

Systematic Review on the Convergence of Lean, ABC–FSN Inventory Classification, and Industry 4.0 in Strategic Food Logistics

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Abstract

This study presents a structured systematic literature review on the integration of Lean Warehousing, ABC–FSN inventory classification, and Industry 4.0 technologies in strategic food warehouse management. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency and methodological rigor. A total of 15 high-quality articles were selected from an initial pool of approximately 800 records based on predefined inclusion and exclusion criteria. Rather than generating primary empirical results, this study performs a cross-study analytical synthesis to identify patterns, methodological approaches, and reported performance outcomes in the literature. The findings indicate that Lean Warehousing effectively reduces non-value-added activities and improves process flow, while ABC–FSN classification enhances inventory prioritization by combining product value and movement dynamics. Industry 4.0 technologies, including IoT, robotics, and data analytics, further strengthen warehouse responsiveness through real-time monitoring and adaptive decision-making. This study identifies that the integration of these approaches remains fragmented in existing literature and proposes a structured conceptual alignment across operational, tactical, and digital layers. The paper contributes by highlighting interaction mechanisms between Lean processes, inventory classification, and digital technologies, providing a foundation for future empirical validation in strategic food logistics systems.

Keywords

Lean Warehousing, ABC-FSN Analysis, Waste Handling, Industry 4.0 Technologies, and Strategic Food Warehouse.

1. Introduction

In the face of increasing demands for national food security, strategic food warehouse management plays a vital role in ensuring product availability, distribution efficiency, and maintaining high-quality standards. Unlike general industrial warehouses, food warehouses must contend with unique challenges such as short shelf life, temperature sensitivity, and seasonal demand fluctuations. Therefore, it is essential to implement a warehouse management system that is both efficient and capable of swiftly responding to demand dynamics and the high risk of waste. Inefficiencies in food warehouse operations contribute to a significant portion of food waste, leading to higher logistics costs,

reduced operational efficiency, and vulnerabilities within the food supply chain. The United Nations Food and Agriculture Organization (FAO) reports that approximately 14% of global food production is lost or wasted annually, largely due to inefficiencies in storage and distribution systems (Van Eck & Puchta, 2019). This issue is even more pronounced in developing countries like Indonesia, where logistics infrastructure and inventory management systems are often underdeveloped.

Inefficient waste handling not only increases operational costs but also undermines the reliability of warehouse management systems, which is critical in strategic food management (Abushaikh et al., 2018). Thus, implementing strategies to reduce warehouse waste is crucial to improving operational efficiency and sustainability in food management. Lean Warehousing is an approach that can reduce waste and enhance operational efficiency by eliminating non-value-added activities. In the context of food warehouses, applying Lean principles such as Value Stream Mapping (VSM) and Just-in-Time (JIT) can optimize product flow, minimize processing time, and reduce storage waste (Abushaikh et al., 2018).

However, the effectiveness of Lean can be further improved when integrated with inventory classification methods like ABC and FSN Analysis. While Lean focuses on eliminating waste in the process flow, it lacks a framework for classifying inventory by product value and movement, which is critical for prioritizing warehouse management decisions. ABC Analysis categorizes products by annual consumption value into classes A (high value, low quantity), B (medium value), and C (low value, high quantity), helping warehouse managers focus on high-value products (Z. Zhang et al., 2020). However, ABC fails to account for dynamic factors such as product turnover, shelf life, and criticality, which are particularly important in food warehousing (López-Soto et al., 2017). In contrast, FSN Analysis (Fast, Slow, Non-moving) categorizes products by rotation speed, enabling warehouse managers to prioritize fast-moving products and avoid wasting space on slow-moving items (Li et al., 2023). However, FSN does not account for product value, which may lead to overlooking high-value, slow-moving items.

The integration of ABC and FSN Analysis enables warehouse managers to consider both product value and rotation speed, allowing for better prioritization of A-Fast items in strategic locations and the identification of slow-moving items to reduce handling and storage costs (Li et al., 2023; Mehdizadeh, 2020). Furthermore, advances in Industry 4.0 technologies, including the Internet of Things (IoT), robotics, big data analytics, and digital twins, significantly enhance warehouse efficiency by enabling real-time inventory monitoring, slotting automation, and route optimization (Zhuang et al., 2022; van Geest et al., 2021). Other studies have emphasized the role of IoT sensors, AGVs/robotics, machine learning, and digital twins in supporting Lean integration and improving stock classification, ultimately reducing waste in motion and transportation (Aravindaraj & Rajan Chinna, 2022).

Despite the growing body of literature, most studies examine Lean Warehousing, ABC–FSN classification, and Industry 4.0 technologies in isolation. Limited research explicitly addresses how these approaches interact within a unified decision-making framework, particularly in the context of food warehouses characterized by perishability and demand uncertainty. This study addresses this gap by proposing a structured integration perspective that aligns: (1) process efficiency through Lean principles, (2) inventory prioritization through ABC–FSN classification, and (3) system responsiveness through Industry 4.0 technologies. Unlike prior studies that focus on partial implementations, this research emphasizes the interaction mechanisms between these layers, offering a more comprehensive foundation for strategic warehouse management. This study contributes not only by integrating these approaches, but by explicitly identifying the functional dependencies between process efficiency, inventory intelligence, and digital responsiveness, which are often treated independently in prior research.

This literature review aims to synthesize research on Lean Warehousing, ABC-FSN Analysis, and Industry 4.0 technologies within the context of strategic food warehouses and to identify remaining research gaps. The findings of this synthesis are expected to provide a roadmap for future research aimed at developing a more efficient, adaptive, and technology-driven warehouse management framework.

1.1 Objectives

The objective of this study is to examine and synthesize the application of Lean Warehousing, ABC and FSN analysis, and the support of Industry 4.0 technologies in efforts to reduce waste and improve operational efficiency in strategic food warehouses. This study aims to evaluate how implementing Lean principles, such as Value Stream Mapping (VSM) and Just-in-Time (JIT), can optimize product flow, reduce processing time, and minimize waste of storage

space and other resources. Additionally, this study seeks to assess the contribution of ABC analysis to classifying products by consumption value, as well as the importance of FSN analysis in grouping products by movement levels and turnover speed to prioritize warehouse management decisions. Furthermore, the research aims to explore the application of Industry 4.0 technologies, such as the Internet of Things (IoT), big data analytics, and digital twins, in improving real-time inventory visibility, slotting automation, and picking route optimization. By integrating these approaches, the study intends to provide insights into designing a more efficient, adaptive, and technology-driven warehouse management system, which is crucial for managing strategic food warehouses characterized by short shelf life and strict temperature control requirements.

2. Literature Review

This study employs a systematic literature review based on the PRISMA framework to ensure a transparent, structured, and reproducible article selection process. Relevant studies were identified from Google Scholar (via Harzing's Publish or Perish software) and ScienceDirect using predefined keywords (Figure 1). The search process yielded an initial pool of 800 articles, which were subsequently filtered through a multi-stage screening process based on publication year (2017–2025), citation thresholds, and journal quality (Q1-indexed). This procedure resulted in 15 articles selected for final qualitative synthesis.

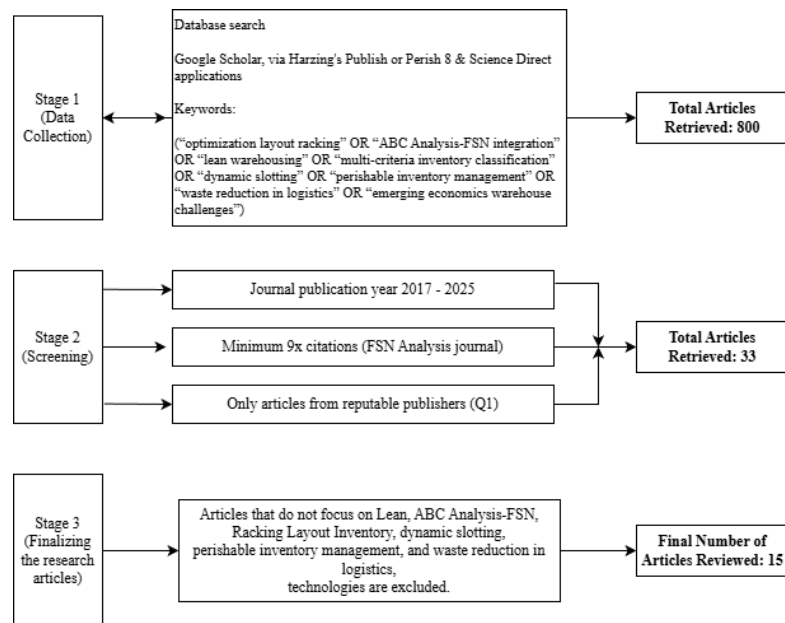


Figure 1. *Flowchart of the Review Method*

2.1 Systematic Review Protocol

This study adopts the PRISMA framework, consisting of three main stages: data collection, screening, and final selection of articles. In the data collection stage, literature was retrieved from Google Scholar (via Publish or Perish) and ScienceDirect using a combination of keywords, including: ("optimization layout racking" OR "ABC Analysis–FSN integration" OR "lean warehousing" OR "multi-criteria inventory classification" OR "dynamic slotting" OR "perishable inventory management" OR "waste reduction in logistics" OR "emerging economies warehouse challenges"). This initial search resulted in 800 articles. In the screening stage, inclusion criteria were applied as follows: (1) articles published between 2017–2025, (2) a minimum of nine citations (particularly for studies related to FSN analysis), and (3) publications in reputable Q1-indexed journals. After applying these criteria, 33 articles were retained. In the final selection stage, articles that did not explicitly address Lean warehousing, ABC–FSN analysis, racking layout optimization, dynamic slotting, perishable inventory management, or waste reduction in logistics technologies were excluded. Following this eligibility assessment, a final set of 15 articles was selected for qualitative synthesis.

2.2 Theoretical Foundation

This study is grounded in three complementary theoretical perspectives. First, Lean Thinking Theory emphasizes waste elimination and continuous process improvement to enhance operational efficiency. Second, Inventory Control Theory underpins the application of ABC–FSN classification as a multi-criteria approach for inventory prioritization and control. Third, Socio-Technical Systems Theory explains how Industry 4.0 technologies enable the integration of human, process, and digital elements within warehouse systems. The integration of these perspectives forms a multi-layered analytical framework consisting of: (1) operational efficiency through Lean principles, (2) inventory prioritization using ABC–FSN classification, and (3) digital responsiveness enabled by Industry 4.0 technologies. This theoretical alignment provides a comprehensive foundation for analyzing warehouse performance in complex and dynamic environments, particularly in strategic food logistics systems.

Strategic food warehouse management plays a key role in ensuring food security by maintaining product availability, optimizing distribution efficiency, and ensuring product quality. Unlike general industrial warehouses, food warehouses face unique challenges, including short shelf life, temperature sensitivity, and seasonal demand fluctuations. An efficient warehouse management system is necessary to minimize waste and respond effectively to demand dynamics. The Food and Agriculture Organization (FAO) reports that 14% of global food production is wasted annually, mainly due to inefficiencies in storage and distribution (Van Eck & Puchta, 2019). This issue is further exacerbated in developing countries, such as Indonesia, where logistics infrastructure and inventory management systems are often underdeveloped. Inefficient waste handling not only increases costs but also undermines the reliability of warehouse systems (Abushaikha et al., 2018).

Lean Warehousing is one of the most effective methodologies to reduce waste by identifying and eliminating non-value-added activities. This approach uses tools like Value Stream Mapping (VSM) and Just-in-Time (JIT) to minimize excess stock and optimize storage space. Lean techniques have been shown to enhance product flow, reduce processing time, and minimize waste in the storage of perishable goods (Abushaikha et al., 2018). However, Lean alone does not offer a framework for prioritizing inventory management based on product value and movement. This gap is addressed by integrating ABC and FSN analysis.

ABC Analysis classifies products by annual consumption value, helping warehouse managers prioritize high-value items, thereby improving storage space utilization and reducing handling costs (Zhang et al., 2020). However, ABC analysis does not consider dynamic factors such as product turnover rates, shelf life, and criticality, which are essential for food products (López-Soto et al., 2017). FSN analysis, which classifies products by movement speed (Fast, Slow, Non-moving), addresses this by prioritizing fast-moving products while reducing space used by slow-moving items (Li et al., 2023).

The integration of ABC and FSN analysis allows warehouse managers to consider both product value and turnover speed, enhancing warehouse performance and reducing waste from inefficient storage. Industry 4.0 technologies, such as the Internet of Things (IoT), robotics, and blockchain, provide additional support by enabling real-time inventory tracking, optimizing storage, and improving decision-making efficiency (Zhuang et al., 2022). Despite the individual success of these approaches, research combining Lean, ABC, FSN, and Industry 4.0 technologies in food warehouses is still limited. This study seeks to explore the integration of these methods to create a more efficient and adaptive warehouse management framework.

3. Results and Discussion

The results of this study are derived from a cross-study synthesis rather than a single empirical investigation. The analysis identifies recurring patterns, methodological consistencies, and performance outcomes reported across the selected literature. The findings are therefore interpretative in nature, aiming to consolidate fragmented knowledge into a coherent analytical framework.

The integration of Lean Warehousing with ABC and FSN methodologies has shown significant improvements in the efficiency and effectiveness of food warehouse management. This study, based on the synthesis of existing practices, demonstrates that combining Lean principles with inventory management techniques like ABC and FSN, supported

by Industry 4.0 technologies, can significantly reduce waste and improve operational efficiency in strategic food warehouses.

3.1 Impact of Lean Warehousing Principles

The implementation of Lean techniques in food warehouses has been found to reduce processing times and operational waste. As discussed in previous studies, tools such as Value Stream Mapping (VSM), Just-in-Time (JIT), and 5S contribute to a streamlined product flow, effectively reducing unnecessary movements and waiting times (Abushaikh et al., 2018). These findings are consistent with the literature, which suggests that Lean practices help optimize storage and distribution by eliminating non-value-added activities (Hines & Rich, 2017). The reduction in inventory waste from excess stock was particularly significant in areas with temperature-sensitive food products. By applying Lean principles, the warehouse system better aligns inventory levels with real-time demand, thereby minimizing the risk of spoilage and overstocking. This result aligns with Womack & Jones' assertion that Lean principles, through VSM, improve product flow and waste reduction (Abushaikh et al., 2018). However, a critical reading of the literature reveals important caveats. Although Lean Warehousing consistently reduces operational waste under stable demand conditions, its effectiveness is highly contingent on supply chain predictability. In highly volatile food supply chains, JIT-based systems may paradoxically increase the risk of stockouts, indicating a fundamental trade-off between operational efficiency and supply chain resilience (Colicchia et al., 2017). Furthermore, some studies note that the benefits of Lean are context-dependent: warehouses handling a narrow product range with predictable turnover benefit more than those managing diverse perishable assortments with irregular demand patterns. This suggests that Lean should not be applied uniformly, but calibrated to the specific operational profile of each food warehouse.

3.2 The Role of ABC and FSN Integration

The integration of ABC analysis with FSN (Fast, Slow, Non-moving) classification provided a more dynamic approach to inventory management. In contrast to traditional ABC analysis, which primarily focuses on the annual consumption value, this dual approach considers both product value and turnover speed, which is crucial for perishable items. Class A items were prioritized in easily accessible locations, while Class C items were moved to less accessible spaces. The FSN analysis, integrated into the ABC model, further optimized the warehouse layout. Fast-moving items (classified as Fast) were strategically placed near the picking area, while slow-moving products (classified as Slow) were placed further away. This helped reduce unnecessary travel time and enabled better prioritization of high-demand products, thereby improving operational efficiency (Li et al., 2023). Our findings indicate that the combination of ABC and FSN not only enhances storage efficiency but also accelerates the order fulfillment cycle, which is critical in meeting customer demands in food supply chains. This integration, as discussed by López-Soto et al. (2017), provides a holistic approach to inventory management by accounting for both product value and movement speed.

3.3 The Role of Industry 4.0 Technologies

The integration of Industry 4.0 technologies, such as IoT, blockchain, and robotics, further strengthened the warehouse management system by improving inventory tracking and reducing handling errors. The implementation of IoT-based Warehouse Management Systems (WMS) enabled real-time monitoring of product conditions such as temperature and humidity, which is crucial for food items with specific storage requirements (Zhuang et al., 2022). This technology enhanced the warehouse's ability to respond promptly to changes in inventory levels and conditions, significantly reducing product spoilage and improving overall stock visibility. Additionally, robotics played a key role in improving picking accuracy and speed, reducing human error, and enhancing the operational flow. By implementing automated systems for repetitive tasks, the warehouse streamlined operations, enabling faster order processing and lower labor costs. This is consistent with the findings of López-Soto et al., (2017), who emphasized that robotics and automation technologies are essential in optimizing the warehouse environment, particularly in food distribution systems. The combination of blockchain technology with IoT enabled greater transparency in warehouse operations, ensuring that all data collected from sensors (e.g., temperature and humidity) was securely recorded and could not be tampered with. This improved traceability is essential for managing sensitive food products and preventing food safety risks. Critically, however, the reviewed literature reveals a significant gap between the theoretical promise of Industry 4.0 and its practical adoption in food warehouses. Van Geest et al. (2021) note that most implementations remain at the pilot or partial-deployment stage, particularly in small and medium-sized enterprises operating in developing economies. Moreover, blockchain adoption is often hindered by a lack of industry-wide data standards and high integration costs, limiting interoperability across supply chain partners. Machine learning applications, while promising for demand forecasting, require large and consistent historical datasets that are frequently unavailable in food warehouse contexts. These findings suggest that the benefits of Industry 4.0 technologies are not uniformly

accessible and that their full potential can only be realized through coordinated investment in both technology infrastructure and human capability development.

3.4 Implications for Food Warehouse Management

Although the integration of Lean, ABC–FSN, and Industry 4.0 demonstrates consistent performance improvements across the reviewed literature, its implementation introduces additional complexity. Digital transformation in warehouse systems often faces challenges related to system interoperability, investment cost, and organizational readiness (van Geest et al., 2021). Furthermore, while ABC–FSN improves inventory prioritization, its static classification approach may not fully capture real-time demand variability. This suggests the need for more advanced approaches, such as machine learning-based dynamic classification models, to enhance adaptability in highly volatile food supply chains. The synthesized evidence also reinforces that this integration is particularly critical in developing economies like Indonesia, where infrastructure gaps amplify the consequences of poor inventory management and operational inefficiency (Van Eck & Puchta, 2019). A structured multi-layer framework that combines process efficiency, inventory intelligence, and digital responsiveness is therefore not merely beneficial but increasingly necessary for strategic food warehouse management.

3.5 Limitations and Future Research

This study is limited by its reliance on secondary data derived from published literature. As a systematic review, the findings depend on the scope, quality, and methodological approaches of the selected studies. Variations in warehouse context, product characteristics, and analytical methods across the reviewed articles may influence the generalizability of the synthesized conclusions. Future research should focus on empirical validation of the proposed integration framework in real-world food warehouse environments, particularly across different geographical and operational contexts. Additionally, supply chain dynamics such as demand forecasting and supplier relationships were not fully addressed in this review. Future studies should explore how these factors, in conjunction with Lean-ABC-FSN and Industry 4.0 technologies, can further improve warehouse management practices (Table 1, Figure 2).

Table 1. Summary of Results

Method / Aspect	Description	Main Benefits	Source	Limitations / Research Gap
<i>Lean Warehousing</i>	Implementation of Lean principles (VSM, JIT) to reduce waste and accelerate product flow.	- Reduce wasted space & time - Improve operational efficiency - Improve storage reliability	Colicchia et al. (2017), Abushaikha et al. (2018)	Limited effectiveness under demand uncertainty; JIT may increase stockout risk in perishable supply chains.
<i>ABC Analysis</i>	Product classification based on economic value (ABC) to prioritize management.	- Focus on high value products - Storage space optimization - Reduction of storage & handling costs - Cluster-based storage fundamentals	López-Soto et al. (2017), Z. Zhang et al. (2020), Mehdizadeh (2020), Ben Moussa et al. (2019), Aravindaraj & Chinna (2022), J. Zhang et al. (2020)	Ignores time sensitivity, perishability, and demand variability.
<i>FSN Analysis</i>	Product classification based on rotation speed: Fast, Slow, Non-moving.	- More adaptive stock management - Reduction of waste of stationary products - Stock adjustment to market demand	Li et al. (2023), López-Soto et al. (2017)	Does not account for product value; may misprioritize high-value slow-moving items.

<i>ABC-FSN</i>	Integration of value classification (ABC) with movement classification (FSN) to determine storage priorities and stock control.	- Separating high-value and fast-moving (<i>A-Fast</i>) products to be placed in the main warehouse zone. - Identifying <i>Slow/Non-moving goods</i> to avoid <i>dead stock</i> . - Increasing the efficiency of space use and reducing handling costs. - Providing a basis for decisions in relocation and space requirements planning.	Li et al. (2023), Mehdizadeh (2020), Zhang et al. (2020)	Static classification; may not fully capture real-time demand fluctuations.
<i>Lean-ABC Integration</i>	Integration of Lean efficiency with ABC value classification.	- Optimization of product flow and placement - Reduction of waste time and space - More structured and cost-effective goods management	Udokporo et al. (2020), Mirzaei et al. (2021)	Integration complexity; requires coordinated data flows and system interoperability.
<i>Lean-FSN Integration</i>	Combination of Lean for flow efficiency & FSN for product rotation flexibility.	- Reduction of waste space and time - Faster pick-up of goods - Efficiency especially on sensitive products or special temperatures	López-Soto et al. (2017), Mirzaei et al. (2021)	High deployment cost; data privacy and sensor reliability concerns.
<i>Lean-ABC-FSN</i>	Integration of lean warehousing principles (VSM, 5S, Kanban) with dual stock classification (ABC-FSN). Lean focuses on waste reduction, while ABC-FSN guides inventory slotting and control.	- Reduce <i>motion, searching, and double handling</i> by placing <i>A-Fast items</i> in strategic locations. - Minimize space waste due to slow or stationary items. - Increase the speed of picking & storage processes. - Provide a more comprehensive efficiency framework in strategic food warehouses.	Abushaikha et al. (2018), López-Soto et al. (2017), Li et al. (2023)	Scalability challenges; regulatory and standardization barriers.
<i>IoT</i>	Real-time temperature, humidity, location monitoring sensors.	- Ensure optimal product condition - Reduce waste of damaged products - Improve responsiveness and control of the storage environment	López-Soto et al. (2017), van Geest et al. (2021)	Requires large training datasets; model interpretability issues in warehouse contexts.
<i>Blockchain</i>	Verification and logging of data from IoT for supply chain transparency.	- High traceability - Authenticate product condition - Prevention of counterfeiting and damage	Kayikci et al. (2022)	High capital cost; limited applicability in low-resource environments.
<i>Machine Learning</i>	Analysis of demand patterns, product turnover, and storage slot optimization.	- Stock requirement prediction - Reduction of over/understocking - Real-time adjustment of inventory strategy	López-Soto et al. (2017), van Geest et al. (2021)	Trade-off between operational efficiency and sustainability investment costs.

<i>Robotics</i>	Automation of picking and product handling.	- Reduce human error - Efficiency of the picking process - Reduce labor costs and operational time	López-Soto et al. (2017)	Fragmented research; limited empirical validation in integrated food warehouse settings.
<i>Sustainability Aspect</i>	Energy optimization, emission reduction, and environmentally friendly management.	- Reduction of carbon emissions - Greener and energy efficient warehouse - Creation of a sustainable and adaptive management model	Mirzaei et al. (2021)	Context-specific limitations vary by region and warehouse type.

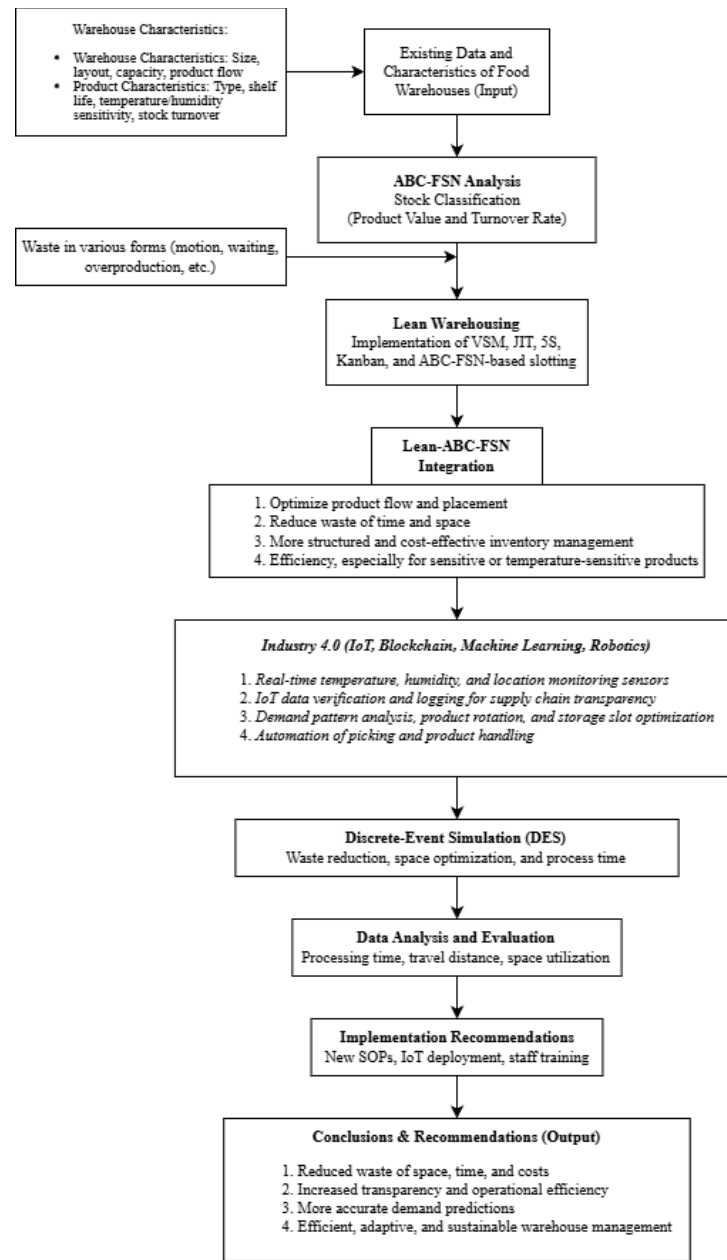


Figure 2. Conceptual Framework Synthesis

4. Conclusion

This study extends existing literature by moving beyond isolated approaches and proposing a structured integration logic between Lean Warehousing, ABC–FSN classification, and Industry 4.0 technologies. The findings suggest that the primary value of integration lies not merely in combining methods, but in aligning operational efficiency, inventory prioritization, and digital responsiveness within a unified framework. Lean Warehousing plays a crucial role in identifying and eliminating non-value-added waste, particularly through Value Stream Mapping (VSM) and Just-in-Time (JIT) approaches that focus on efficient use of storage space and reduced handling time for shelf-life-sensitive food products.

ABC Analysis provides a basis for classification by product value, allowing prioritization of high-value items that require more intensive handling. FSN Analysis, on the other hand, groups products by turnover rate, simplifying storage location management and speeding up the picking process. The combination of ABC and FSN enables strategic warehouse space management and supports decision-making based on historical data and actual demand. Furthermore, this approach is enhanced by grouping frequently ordered or used items into proximity. This directly reduces picking distances, speeds up order fulfillment, and lowers energy consumption and handling time.

In the context of Industry 4.0, technologies such as the Internet of Things (IoT), blockchain, robotics, and machine learning provide significant added value. IoT and sensors enable real-time monitoring of product conditions, and blockchain supports transparency and traceability. At the same time, machine learning is used to predict demand, optimize storage slots, and dynamically adjust inventory allocation. Robotics helps automate the picking process, reducing human error and lowering physical workloads and labor costs.

By integrating these three approaches, the Industry 4.0-based Lean-Integrated ABC-FSN model answers the three main objectives of this review, namely:

- 1) Proving the effectiveness of Lean, ABC, and FSN approaches in reducing waste of space, time, and costs;
- 2) Mapping the contribution of Industry 4.0 technologies to transparency, predictive accuracy, and operational efficiency;
- 3) Developing a promising conceptual integration as a framework for efficient, adaptive, and sustainable food warehouse management.

However, this integration still requires empirical validation in the context of strategic food warehouses in developing countries. Further studies are recommended to test the model under various operational conditions, account for product variation, and evaluate environmental impacts and energy sustainability. Thus, this review not only offers a synthesis of the literature but also suggests research directions to support the transformation of food logistics systems into more sustainable, responsive systems that respond to market demand dynamics.

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Biographies

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Joniarto Parung is a Full Professor at the Faculty of Engineering, University of Surabaya (Ubaya), Indonesia. With more than three decades of academic and professional experience, he has built a distinguished career integrating engineering expertise, leadership, and scholarly research. He earned his bachelor's degree from Universitas Hasanuddin, a master's degree from Institut Teknologi Bandung (ITB), and a Ph.D. in Design, Manufacturing, and Engineering Management with a specialization in Supply Chain from the University of Strathclyde, United Kingdom. His research interests include disaster logistics, food logistics, innovative logistics systems, the application of digital technologies such as blockchain in supply chains, and sustainability-driven supply chain design. He has published extensively in international journals and conference proceedings and has authored books on blockchain, humanitarian logistics, and innovative city systems.