential insights for warehouse managers and decision-makers. The suggested framework offers a systematic and transparent method for assessing automated storage options, minimizing dependence on subjective evaluation and improvised decision-making. The study bolsters decision-makers' trust in the recommended solution by showcasing the model's robustness across various preference scenarios. The designation of Vertical Lift as the optimal method indicates that investments in vertically oriented automation technology may yield long-term benefits in efficiency, ergonomics, and space use.

This work, notwithstanding its merits, has some limitations that must be recognized. The research relies on a limited set of criteria and alternatives, potentially failing to capture the intricacies of different warehouse environments. Cost considerations, technological flexibility, and sustainability variables were not explicitly incorporated into the review and may affect decision outcomes in practical applications. Subsequent investigations may enhance the suggested framework by integrating supplementary criteria, employing fuzzy or probabilistic MCDM methodologies to address uncertainty, and corroborating the model through practical implementation scenarios. The talk concludes that the proposed AHP–TOPSIS framework effectively addresses the multi-criteria aspects of automated storage system selection. The endorsement of all offered hypotheses underscores the significance of throughput, accuracy, ergonomics, and space utilization as essential decision factors, illustrating the resilience of the integrated decision model. This study establishes a robust basis for academic research and practical decision-making in warehouse automation by connecting empirical findings with existing literature and delineating explicit consequences.

V. Conclusion

This study demonstrates the effectiveness of integrating the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in supporting multi-criteria decision-making for selecting automated storage systems in the warehousing industry. The AHP method was applied to determine the relative weights of evaluation criteria — Throughput, Accuracy, Ergonomics, and Space Utilization — while TOPSIS was employed to rank the alternatives based on their proximity to the ideal solution. The results indicate that Vertical Lift represents the most suitable automated storage system, achieving the highest closeness coefficient (0.6657), followed by Vertical Carousel and Miniload. This finding suggests that Vertical Lift provides an optimal balance between throughput efficiency and space utilization without compromising accuracy and ergonomic considerations.

The sensitivity analysis further confirmed the robustness of these results. Both the One-at-a-Time (OAT) and scenario-based analyses revealed that changes in criteria weights did not significantly alter the ranking order, demonstrating the stability and reliability of the AHP–TOPSIS decision model. In summary, the integrated AHP–TOPSIS framework offers a systematic, transparent, and rational approach to evaluating and selecting automated storage systems. It provides valuable insights for decision-makers seeking to enhance warehouse performance, optimize resource utilization, and strengthen supply chain reliability. Future research may extend this model by incorporating cost factors, technological adaptability, and sustainability considerations to refine decision-making in warehouse automation further.

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