



# Hybrid BWM–VIKOR Evaluation under PLTS Conditions for the Application of Industry 4.0 Technologies in Retail Management with Emphasis on Warehouse Systems

Amirmohammad Shirani<sup>1</sup>, Mansour Momeni<sup>2</sup> Fatemeh Saghafi<sup>3\*</sup>

<sup>1</sup> MA, Department of System Management and Decision Sciences, Faculty of Industrial Management and Technology, University of Tehran, Tehran, Iran

<sup>2</sup> Professor, Department of System Management and Decision Sciences, Faculty of Industrial Management and Technology, University of Tehran, Tehran, Iran

<sup>3</sup> Associate Professor, Department of System Management and Decision Sciences, Faculty of Industrial Management and Technology, University of Tehran, Tehran, Iran

\* Corresponding author email address: Fsaghafi@ut.ac.ir

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## Abstract

Traditional warehousing methods not only fail to meet current requirements but also lead to increased operational errors, product waste, and reduced productivity. In recent decades, the retail industry has undergone significant transformations in technology, consumer behavior, and supply chain structures. The emergence of the Fourth Industrial Revolution (Industry 4.0) has created unprecedented opportunities for optimizing operational processes. In this context, warehouse management within the complex and multi-branch structure of chain stores, as one of the critical pillars of the supply chain, plays a key role in achieving productivity, flexibility, and customer satisfaction. Therefore, the aim of this study is to evaluate a hybrid BWM–VIKOR approach under PLTS conditions for the application of Industry 4.0 technologies in retail management, with an emphasis on warehouse systems. This study is categorized as an analytical–survey research. Given the application of the VIKOR and BWM techniques, the statistical population and sample consist of 10 experts in retail management with extensive experience, as well as specialists in Industry 4.0 technologies, selected through a census approach. Purposeful sampling is employed in this research. Data collection methods include both library research (articles, journals, books, and theses) and field studies (pairwise comparison questionnaires). The findings indicate that this study introduces a hybrid model to enhance decision-making efficiency. The limitations associated with subjective absolutism in single subjective weighting methods are reduced by this model, and the logical consistency of evaluation results is improved. Furthermore, the use of PLTS ensures the accuracy of evaluation data. In the domain of warehouse management, this hybrid model represents an advanced approach to multi-criteria decision-making (MCDM) that balances subjective judgments with objective data, thereby increasing the robustness and validity of decision-making. By reducing biases and improving overall performance, this method supports more informed and balanced decision-making. The results demonstrate that the model for implementing Industry 4.0 technologies in warehouse management of chain stores, developed in this study using the BWM–VIKOR method, has practical value for future decision-making evaluations regarding Industry 4.0 technologies in warehouse management of chain stores. The integration of the BWM–VIKOR approach into Industry 4.0 implementation processes is recognized as an advanced analytical tool that can enhance strategic planning and operational efficiency. This model provides a comprehensive understanding of the indicators, enabling chain store managers to develop effective warehouse management strategies and ultimately ensuring readiness and resilience in modern and intelligent warehousing systems.

**Keywords:** Industry 4.0 technologies, retail management, warehousing, PLTS, BWM–VIKOR

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## 1. Introduction

The rapid evolution of global retail systems has intensified the need for efficient, responsive, and technology-driven supply chain management practices. Among the various operational components of retail systems, warehouse management plays a central role in ensuring the timely availability of goods, cost efficiency, and customer satisfaction. Traditional warehousing systems, which are often characterized by manual operations, fragmented information flows, and limited real-time visibility, have increasingly been recognized as inadequate in addressing the complexities of modern retail environments. These limitations manifest in the form of operational inefficiencies, increased error rates, higher inventory holding costs, and reduced responsiveness to market fluctuations [1, 2]. Consequently, the transformation of warehouse systems has become a strategic priority for organizations seeking to remain competitive in an increasingly dynamic and digitalized marketplace.

The emergence of the Fourth Industrial Revolution, commonly referred to as Industry 4.0, has introduced a paradigm shift in the way supply chains and warehouse operations are designed and managed. Industry 4.0 is characterized by the integration of advanced digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, cloud computing, and cyber-physical systems into industrial processes [3, 4]. These technologies enable real-time data acquisition, predictive analytics, and intelligent decision-making, thereby significantly enhancing operational performance and flexibility. In the context of warehouse management, Industry 4.0 technologies facilitate the development of smart warehouses that are capable of autonomous operations, dynamic inventory management, and seamless coordination with upstream and downstream supply chain activities [5, 6].

Recent studies have emphasized the transformative impact of Industry 4.0 on supply chain performance and resilience. Digital transformation initiatives driven by Industry 4.0 technologies have been shown to improve operational efficiency, reduce lead times, and enhance the adaptability of supply chains to external disruptions [7, 8]. Moreover, the integration of automation technologies such as autonomous mobile robots (AMRs), automated guided vehicles (AGVs), and advanced warehouse management systems has led to substantial improvements in warehouse productivity and safety [9, 10]. These advancements not only reduce human intervention and associated errors but also

enable more precise and efficient handling of goods within warehouse environments.

Despite the considerable potential of Industry 4.0 technologies, their implementation in warehouse management systems is associated with several challenges. These challenges include high initial investment costs, technological complexity, lack of skilled human resources, and organizational resistance to change [11, 12]. In addition, the successful deployment of these technologies requires a comprehensive evaluation framework that can systematically assess multiple criteria, including technical feasibility, economic viability, environmental sustainability, safety considerations, managerial capabilities, and supervisory requirements. The multidimensional nature of this evaluation process necessitates the use of advanced decision-making approaches capable of handling both qualitative and quantitative information under conditions of uncertainty.

Multi-criteria decision-making (MCDM) methods have been widely applied in the evaluation and selection of complex systems, including the adoption of Industry 4.0 technologies. Among these methods, the Best–Worst Method (BWM) and the VIKOR technique have gained significant attention due to their robustness and effectiveness in handling conflicting criteria. The BWM approach is particularly advantageous for determining the relative importance of criteria based on expert judgments, as it requires fewer pairwise comparisons and provides more consistent results compared to traditional methods such as the Analytic Hierarchy Process (AHP). On the other hand, the VIKOR method focuses on identifying a compromise solution by simultaneously maximizing group utility and minimizing individual regret, making it well-suited for decision-making scenarios involving multiple stakeholders and conflicting objectives.

However, conventional MCDM approaches often assume precise numerical inputs, which may not adequately capture the inherent uncertainty and vagueness associated with human judgments. To address this limitation, recent research has introduced probabilistic linguistic term sets (PLTS) as a powerful tool for representing uncertain and hesitant information in decision-making processes. PLTS allows experts to express their evaluations using linguistic terms with associated probabilities, thereby providing a more flexible and realistic representation of their preferences and perceptions. The integration of PLTS with MCDM methods enhances the accuracy and reliability of evaluation results, particularly in complex and uncertain environments such as

Industry 4.0 implementation in warehouse management systems.

The combination of subjective and objective weighting methods further strengthens the decision-making process by incorporating both expert opinions and data-driven insights. Subjective weighting methods, such as BWM, reflect the preferences and expertise of decision-makers, while objective weighting methods, such as CRITIC, rely on statistical properties of the data to determine the relative importance of criteria. The integration of these approaches through a combined weighting scheme ensures a balanced evaluation that minimizes biases and enhances the robustness of the results. This hybrid approach is particularly relevant in the context of Industry 4.0, where decision-making involves complex interactions between technological, economic, environmental, and organizational factors.

In the specific context of retail warehouse management, the adoption of Industry 4.0 technologies has the potential to revolutionize traditional practices by enabling intelligent, automated, and data-driven operations. Smart warehousing systems leverage IoT-enabled sensors, real-time tracking technologies, and advanced analytics to optimize inventory management, reduce operational costs, and improve service levels [13]. Furthermore, the integration of AI-based decision support systems enhances the ability of organizations to predict demand patterns, optimize resource allocation, and respond proactively to changing market conditions. These capabilities are particularly critical in large-scale retail environments characterized by high product variety, fluctuating demand, and complex distribution networks.

Empirical evidence suggests that the successful implementation of Industry 4.0 technologies in warehouse systems can lead to significant improvements in operational performance and competitiveness. For instance, the use of automation and robotics has been shown to increase throughput, reduce labor costs, and enhance workplace safety [9]. Similarly, the application of IoT and machine learning technologies enables more accurate demand forecasting and inventory optimization, thereby reducing stockouts and excess inventory [5]. These benefits highlight the importance of adopting a systematic and comprehensive approach to evaluating and selecting appropriate technologies for warehouse management.

Nevertheless, the complexity and uncertainty associated with Industry 4.0 implementation necessitate the development of advanced evaluation frameworks that can

effectively integrate multiple criteria and stakeholder perspectives. The hybrid BWM–VIKOR approach under PLTS conditions represents a promising solution to this challenge, as it combines the strengths of subjective and objective weighting methods with the ability to handle uncertain and linguistic information. By providing a structured and transparent decision-making process, this approach enables organizations to identify the most suitable technologies and strategies for enhancing their warehouse management systems.

In addition, the growing emphasis on sustainability and environmental responsibility in supply chain management further underscores the need for comprehensive evaluation models. Industry 4.0 technologies offer significant opportunities for improving environmental performance through energy-efficient operations, waste reduction, and sustainable resource utilization. However, these benefits must be carefully balanced with economic and operational considerations to ensure the overall viability and effectiveness of implementation initiatives. The integration of environmental criteria into the evaluation framework is therefore essential for achieving sustainable and resilient warehouse systems.

Moreover, the role of human factors in the adoption of Industry 4.0 technologies cannot be overlooked. The successful implementation of advanced technologies requires not only technical capabilities but also organizational readiness, employee skills, and effective change management strategies. Training and development programs, as well as the integration of human-centered design principles, are critical for ensuring the acceptance and effective utilization of new technologies within warehouse environments. This highlights the importance of incorporating managerial and organizational criteria into the evaluation process to capture the full spectrum of factors influencing implementation success.

In summary, the transformation of warehouse management systems through the adoption of Industry 4.0 technologies represents a critical opportunity for enhancing the efficiency, flexibility, and competitiveness of retail supply chains. However, the complexity and multidimensional nature of this transformation require the use of advanced decision-making approaches capable of integrating diverse criteria and handling uncertainty. The hybrid BWM–VIKOR approach under PLTS conditions provides a comprehensive and robust framework for evaluating and prioritizing Industry 4.0 technologies in warehouse management. Therefore, the aim of this study is

to evaluate a hybrid BWM–VIKOR approach under PLTS conditions for the application of Industry 4.0 technologies in retail management with an emphasis on warehouse systems.

## 2. Methodology

This study was designed as an analytical–survey research within the framework of multi-criteria decision-making (MCDM). The primary objective was to evaluate and prioritize the application of Industry 4.0 technologies in retail warehouse management using a hybrid BWM–VIKOR approach under probabilistic linguistic term set (PLTS) conditions. The research population consisted of experts in retail management and specialists in Industry 4.0 technologies. A total of 10 participants were selected through a census sampling approach due to the limited number of qualified experts with sufficient domain knowledge. Purposeful sampling was applied to ensure that all selected individuals possessed substantial professional experience in retail operations, warehouse systems, and emerging digital technologies. The unit of analysis was the expert judgment regarding evaluation criteria and technological alternatives. The study incorporated both subjective and objective perspectives to enhance the robustness of the decision-making framework, thereby addressing the inherent uncertainty and ambiguity associated with expert-based evaluations in complex operational environments.

Data collection was conducted through a combination of library research and field-based methods. The library phase involved an extensive review of scientific articles, academic journals, books, and prior studies to identify relevant evaluation criteria and construct the conceptual framework of Industry 4.0 implementation in warehouse management. In the field phase, structured pairwise comparison questionnaires were administered to the selected experts to capture their judgments regarding the relative importance of criteria and the performance of alternatives. These evaluations were expressed using probabilistic linguistic term sets (PLTS) to account for uncertainty and hesitation in human judgment. A PLTS can be represented as

$$L(p) = \{(l_k, p_k) \mid k = 1, 2, \dots, K, \sum_{k=1}^K p_k = 1\}$$

where  $l_k$  denotes the linguistic term and  $p_k$  represents its associated probability.

The Best–Worst Method (BWM) was employed to derive subjective weights of criteria. In this method, experts first identify the best (most important) and worst (least important)

criteria. Pairwise comparisons are then conducted between the best criterion and other criteria, and between all criteria and the worst criterion. The optimal weights are obtained by solving the following minimization model:

$$\min_{w, \xi} \xi$$

subject to

$$\begin{aligned} & \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \forall j \\ & \left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, \forall j \\ & \sum_j w_j = 1, w_j \geq 0 \end{aligned}$$

where  $w_B$  and  $w_W$  represent the weights of the best and worst criteria, respectively, and  $a_{Bj}$  and  $a_{jW}$  denote the pairwise comparison values.

In addition to subjective weights, objective weights were determined using an improved CRITIC method adapted to the PLTS environment. This approach incorporates the standard deviation and correlation among criteria to measure the amount of information each criterion provides. The objective weight  $w_j^o$  is calculated based on the contrast intensity and conflict among criteria, ensuring that criteria with higher variability and lower correlation receive greater importance. Finally, a combined weighting scheme was applied to integrate subjective and objective weights as follows:

$$w_j = \alpha w_j^s + (1 - \alpha) w_j^o$$

where  $w_j^s$  and  $w_j^o$  denote subjective and objective weights, respectively, and  $\alpha$  represents the relative importance of subjective judgment.

The analysis phase employed the VIKOR method to rank and prioritize the alternatives based on the combined weights obtained from the previous stage. First, the decision matrix was constructed using aggregated PLTS evaluations and then normalized to ensure comparability across criteria. The positive ideal solution  $f_j^*$  and negative ideal solution  $f_j^-$  for each criterion were determined based on the best and worst performance values. Subsequently, the group utility measure  $S_i$  and individual regret measure  $R_i$  for each alternative were calculated using the following equations:

$$S_i = \sum_j w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}$$

$$R_i = \max_j \left[ w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right]$$

where  $f_{ij}$  represents the performance value of alternative  $i$  on criterion  $j$ .

Finally, the VIKOR index  $Q_i$  was computed to determine the compromise ranking of alternatives:

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}$$

where  $S^* = \min S_i$ ,  $S^- = \max S_i$ ,  $R^* = \min R_i$ , and  $R^- = \max R_i$ , and  $v \in [0,1]$  is the decision-making strategy coefficient reflecting the balance between group utility and individual regret. The alternatives were ranked in ascending order of  $Q_i$ , with the lowest value indicating the optimal compromise solution. This integrated analytical framework

enabled a rigorous and systematic evaluation of Industry 4.0 technologies in warehouse management, accounting for both uncertainty in expert judgments and the multi-dimensional nature of decision criteria.

### 3. Findings and Results

In this section, a comprehensive evaluation model framework based on the hybrid BWM–VIKOR approach under PLTS settings is presented, as illustrated in Figure 1.

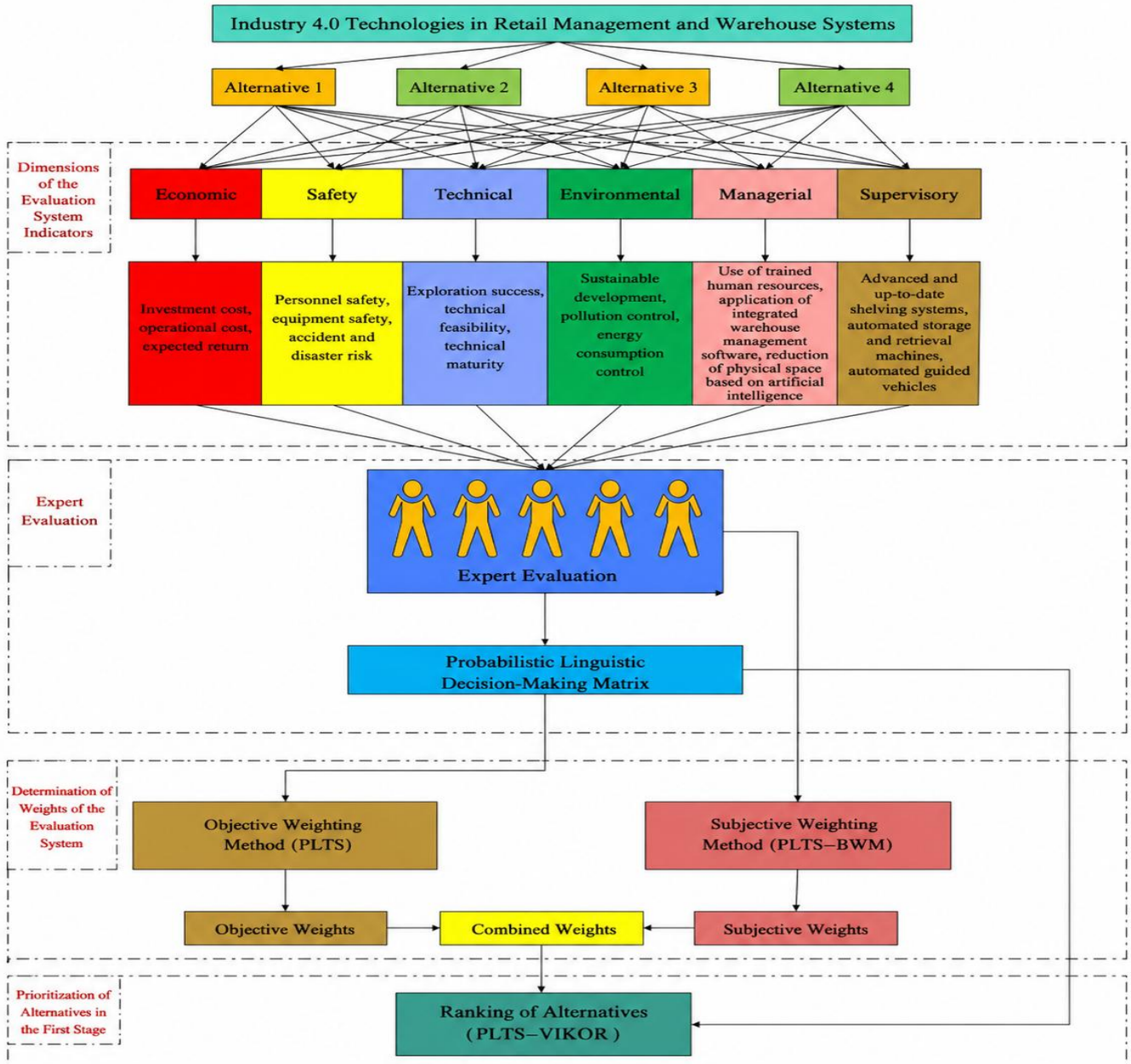


Figure 1. Framework of the integrated appraisal model

Within the probabilistic linguistic term set (PLTS) environment, multi-criteria decision-making (MCDM) problems require the participation of multiple experts to evaluate several alternatives from diverse perspectives. Let  $E = \{e_1, e_2, \dots, e_k\}$  denote the set of experts,  $L = \{l_1, l_2, \dots, l_s\}$  the set of linguistic terms,  $A = \{A_1, A_2, \dots, A_m\}$  the set of alternatives, and  $C = \{C_1, C_2, \dots, C_n\}$  the set of evaluation criteria with corresponding weight vector  $\mathbf{w} = (w_1, w_2, \dots, w_n)$ . Each expert provides qualitative evaluation information for each alternative under each criterion using probabilistic linguistic expressions. These evaluations are aggregated to construct a probabilistic linguistic decision matrix (PLDM), expressed as:

$$D = [L_{ij}]_{m \times n}$$

where  $L_{ij} = \{(l_k, p_k)\}$  represents the probabilistic linguistic evaluation of alternative  $A_i$  under criterion  $C_j$ .

The determination of subjective weights using the BWM method is based on identifying the best and worst criteria and forming pairwise comparison vectors. The optimization model used to derive the optimal weights is defined as:

$$\min \xi$$

subject to

$$|\frac{w_B}{w_j} - a_{Bj}| \leq \xi, |\frac{w_j}{w_W} - a_{jW}| \leq \xi, \sum_{j=1}^n w_j = 1, w_j \geq 0$$

For determining objective weights, an improved CRITIC method under PLTS is applied. Initially, linguistic evaluations are transformed into crisp values:

$$X = [x_{ij}]$$

The normalized decision matrix is computed as:

$$r_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j}$$

The coefficient of variation is calculated as:

$$CV_j = \frac{\sigma_j}{\mu_j}$$

The amount of information for each criterion is defined as:

$$C_j = CV_j \sum_{k=1}^n (1 - r_{jk})$$

Finally, objective weights are obtained as:

$$w_j^o = \frac{C_j}{\sum_{j=1}^n C_j}$$

The combined weights integrating subjective and objective components are calculated as:

$$w_j = \alpha w_j^s + (1 - \alpha) w_j^o$$

where  $\alpha = 0.5$  in this study.

The VIKOR method is employed to rank the alternatives. The group utility and individual regret measures are computed as:

$$S_i = \sum_{j=1}^n w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}$$

$$R_i = \max_j \left[ w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right]$$

The overall ranking index is calculated as:

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}$$

where  $v$  represents the decision-making strategy coefficient.

The screening of implementation indicators was conducted using pairwise comparisons with a 1–9 scale and a consistency threshold of  $\mu = 0.1$ . The analysis indicated that technical innovation and waste management criteria should be removed due to their low weights, suggesting that experts prioritize feasibility, sustainability, and operational success over innovation novelty and waste management considerations.

**Table 1.** Subjective weights of indicators determined by BWM

Level 1 Criteria	Weight	Level 2 Criteria	Local Weight	Subjective Weight
Technical (C1)	0.161	Exploration success (C11)	0.379	0.061
		Technical feasibility (C12)	0.330	0.053
		Technical maturity (C13)	0.291	0.047
Economic (C2)	0.193	Investment cost (C21)	0.291	0.056
		Operational cost (C22)	0.327	0.063

Environmental (C3)	0.145	Expected return (C23)	0.382	0.074
		Sustainable development (C31)	0.389	0.056
		Pollution control (C32)	0.256	0.037
Safety (C4)	0.205	Energy consumption control (C33)	0.355	0.051
		Personnel safety (C41)	0.367	0.075
		Equipment safety (C42)	0.289	0.059
Managerial (C5)	0.113	Disaster risk (C43)	0.344	0.071
		Skilled workforce (C51)	0.345	0.039
		Integrated software (C52)	0.284	0.032
Supervisory (C6)	0.183	AI-based space reduction (C53)	0.371	0.042
		Advanced shelving systems (C61)	0.335	0.061
		Automated storage/retrieval (C62)	0.396	0.072
		Automated guided vehicles (C63)	0.269	0.049

The probabilistic linguistic evaluation data were aggregated and transformed into crisp values, which served as the basis for objective weight calculation. The results of

the objective weighting process indicate that expected return, automated guided vehicles, and sustainable development are the most influential criteria.

**Table 2.** Objective weights of indicators determined by CRITIC

Indicator	Weight
C11	0.046
C12	0.060
C13	0.022
C21	0.069
C22	0.071
C23	0.094
C31	0.077
C32	0.049
C33	0.076
C41	0.063
C42	0.066
C49	0.049
C51	0.029
C52	0.044
C53	0.029
C61	0.036
C62	0.036
C63	0.082

The integration of subjective and objective weights yields the combined weights, which provide a balanced representation of expert judgment and data-driven insights.

**Table 3.** Combined weights of indicators

Indicator	Subjective Weight	Objective Weight	Combined Weight
C11	0.061	0.046	0.053
C12	0.053	0.060	0.057
C13	0.047	0.022	0.035
C21	0.056	0.069	0.062
C22	0.063	0.071	0.067
C23	0.074	0.094	0.084
C31	0.056	0.077	0.067
C32	0.037	0.049	0.043
C33	0.051	0.076	0.064

C41	0.075	0.063	0.069
C42	0.059	0.066	0.063
C49	0.071	0.049	0.060
C51	0.039	0.029	0.034
C52	0.032	0.044	0.038
C53	0.042	0.029	0.036
C61	0.061	0.036	0.049
C62	0.072	0.036	0.054
C63	0.049	0.082	0.066

The final results indicate that expected return (C23) has the highest combined weight, emphasizing the dominant role of economic benefits in the implementation of Industry 4.0 technologies. Sustainable development and operational

efficiency indicators also rank highly, confirming the importance of balancing economic performance with environmental and operational considerations.

**Table 4.** Final prioritization insights of key indicators

Rank	Indicator	Combined Weight
1	Expected return (C23)	0.084
2	Personnel safety (C41)	0.069
3	Sustainable development (C31)	0.067
4	Operational cost (C22)	0.067
5	Automated guided vehicles (C63)	0.066

Overall, the findings demonstrate that the hybrid BWM–VIKOR approach under PLTS conditions effectively integrates subjective and objective information, improves decision-making consistency, and provides a robust framework for prioritizing Industry 4.0 technologies in warehouse management systems.

#### 4. Discussion and Conclusion

The findings of this study demonstrate that the proposed hybrid BWM–VIKOR model under PLTS conditions provides a robust and systematic framework for evaluating the implementation of Industry 4.0 technologies in retail warehouse management. The results indicate that among the evaluated criteria, expected return (C23) achieved the highest combined weight, followed by personnel safety (C41), sustainable development (C31), operational cost (C22), and automated guided vehicles (C63). This prioritization reflects the dominance of economic considerations in decision-making processes while simultaneously emphasizing the importance of safety, environmental sustainability, and technological advancement. The prominence of expected return highlights that decision-makers in retail systems are primarily driven by financial performance and investment efficiency when adopting Industry 4.0 technologies. This finding is consistent with prior research suggesting that economic

viability remains a central determinant in technology adoption decisions within supply chains [2, 8].

At the same time, the high ranking of safety-related indicators, particularly personnel safety, underscores the increasing importance of risk reduction and workplace protection in modern warehouse environments. The integration of automated systems such as AGVs and robotics reduces human exposure to hazardous tasks, thereby improving safety outcomes. This result aligns with the findings of Qi et al., who demonstrated that intelligent systems and real-time monitoring technologies significantly enhance safety and operational efficiency in warehouse logistics [10]. Similarly, the growing adoption of automation technologies in large-scale logistics operations has been shown to improve both safety and productivity, reinforcing the relevance of safety considerations in technology selection [9].

Environmental sustainability also emerged as a critical factor, with sustainable development ranking among the top indicators. This reflects a broader shift in supply chain management toward environmentally responsible practices and the integration of sustainability into operational decision-making. Industry 4.0 technologies enable energy optimization, waste reduction, and efficient resource utilization, thereby contributing to environmental performance. This finding is consistent with the work of Peron et al., who emphasized the role of smart warehousing

systems in achieving sustainability objectives through the integration of digital technologies and just-in-time principles [13]. Furthermore, recent studies have highlighted the importance of incorporating circular economy principles and sustainability considerations into Industry 4.0 implementation strategies [11].

The results also indicate that technical criteria such as feasibility and maturity are important but not dominant compared to economic and sustainability-related factors. This suggests that while technological readiness is necessary, it is not sufficient to drive decision-making in isolation. Instead, decision-makers adopt a holistic perspective that considers the interplay between technical capabilities, economic outcomes, and organizational requirements. This finding is in line with previous research demonstrating that successful Industry 4.0 adoption requires a balanced evaluation of multiple dimensions, including technological, organizational, and environmental factors [7, 12].

The relatively lower ranking of certain indicators, such as technical innovation and waste management (which were removed during the screening process), provides additional insights into expert preferences. The exclusion of these indicators suggests that decision-makers prioritize practical and immediately applicable solutions over highly innovative but uncertain technologies. This aligns with the argument that organizations tend to adopt technologies that offer clear and measurable benefits while minimizing implementation risks [14]. Similarly, the lower weight assigned to waste management compared to broader sustainability indicators indicates that decision-makers focus more on systemic environmental impacts rather than isolated operational aspects.

Another important finding of this study is the effectiveness of integrating subjective and objective weighting methods. The combined weighting approach successfully balances expert judgment with data-driven insights, thereby enhancing the reliability and validity of the evaluation results. This hybrid approach addresses the limitations of purely subjective or objective methods, which may either introduce bias or overlook contextual nuances. The use of PLTS further strengthens the model by allowing experts to express their evaluations in a flexible and probabilistic manner, capturing the inherent uncertainty in decision-making processes. This finding is consistent with previous studies highlighting the advantages of probabilistic linguistic approaches in improving decision accuracy and robustness in complex environments [3, 6].

The application of the VIKOR method in this study also proved effective in identifying a compromise solution that balances group utility and individual regret. This is particularly important in multi-stakeholder environments such as retail supply chains, where different decision-makers may have conflicting priorities. The ability of VIKOR to generate a consensus-based ranking enhances its applicability in real-world decision-making scenarios. This result supports earlier research emphasizing the suitability of VIKOR for addressing multi-objective optimization problems in supply chain management [15].

Furthermore, the findings highlight the critical role of digital transformation in enhancing warehouse performance. The adoption of IoT, AI, and automation technologies enables real-time data collection, predictive analytics, and intelligent decision-making, leading to improved efficiency and responsiveness. This is consistent with the findings of Li et al., who demonstrated that IoT and machine learning-based systems significantly enhance warehouse management capabilities [5]. Similarly, the integration of digital technologies into supply chains has been shown to improve resilience and adaptability in the face of disruptions [7].

Overall, the results of this study confirm that the implementation of Industry 4.0 technologies in retail warehouse management is a multidimensional decision-making problem that requires the integration of economic, technical, environmental, safety, managerial, and supervisory considerations. The hybrid BWM–VIKOR model under PLTS conditions provides a comprehensive and effective framework for addressing this complexity. By combining advanced decision-making techniques with probabilistic linguistic modeling, the proposed approach enhances the accuracy, consistency, and practical relevance of evaluation results. These findings contribute to the growing body of literature on Industry 4.0 and supply chain management by providing a novel methodological approach for technology evaluation and prioritization.

The limitations of this study should be acknowledged. First, the sample size of experts was relatively small, which may limit the generalizability of the findings. Second, the study focused on a specific context of retail warehouse management, and the results may not be directly applicable to other industries or sectors. Third, the evaluation criteria were selected based on expert judgment and literature review, which may introduce some degree of subjectivity. Finally, the dynamic and rapidly evolving nature of Industry

4.0 technologies means that the relevance of certain criteria may change over time.

Future research could expand the scope of this study by including a larger and more diverse sample of experts from different industries and geographical regions. Comparative studies could be conducted to evaluate the applicability of the proposed model in different contexts, such as manufacturing, healthcare, or logistics. In addition, future studies could integrate other advanced decision-making techniques, such as fuzzy logic or machine learning approaches, to further enhance the robustness of the evaluation framework. Longitudinal studies could also be conducted to examine the impact of Industry 4.0 implementation over time and to validate the long-term effectiveness of the proposed model.

From a practical perspective, the findings of this study provide valuable insights for managers and decision-makers in retail organizations. The prioritization of economic, safety, and sustainability criteria highlights the need for a balanced approach to technology adoption that considers both financial performance and social responsibility. Managers should focus on implementing technologies that offer clear economic benefits while also enhancing safety and environmental performance. In addition, organizations should invest in training and development programs to ensure that employees are equipped with the necessary skills to operate and manage advanced technologies. Finally, the adoption of structured decision-making frameworks, such as the hybrid BWM–VIKOR model, can support more informed and transparent decision-making processes, ultimately leading to improved operational performance and competitive advantage.

#### Authors' Contributions

Authors equally contributed to this article.

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#### Declaration of Interest

The authors report no conflict of interest.

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#### Ethical Considerations

All procedures performed in this study were under the ethical standards.

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