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Investigation of Effective Indicators in the Implementation of Industry 4.0 Technologies for Improving Warehousing Operations in Chain Stores

Amirmohammad. Shirani[1], Mansour. Momeni[2], Fatemeh. Saghafi[3*]

[1] MA student, Department of System Management and Decision Sciences, University of Tehran, Tehran, Iran
[2] Professor, , Department of System Management and Decision Sciences, University of Tehran, Tehran, Iran
[3] Associate Professor, Department of System Management and Decision Sciences, University of Tehran, Tehran, Iran

*** Corresponding author email address**: fsaghafi@ut.ac.ir

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ABSTRACT

The aim of this study is to investigate the effective indicators in the implementation of Industry 4.0 technologies for improving warehousing operations in chain stores. This research is classified as an analytical–software-based study. The study is cross-sectional in nature. In terms of purpose, it is applied research. From the spatial perspective, it is a field study, and the temporal scope of the research is 2025. Since the m-TISM model within the MICMAC technique framework was employed in this study, the statistical population and sample consisted of 15 managers, warehouse management experts, and specialists in the fields of information technology and artificial intelligence, selected through a census method. In this study, convenience sampling was used. The required data were collected using a pairwise comparison questionnaire and analyzed through MICMAC software. The findings obtained from the conducted analyses indicate that multiple indicators should be considered in warehouse management. When applying technology in warehouse management for chain stores, a defined and context-specific indicator system should be established for this domain. This section introduces an implementation indicator system encompassing six critical dimensions: technical, economic, environmental, safety, managerial, and supervisory dimensions. This comprehensive indicator system includes six primary indicators, which are divided into 20 secondary indicators. The results demonstrate that investment cost (economic), operational cost (economic), expected return (economic), personnel safety (safety), pollution control (environmental), and the use of specialized integrated warehouse operations management software (managerial) are among the key indicators for implementing Industry 4.0 technologies to improve warehousing operations in chain stores. A high success rate in exploration is associated with an increased probability of identifying relevant resources, which enhances the implementation of Industry 4.0 technologies. The availability and effectiveness of the required technology are evaluated to ensure that the implementation achieves the research objectives.

Keywords: *Effective Indicators, Implementation, Industry 4.0, Warehousing, Chain Stores*

1. Introduction

The rapid expansion of Industry 4.0 has transformed warehouse management from a traditionally operational function into a digitally enabled, data-driven, and strategically integrated component of retail supply chains. In chain stores, warehousing operations are no longer limited to storage, order preparation, and inventory control; rather, they have become central nodes in omnichannel retailing, customer responsiveness, inventory visibility, cost control, sustainability, and service quality. Industry 4.0 refers to the convergence of cyber-physical systems, artificial intelligence, the Internet of Things, blockchain, robotics, automation, digital twins, cloud computing, advanced analytics, and interconnected platforms that enable intelligent coordination between physical operations and digital decision-making. In this context, digital innovation is not simply an auxiliary technological upgrade, but a structural requirement for improving competitiveness, operational agility, and supply chain resilience (Gupta & Jauhar, 2023). Studies on the next generation of supply chain management emphasize that Industry 4.0 changes the basic logic of supply chains by enabling real-time connectivity, predictive decision-making, automated coordination, and integrated performance management (Mayounga, 2022). Therefore, identifying the effective indicators that support or constrain the implementation of Industry 4.0 technologies in warehousing operations is a fundamental issue for chain stores that seek to enhance operational efficiency and strategic performance.

The importance of this issue is intensified by the specific operational characteristics of chain stores. Chain retailers usually operate across multiple branches, geographically dispersed warehouses, heterogeneous product categories, fluctuating demand patterns, and high service expectations. These features increase the complexity of inventory allocation, replenishment, order fulfillment, product availability, warehouse layout, and last-mile coordination. Recent research on retail digital transformation indicates that retail businesses must improve their digital transformation capacity to remain competitive in dynamic markets, particularly through the adoption of digital infrastructures, data-driven management, and organizational readiness (ThiPham, 2024). Similarly, studies on new retail enterprises show that the integration of artificial intelligence and robotic process automation can support process optimization, reduce operational redundancy, and strengthen enterprise responsiveness in digitally mediated retail environments (Fu et al., 2023). From this perspective, warehouse operations in chain stores constitute a critical domain in which technological implementation must be evaluated not only through technical feasibility, but also through economic, managerial, environmental, safety, and supervisory indicators.

Warehouse management has entered a new phase in which digital-era technologies are increasingly linked to key performance measures such as accuracy, productivity, responsiveness, cost efficiency, space utilization, safety, and service reliability. Research on warehouse performance in the digital era highlights that technologies such as warehouse management systems, automated storage and retrieval systems, robotics, IoT, RFID, analytics, and cloud-based platforms can improve operational visibility and decision quality when aligned with appropriate performance indicators (ran & Öztürkoğlu, 2022). In a similar direction, studies on third-party logistics warehouse operations show that technological features such as automation, tracking systems, information integration, and warehouse process digitalization significantly shape the effectiveness of logistics services (Raja & Venkatachalam, 2024). These findings imply that the success of Industry 4.0 implementation in warehouse operations depends on the careful identification of indicators that reflect both technological capacity and operational applicability. Without such indicators, chain stores may adopt advanced technologies without achieving meaningful improvements in warehousing performance.

The technical dimension is one of the most fundamental aspects of Industry 4.0 implementation in warehouse operations. Technical feasibility, technological maturity, innovation capacity, and the probability of successful implementation determine whether a technological solution can be adapted to existing warehouse processes and scaled across retail branches. Emerging research on smart warehouse management systems demonstrates that digital technologies must be designed according to operational context, product characteristics, spare-part or inventory requirements, data availability, and system integration needs (Khan et al., 2024). Digital twin-based warehouse management also illustrates the importance of creating virtual representations of warehouse processes to improve simulation, monitoring, optimization, and future-oriented planning (Maheshwari et al., 2023). In addition, interconnected emerging technologies can strengthen supply chain intelligence when smart manufacturing, IoT, automation, artificial intelligence, and data platforms are combined within an integrated technological architecture (Kandarkar & Ravi, 2024). Accordingly, technical indicators must evaluate whether Industry 4.0 technologies are mature, compatible, innovative, and operationally feasible for improving warehousing operations in chain stores.

The economic dimension is equally decisive because technological implementation in warehouses often requires considerable investment in hardware, software, infrastructure, training, maintenance, cybersecurity, and process redesign. Investment cost, operational cost, and expected return are therefore central indicators in the implementation of Industry 4.0 technologies. Operations management research shows that artificial intelligence and Industry 4.0 technologies can transform operational decision-making, but their organizational value depends on the ability to connect technological capabilities with measurable performance improvements (Mithas et al., 2022). In retail supply chains, 5G technology has been identified as a driver of improved connectivity, real-time communication, customer responsiveness, and supply chain coordination, but its implementation also requires financial evaluation and infrastructural readiness (Brown et al., 2024). Similarly, dynamic pricing in ship-from-store omnichannel retailing reveals that advanced digital systems can improve decision-making under uncertainty, but these systems require robust optimization logic and economic justification to generate value (Yu & Su, 2025). Thus, the economic feasibility of Industry 4.0 in warehousing cannot be separated from questions of investment efficiency, operational savings, return on implementation, and long-term competitiveness.

Environmental indicators have also become increasingly important in evaluating warehouse technology implementation. Chain stores face growing pressure to reduce energy consumption, improve resource efficiency, control pollution, minimize waste, and align logistics processes with sustainability goals. IoT-driven sustainability initiatives in retail chains indicate that sensor-based systems, smart monitoring, and real-time data can support more sustainable inventory and logistics practices (Karthikeyan & Nagaprakash, 2023). Blockchain-enabled IoT capabilities have also been associated with sustainable firm performance by improving transparency, traceability, accountability, and resource coordination in retail operations (Nazir & Fan, 2024). Studies on blockchain-based supply chains in the Fourth Industrial Revolution further show that distributed digital infrastructures can enhance trust, traceability, and sustainability across supply chain networks (Raza et al., 2023). These studies support the view that environmental indicators such as sustainable development, pollution control, energy consumption control, and waste management should be incorporated into the assessment of Industry 4.0 implementation in warehouse operations.

The safety dimension is another crucial component of warehouse transformation. Warehouses are environments with physical risks related to equipment movement, manual handling, shelving systems, forklifts, automated vehicles, machine-human interaction, accidents, and disaster exposure. Industry 4.0 technologies may improve safety through automation, monitoring, predictive maintenance, sensor-based alerts, and data-driven risk management, but they may also introduce new risks if implemented without sufficient governance and training. Smart systems research emphasizes that advanced technologies can improve business quality, performance, and supply chain integration when they are implemented through standards, process discipline, and quality-oriented management (Schmidt et al., 2022). Business education literature on smart supply chain management also stresses the need to understand digital supply chain capabilities in relation to risk, uncertainty, and post-pandemic disruptions (Shi et al., 2023). Therefore, personnel safety, equipment safety, and accident and disaster risk should be regarded as essential indicators in the implementation of Industry 4.0 technologies, particularly in chain-store warehousing contexts where automation and human labor often coexist.

Managerial readiness determines whether technical investments can be converted into operational improvement. Industry 4.0 implementation requires trained human resources, digital leadership, process redesign, knowledge sharing, cross-functional coordination, software integration, and data-based decision-making. Research on digital technologies in logistics and supply chain management emphasizes that technological transformation depends not only on digital tools, but also on managerial capacity, organizational processes, and the ability to integrate logistics information across activities (Rodchenko & Prus, 2023). Studies on logistics centers also highlight the importance of technological trends and policy implications in designing advanced logistics infrastructures that support efficiency and regional competitiveness (Nguyen et al., 2023). Moreover, evidence from retail branch banking shows that service quality, customer satisfaction, and knowledge sharing are interrelated organizational capabilities, suggesting that digital transformation must be supported by internal knowledge flows and managerial learning (Ranjan &

Kadam, 2025). Thus, the employment of trained personnel, the use of specialized integrated warehouse operations management software, and AI-based reduction of physical warehouse space represent managerial indicators that influence the effectiveness of technological implementation.

Supervisory and infrastructural indicators are also important because Industry 4.0 implementation in warehouses often requires physical and digital modernization of operational systems. Updated shelving systems, automated storage and retrieval machines, automated guided vehicles, monitoring platforms, and supervisory control systems determine the extent to which warehouse operations can become intelligent, integrated, and scalable. Research on Logistics 4.0 in retailing indicates that digital logistics technologies can improve supply chain performance by enhancing process visibility, responsiveness, and operational coordination (Hrouga & Sbihi, 2023). Studies on e-commerce retail logistics after the COVID-19 pandemic show that retail logistics ecosystems increasingly depend on symbiotic relations among platforms, logistics providers, digital infrastructure, and consumer demand patterns (Zhao & Smirnova, 2023). In addition, technological transformation in fashion and retail-related industries demonstrates that digital tools influence multiple facets of production, distribution, marketing, and consumer engagement (R. & Keserwani, 2024). These findings show that warehouse supervision and technological infrastructure are not peripheral concerns; rather, they are core conditions for achieving the operational advantages promised by Industry 4.0.

Artificial intelligence and IoT have become particularly influential in retail and warehouse transformation because they enable prediction, personalization, automation, monitoring, and adaptive decision-making. Research on AI and IoT in retail marketing demonstrates that smart stores and personalized shopping systems depend on connected data infrastructures and intelligent interaction between operational and customer-facing processes (Gupta et al., 2025). Artificial intelligence in retail marketing also improves product recommendations and customer engagement, showing that AI-based retail transformation extends beyond the front end of marketing and affects inventory, fulfillment, and warehouse responsiveness (Sivasankari, 2025). In e-commerce, AI-driven business models under new retail environments illustrate that artificial intelligence supports business model innovation, process automation, and customer-oriented operational redesign (Guo & Palaoag, 2023). These studies indicate that AI-enabled warehouse management is not merely a technical upgrade; it is a strategic mechanism for synchronizing supply, demand, storage, distribution, and customer expectations across chain-store networks.

Inventory management is one of the most direct areas affected by Industry 4.0 technologies in warehousing. IoT applications in inventory management enable real-time tracking, automated data collection, stock-level monitoring, demand synchronization, and improved replenishment decisions (Mashayekhy et al., 2022). These capabilities are especially relevant for chain stores, where stockouts, overstocking, inaccurate inventory records, and delayed replenishment can create major operational and financial consequences. Digital transformation in post-harvest activities also shows that sector-specific operational environments can benefit from data-driven monitoring, automation, and process integration when technologies are adapted to practical workflow requirements (Schmidt et al., 2023). Although the sectoral context differs, the underlying implication is highly relevant to warehousing: digital transformation succeeds when technologies are aligned with operational processes, performance objectives, and implementation constraints. Therefore, a systematic framework is needed to identify which indicators have stronger driving power and which indicators are more dependent on other implementation conditions.

Despite the recognized importance of Industry 4.0 in retail supply chains, many organizations still face uncertainty regarding how to prioritize implementation indicators. Some indicators may function as root drivers, while others may emerge as dependent outcomes of broader technological, economic, managerial, or environmental conditions. For this reason, structural modeling methods such as ISM, m-TISM, and MICMAC are useful because they allow researchers to identify hierarchical relationships, driving power, dependence, and interaction among indicators. Such approaches are particularly valuable in complex management problems where technological adoption is shaped by multiple interdependent factors rather than isolated variables. The literature confirms that smart supply chains, digital logistics, AI-based retail systems, and warehouse technologies are increasingly interconnected, but it also reveals the need for context-specific models that explain how these indicators interact in specific operational settings such as chain-store warehousing (Hrouga & Sbihi, 2023; Khan et al., 2024; Maheshwari et al., 2023; Rodchenko & Prus, 2023). Therefore, the present study responds to a methodological and practical need by structuring the effective indicators of Industry 4.0 implementation in warehouse operations through a systematic interpretive and MICMAC-based approach.

Accordingly, the aim of this study is to identify and analyze the effective indicators in the implementation of Industry 4.0 technologies for improving warehousing operations in chain stores.

2. Methods and Materials

This study is categorized as an analytical–software-based research design. The research is cross-sectional in nature. In terms of purpose, it is classified as applied research. From a spatial perspective, the study is field-based, and the temporal scope of the research corresponds to the year 2025. Since the m-TISM model within the MICMAC framework was employed in this study, the statistical population and sample consisted of 15 managers, warehouse management experts, and specialists in the fields of information technology and artificial intelligence, selected through a census approach. Convenience sampling was utilized in this research. The required data were collected through a pairwise comparison questionnaire and analyzed using MICMAC software.

3. Findings and Results

The analysis in this section is based on MICMAC analysis. Effective indicators for the implementation of Industry 4.0 technologies were developed from six perspectives. From the technical perspective: exploration success, technical feasibility, technological maturity, and innovation were identified. From the economic perspective: investment cost, operational cost, and expected return were selected. From the environmental perspective: sustainable development, pollution control, energy consumption control, and waste management were considered. From the safety perspective: personnel safety, equipment safety, and accident and disaster risk were included. From the managerial perspective: employment of trained personnel, utilization of specialized integrated warehouse operations management software, and reduction of physical space based on artificial intelligence were selected. From the supervisory perspective: advanced and updated shelving systems, automated storage and retrieval machines, and automated guided vehicles were identified.

Table 1

Identification of Requirements and Deficiencies

Indicator	Abbreviation	Indicator	Abbreviation
Exploration Success (Technical)	S1	Waste Management (Environmental)	S11
Technical Feasibility (Technical)	S2	Personnel Safety (Safety)	S12
Technological Maturity (Technical)	S3	Equipment Safety (Safety)	S13
Innovation (Technical)	S4	Accident and Disaster Risk (Safety)	S14
Investment Cost (Economic)	S5	Employment of Trained Personnel (Managerial)	S15
Operational Cost (Economic)	S6	Use of Specialized Integrated Warehouse Operations Management Software (Managerial)	S16
Expected Return (Economic)	S7	Reduction of Physical Space Based on Artificial Intelligence (Managerial)	S17
Sustainable Development (Environmental)	S8	Advanced and Updated Shelving Systems (Supervisory)	S18
Pollution Control (Environmental)	S9	Automated Storage and Retrieval Machines (Supervisory)	S19
Energy Consumption Control (Environmental)	S10	Automated Guided Vehicles (Supervisory)	S20

The implementation stages are described as follows:

Stage 1: Construction of the Adjacency Matrix

The adjacency matrix A is constructed based on the relationships among the factors. If the row factor Si affects the column factor Sj, it is represented by 1; otherwise, it is represented by 0.

Stage 2: Calculation of the Reachability Matrix

The adjacency matrix A is added to the identity matrix I, followed by matrix power operations until the results of two consecutive operations become identical, resulting in the reachability matrix M. After identifying the elements belonging to the first level, the rows and columns containing these elements are removed. Subsequently, the elements of the second level are identified, and the process continues until all levels are determined.

Stage 3: Development of the Hierarchical Diagram

The hierarchical diagram is developed based on the hierarchical relationships identified. The first-level elements are placed at the top and arranged in descending order. The relationships between adjacent levels are represented by direct lines with arrows according to the relationships among the initially identified indicators.

The Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) is a tool proposed by Dupre and Godet in 1973. This tool is used to analyze relational dependencies among indicators within a system and to determine the position of each indicator in the system through the analysis of driving forces and dependencies. Chang and Wang suggested that this model can represent the relationships among indicators through a virtual dependence–driving matrix. Furthermore, compared with the ISM model, which can only determine whether indicators influence one another, MICMAC can also express the magnitude of influence.

The implementation stages are as follows:

Stage 1: Calculation of Driving Force and Dependence of Each Indicator

The driving force of each indicator represents the extent to which that indicator affects other indicators and can be expressed by the number of "1" elements in its row. The dependence of each indicator reflects the extent to which other indicators affect that indicator and can be expressed by the number of "1" elements in its column.

Stage 2: Construction of the Driving–Dependence Matrix

The driving–dependence matrix is constructed using dependence as the horizontal coordinate and driving force as the vertical coordinate. The indicators are then positioned within the matrix.

Stage 3: Classification and Analysis

The mean values of dependence and driving force for each indicator are calculated. Based on these values, four quadrants are formed: linkage, independence, autonomy, and dependence. The linkage quadrant indicates both high dependence and high driving force. The independence quadrant refers to high driving force but low dependence. The autonomy quadrant represents low values for both dimensions, whereas the dependence quadrant refers to high dependence with low driving force. Subsequently, the quadrant corresponding to each indicator is determined, and the analysis proceeds accordingly.

Stage 1: Determination of the Adjacency Matrix

Numerous indicators influence the implementation of Industry 4.0 technologies. There is a logical relationship among the indicators, as they either support or constrain one another. The purpose of this section is to understand the structural framework of Industry 4.0 technology implementation and the indicators affecting warehouse operation improvement in chain stores. A team of 15 individuals was organized to implement the ISM approach. The team members consisted of theoretical and practical experts in Industry 4.0 technologies who served as technical experts, coordinators, and participants. In accordance with the requirements for ISM team members, interviews were conducted with managers, warehouse management experts, and specialists in information technology and artificial intelligence. The responses of managers and experts were based on practical experience, whereas the responses of researchers were derived from their scientific investigations. The primary objective of the interviews was to determine the logical relationships among the effective indicators listed in Table 1, based on which the adjacency matrix A was established, as shown in Table 2. Aij = 1 indicates that Si affects Sj, whereas Aij = 0 indicates that Si has no effect on Sj. The columns in the following table represent Si, while the rows represent Sj.

Table 2

Adjacency Matrix

Indicator	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
S1	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
S2	0	0	1	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	1
S3	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1
S4	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1
S6	0	0	0	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0
S7	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	0	0	0	1
S9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
S10	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	1
S11	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1
S12	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	1
S13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

S14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
S17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
S18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
S19	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0

Stage 2: Calculation of the Reachability Matrix

Assume that A is the original adjacency matrix, I is the identity matrix, and R is the reachability matrix. The reachability matrix was calculated according to Equation 1, as presented in Table 3.

Table 3

Reachability Matrix

Indicator	Reachability Characteristics
S1–S14	High reachability and interdependence across most indicators
S15	No direct reachability relationship identified
S16	Reachability primarily associated with S17–S20
S17	Reachability associated with S17 and S18
S18	Reachability associated with S19
S19	Limited reachability relationship
S20	Reachability associated with S18 and S19

Stage 3: Determination of Indicator Hierarchy

Based on the reachability matrix, the hierarchical structure of the indicators was classified, and the analytical structural model for implementing Industry 4.0 technologies was developed as presented in Table 4.

Table 4

Implementation Hierarchy of Industry 4.0 Technologies in Improving Warehousing Operations in Chain Stores

Effective Indicator	Reachable Set R(nj)	Antecedent Set Q(nj)	Common Set T(nj)
S1	1–20 except S5	1, 2, 4, 5	1, 2, 4
S2	1–20 except S5	1, 2, 4, 5	1, 2, 4
S3	6–20	1, 2, 4, 5	—
S4	1–20 except S5	1, 2, 4, 5	1, 2, 4
S5	1–20 except S5	1–14	—
S6	6–20	1–14	6–14
S7	6–20	1–14	6–14
S8	6–20	1–14	6–14
S9	6–20	1–14	6–14
S10	6–20	1–14	6–14
S11	6–20	1–14	6–14
S12	6–20	1–14	6–14
S13	6–20	1–14	6–14
S14	6–20	1–14	6–14
S15	—	1–14	—
S16	17–20	1–14	—
S17	17–18	1–17	17
S18	19	1–20 except S19	—
S19	—	1–20 except S19	—
S20	18–19	1–16	—

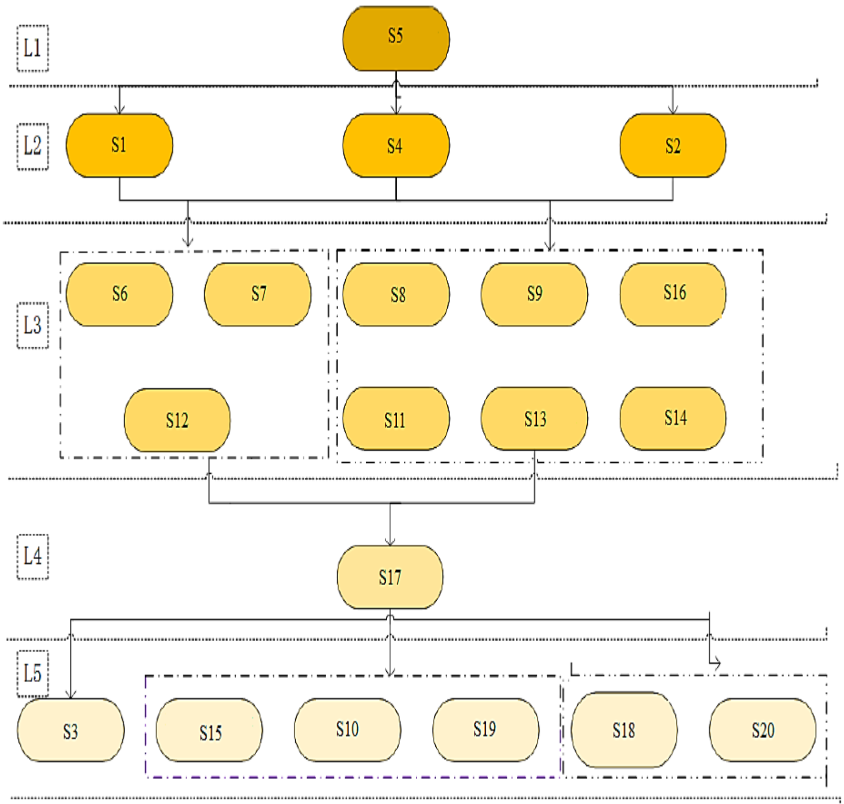
According to T(nj) = Q(nj), the first-layer decomposition was performed, identifying S5 as the first-layer indicator coefficient (L1). After removing the first-layer coefficient, the second-layer indicator coefficients (L2), including S1, S2, S3, and others, were determined. This process subsequently identified the coefficients for the following levels. Ultimately, the effective indicators for implementing Industry 4.0 technologies were classified into five levels.

Stage 4: Development of the Structural Model

Based on the final decomposition results of the effective indicators for implementing Industry 4.0 technologies, the analytical structural model diagram was developed (as illustrated in Figure 1). For chain stores, the 20 identified indicators were distributed across five hierarchical levels, and a progressive relationship exists among these levels. As shown in Figure 1, investment cost (economic) is a key indicator for implementing Industry 4.0 technologies, influencing three fundamental indicators at the L2 level. At the L3 level, operational cost (economic), expected return (economic), and personnel safety (safety) are interrelated, and a specific relationship exists among these three indicators. The remaining indicators exhibit a closer association with the implementation of Industry 4.0 technologies in chain stores. Only one indicator, personnel safety, exists in the L4 layer, and it exerts a specific influence on the indicators in the fifth layer.

Figure 1

Analytical Structural Model of Effective Indicators in the Implementation of Industry 4.0 Technologies



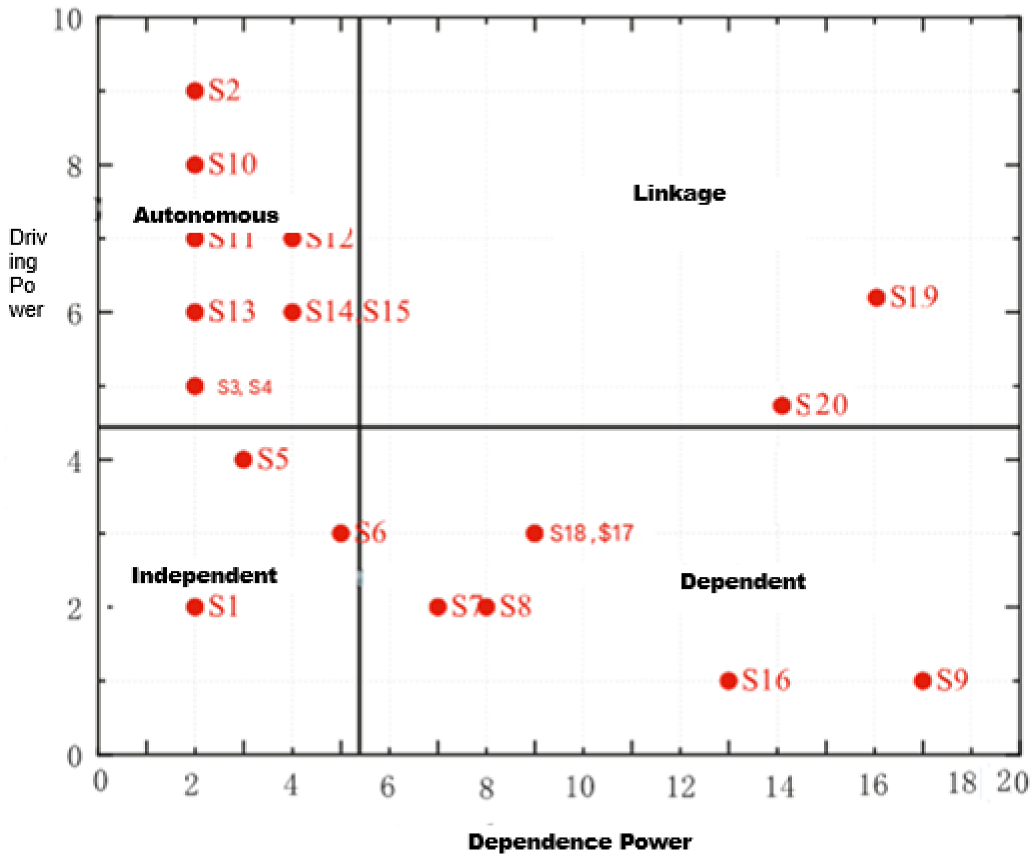
After applying the ISM model to analyze the logical structure of the effective indicators for implementing Industry 4.0 technologies in improving warehousing operations in chain stores, the MICMAC analysis method was employed to calculate iterative matrix operations, determine the driving force and dependence of each indicator, and express the interactions among the effective indicators through the dependence–driving force matrix.

First, the initial adjacency matrix of the indicators was iteratively calculated, and the relationships among indicators were represented by 0 or 1. During each iteration, a new indirect relationship matrix was formed. Once the matrix iteration results stabilized, the driving force and dependence of each indicator were calculated.

Second, in the driving force–dependence matrix, the horizontal axis represents indicator dependence, whereas the vertical axis represents indicator driving force. The indicators were classified into four clusters: independent, dependent, linkage, and autonomous. Based on the driving force and dependence values of the effective indicators in implementing Industry 4.0 technologies, the following matrix coordinate diagram was developed.

Figure 2

MICMAC Diagram of Effective Indicators in the Implementation of Industry 4.0 Technologies



Based on the findings, the greater the dependence values of the components in the upper layers of the ISM model, such as S9 pollution control (environmental) and S16 use of specialized integrated warehouse operations management software (managerial), the more these indicators are stimulated or interact with other indicators for their realization. Conversely, effective indicators such as S2 technical feasibility (technical) and S10 energy consumption control (environmental), when associated with a larger number of variables at the lower levels of the ISM model and generally high driving-force values, are more likely to represent the root causes of improving warehousing operations in chain stores through the implementation of Industry 4.0 technologies and to generate other indicators. Therefore, in prioritization processes, greater attention should be devoted to managing the identified indicators with high driving-force values and those located at the lower levels of the ISM hierarchy.

4. Discussion and Conclusion

The findings of this study demonstrated that the implementation of Industry 4.0 technologies in improving warehousing operations in chain stores is influenced by a multilayered structure of technical, economic, environmental, safety, managerial, and supervisory indicators. The results of the ISM and MICMAC analyses revealed that the indicators do not operate independently; rather, they form a hierarchical and interactive system in which some indicators possess high driving power while others are strongly dependent on the broader technological and operational environment. In particular, investment cost, operational cost, expected return, personnel safety, pollution control, and the use of specialized integrated warehouse operations management software emerged as critical indicators in the successful implementation of Industry 4.0 technologies. These findings confirm that digital transformation in warehousing is not solely a technological process, but a multidimensional managerial and strategic transformation requiring coordination among financial, operational, environmental, and human-resource dimensions.

One of the most significant findings of the study was the identification of investment cost as a key driving indicator within the Industry 4.0 implementation hierarchy. The results showed that investment cost directly influences multiple lower-level operational and technological indicators and serves as a foundational determinant for warehouse modernization in chain stores. This finding is consistent with previous studies emphasizing that Industry 4.0 implementation requires substantial infrastructural investment in digital systems, automation technologies, IoT platforms, AI-driven applications, and integrated software systems (Mithas et al., 2022). Similarly, research on smart manufacturing and interconnected technologies demonstrated that the development of intelligent supply chains depends heavily on strategic investment in technological infrastructure and digital integration capabilities (Kandarkar & Ravi, 2024). In chain-store warehousing, investment decisions determine the ability of organizations to adopt automated storage systems, advanced tracking technologies, predictive analytics, and intelligent inventory platforms. Therefore, insufficient investment may create structural barriers that prevent organizations from achieving operational benefits associated with Industry 4.0 technologies.

The findings further revealed that operational cost and expected return were among the most influential economic indicators affecting the implementation process. This result highlights that organizations evaluate digital transformation initiatives not only based on technological capability but also according to financial sustainability and operational efficiency. Previous studies have similarly argued that digital transformation initiatives in retail and logistics environments are strongly connected to cost optimization and return on investment expectations (Brown et al., 2024). The implementation of AI, IoT, robotics, and warehouse automation technologies may initially increase operational expenditures due to maintenance requirements, system integration, employee training, and cybersecurity demands; however, these technologies are expected to generate long-term reductions in inventory costs, labor inefficiencies, warehousing errors, and supply chain delays. Research on digital innovation and Industry 4.0 has shown that organizations increasingly view digital technologies as mechanisms for improving process efficiency, reducing waste, and enhancing organizational competitiveness (Gupta & Jauhar, 2023). Therefore, the strong position of operational cost and expected return in the present study reflects the economic rationality underlying warehouse digitalization in chain stores.

Another important finding was the critical role of personnel safety within the implementation structure. Personnel safety appeared as a highly influential safety-related indicator affecting the interaction between technological implementation and warehouse operational performance. Warehousing environments involve complex interactions among employees, machinery, shelving systems, transportation equipment, and automated systems, making safety management an essential organizational concern. Previous studies on smart systems and digital supply chains emphasized that advanced technologies can improve organizational quality and operational safety through monitoring systems, predictive maintenance, and automation-based risk reduction (Schmidt et al., 2022). The findings of the current study suggest that Industry 4.0 technologies contribute to safer warehouse operations by minimizing human exposure to hazardous tasks, reducing operational errors, and enhancing process visibility. At the same time, the implementation of automated systems introduces new technological risks that require specialized training and safety governance. Consequently, organizations must integrate safety-oriented planning into their digital transformation strategies to ensure that technological advancement contributes positively to workforce protection and operational stability.

The environmental dimension also emerged as a critical component of warehouse transformation, particularly through the indicator of pollution control. The findings demonstrated that pollution control possessed high dependence within the ISM hierarchy, indicating that environmental sustainability is closely linked to the successful interaction of multiple technological and managerial indicators. This finding aligns with previous studies emphasizing that Industry 4.0 technologies support sustainable logistics and environmentally responsible supply chain operations (Nazir & Fan, 2024). IoT-enabled monitoring systems, AI-based optimization tools, and intelligent inventory management systems can reduce unnecessary transportation, energy waste, carbon emissions, and material inefficiencies. Similarly, studies on sustainability initiatives in retail chains showed that digital technologies improve environmental performance through data-driven resource management and smart operational coordination (Karthikeyan & Nagaprakash, 2023). In the context of chain-store warehousing, pollution control reflects the broader organizational shift toward green logistics and sustainable retail operations. Therefore, the findings suggest that environmental considerations should be integrated into warehouse technology implementation frameworks rather than treated as secondary outcomes.

The use of specialized integrated warehouse operations management software was another key indicator identified in the findings. The MICMAC analysis demonstrated that this indicator had strong dependence and interaction with several technical and managerial variables, highlighting its integrative role within the warehouse digitalization process. This finding is strongly supported by previous research indicating that warehouse management systems constitute the operational core of smart warehousing environments (Khan et al., 2024). Integrated software platforms facilitate real-time inventory tracking, automated decision-making, warehouse coordination, order processing, labor allocation, and data synchronization across supply chain activities. Research on digital transformation in retail enterprises also emphasized that AI- and RPA-enabled software systems improve operational responsiveness and organizational agility (Fu et al., 2023). Moreover, digital twin-based warehouse management research demonstrated that integrated software infrastructures are essential for simulation, predictive analysis, and operational optimization in future-oriented warehouse systems (Maheshwari et al., 2023). Accordingly, the findings of the current study confirm that software integration is not merely a supporting technological tool; rather, it is a strategic enabler of intelligent warehouse management.

The results of the MICMAC analysis further showed that technical feasibility and energy consumption control possessed high driving power and functioned as root indicators influencing other variables within the implementation structure. This finding suggests that organizations cannot achieve effective Industry 4.0 implementation unless technologies are both operationally feasible and environmentally efficient. Technical feasibility determines whether digital technologies are compatible with organizational infrastructure, operational workflows, employee capabilities, and supply chain processes. Previous studies on smart warehouse systems emphasized that technological implementation must consider system compatibility, operational readiness, and infrastructural integration requirements (Khan et al., 2024). Likewise, digital transformation studies in logistics highlighted that the success of warehouse modernization depends on the ability of organizations to integrate technologies into existing operational ecosystems (Rodchenko & Prus, 2023). Energy consumption control, meanwhile, reflects the growing importance of sustainable digital transformation. Intelligent energy management systems, automated lighting, sensor-based monitoring, and AI-driven optimization tools allow organizations to reduce energy waste and improve environmental efficiency. Consequently, the findings indicate that technical and environmental readiness are foundational conditions for successful warehouse transformation in chain stores.

The hierarchical structure generated through the ISM model also demonstrated that Industry 4.0 implementation in warehousing follows a progressive and interconnected logic. Lower-level indicators with strong driving power influence higher-level dependent indicators, creating a cascading effect throughout the implementation process. This result supports theoretical perspectives suggesting that digital transformation is a systemic phenomenon in which organizational, technological, managerial, and economic factors interact dynamically rather than independently (Mayounga, 2022). The existence of interconnected relationships among indicators further confirms the relevance of using ISM and MICMAC approaches in warehouse digitalization studies because these methods reveal causal structures that traditional statistical analyses may fail to capture. Similar studies in logistics and retail supply chains have argued that digital ecosystems operate through interdependent technological and managerial relationships rather than isolated operational variables (Hrouga & Sbihi, 2023; Zhao & Smirnova, 2023). Therefore, the current findings contribute to the literature by providing a structured framework for understanding how Industry 4.0 implementation indicators interact in chain-store warehousing environments.

Another important implication of the findings concerns the strategic role of artificial intelligence, IoT, and automation technologies in transforming warehouse operations. Previous research demonstrated that AI-driven retail systems enhance operational intelligence, customer responsiveness, and decision quality (Gupta et al., 2025). Similarly, IoT-based inventory systems improve inventory visibility, replenishment accuracy, and logistics coordination (Mashayekhy et al., 2022). The current study extends these findings by demonstrating that such technologies exert influence through interconnected technical, economic, managerial, and environmental indicators rather than through isolated operational mechanisms. In practical terms, this means that warehouse digitalization should be approached as an integrated transformation strategy rather than a collection of separate technological initiatives.

The findings also suggest that organizational readiness and trained human resources remain essential despite increasing automation. The employment of trained personnel emerged as a relevant managerial indicator, reflecting the continued importance of human expertise in digitally transformed warehouse systems. This result supports previous studies emphasizing that digital transformation requires organizational learning, knowledge sharing, and employee adaptation to new technological environments (Ranjan & Kadam, 2025). Even highly automated warehouses require skilled employees capable of managing software systems, interpreting operational data, responding to system failures, and coordinating digital workflows. Therefore, successful Industry 4.0 implementation depends not only on technological investment but also on workforce development and managerial capability.

Overall, the findings of this study confirm that the implementation of Industry 4.0 technologies in improving warehousing operations in chain stores is a multidimensional and hierarchical process shaped by complex interactions among technical, economic, environmental, safety, managerial, and supervisory indicators. The study demonstrates that indicators with high driving power, particularly investment cost, technical feasibility, and energy consumption control, should receive strategic priority because they influence broader implementation outcomes. Simultaneously, highly dependent indicators such as pollution control and integrated warehouse management software reflect the outcomes of successful interaction among multiple organizational and technological conditions. These findings contribute to the growing literature on smart warehousing, digital logistics, and retail supply chain transformation by providing a structured analytical framework for understanding the implementation dynamics of Industry 4.0 technologies in chain-store warehouse operations.

The present study has several limitations. First, the study relied on a relatively small expert sample consisting of 15 participants, which may limit the generalizability of the findings to broader retail and logistics contexts. Second, the research was conducted within the specific context of chain-store warehousing, and therefore the identified relationships among indicators may differ in other industries or operational environments. Third, the study used ISM and MICMAC approaches, which depend significantly on expert judgment and qualitative interpretation, potentially introducing subjectivity into the analysis process. Fourth, the cross-sectional nature of the research limits the ability to examine how Industry 4.0 implementation indicators evolve over time. Finally, the study primarily focused on structural relationships among indicators and did not empirically measure the direct operational performance outcomes associated with Industry 4.0 implementation.

Future research should expand the scope of investigation by examining Industry 4.0 implementation indicators across different retail sectors, manufacturing environments, and international supply chain systems. Comparative studies between small retailers and large chain stores may provide deeper insight into contextual differences in digital transformation readiness. Researchers are also encouraged to employ quantitative modeling approaches such as structural equation modeling, machine learning, or system dynamics to validate and extend the relationships identified in the current study. Longitudinal studies may further help explain how technological implementation evolves over time and how organizational learning influences implementation success. In addition, future research could investigate the role of cybersecurity, employee resistance, organizational culture, and data governance in shaping the effectiveness of Industry 4.0 technologies in warehouse operations.

From a practical perspective, managers of chain stores should prioritize strategic investment in digital warehouse infrastructure while simultaneously ensuring organizational readiness and employee training. Organizations should focus on implementing integrated warehouse management software capable of connecting inventory, logistics, operational monitoring, and decision-support functions within a unified digital environment. Greater attention should also be devoted to sustainability-oriented technologies that improve pollution control, reduce energy consumption, and support environmentally responsible logistics operations. Managers should adopt phased implementation strategies that begin with high-driving indicators such as technical feasibility and infrastructural readiness before expanding toward more advanced automation systems. Furthermore, organizations should strengthen safety governance frameworks to ensure that warehouse digitalization enhances personnel protection alongside operational efficiency.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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