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An Integrated Warehouse Redesign Framework For Improving Operational Efficiency Through Systematic Layout Planning, Material Handling Analysis, Risk Assessment, And Error-Proofing

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Abstract

Warehouse operational efficiency has become increasingly important for manufacturing companies because it directly affects material flow continuity, logistics costs, production responsiveness, and overall supply chain performance. However, inefficient warehouse layouts often result in excessive material handling distances, prolonged transportation time, underutilized storage space, and increased operational risks that reduce warehouse productivity. Although previous studies have demonstrated the effectiveness of facility layout optimization, material handling analysis, risk assessment, and error-proofing techniques, these approaches have largely been applied independently, limiting their ability to simultaneously improve operational efficiency and process reliability. This study proposes, implements, and validates an Integrated Warehouse Redesign Framework for enhancing warehouse operational efficiency through the integration of Systematic Layout Planning (SLP), Material Handling Analysis, Risk Assessment, and Error-Proofing within a unified improvement methodology. In the proposed framework, SLP was employed to redesign the warehouse layout based on activity relationships and space requirements, Material Handling Analysis was used to evaluate transportation performance through distance, time, and handling cost measurements, operational risk assessment was conducted using Failure Mode and Effects Analysis (FMEA) to identify and prioritize critical failure modes, and error-proofing strategies were developed using Poka-Yoke to prevent recurring operational errors. The framework was validated through an industrial case study in a manufacturing warehouse. The implementation results demonstrated significant operational improvements, including a 32.53% reduction in total material travel distance, a 28.86% reduction in material handling time, a 30.30% reduction in material handling costs, a 66.67% decrease in backtracking movements, and a 72.73% reduction in cross movements. Furthermore, warehouse space utilization increased from 71.5% to 86.9%, while overall material handling efficiency improved from 68.2% to 89.1%, indicating substantial enhancements in warehouse operational performance. The proposed framework extends conventional warehouse layout optimization by integrating facility layout planning, material handling optimization, operational risk assessment, and error-proofing into a systematic decision-making process for warehouse redesign. This study contributes to the Industrial Engineering literature by providing a comprehensive and validated methodological framework for warehouse improvement, while offering manufacturing practitioners a practical guideline for reducing operational waste, improving process reliability, and enhancing warehouse performance without requiring major facility expansion.

Keywords: *Integrated Warehouse Redesign Framework; Warehouse Operational Efficiency; Systematic Layout Planning; Material Handling Analysis; Risk Assessment; Error-Proofing.*

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INTRODUCTION

The increasing complexity of global manufacturing and supply chain networks has intensified the need for organizations to enhance operational efficiency across all logistics activities. Growing product variety, shorter product life cycles, fluctuating customer demand, and increasing expectations for rapid order fulfillment have transformed warehouses from passive storage facilities into strategic operational hubs that directly support production continuity and supply chain responsiveness. Consequently, warehouse performance has become a critical determinant of manufacturing competitiveness because it influences inventory availability, material flow continuity, production lead time, logistics costs, and customer service performance. As manufacturing systems continue to evolve toward more integrated and data-driven operations, improving warehouse efficiency has become an essential strategy for achieving operational excellence and sustainable competitive advantage (Albert et al., 2023; Chen, 2025; Zhen & Li, 2022).

Within modern warehouse systems, operational efficiency is strongly influenced by the effectiveness of facility layout and material handling processes. An efficient warehouse layout facilitates smooth material flow, minimizes transportation distance, reduces internal travel time, improves space utilization, and lowers material handling costs. Conversely, poorly designed layouts create unnecessary transportation, excessive backtracking, waiting time, and other non-value-added activities that negatively affect warehouse productivity and operational performance. Recent advances in warehouse management research have therefore emphasized the importance of systematic facility planning that considers spatial relationships, operational workflows, and material movement simultaneously. Such approaches have been shown to significantly improve warehouse performance by optimizing material flow and reducing operational waste, particularly in manufacturing environments characterized by high material movement frequency and complex logistics activities (Aiello et al., 2002; Castillo & Peters, 2002; Erik & Kuvvetli, 2024; Klausnitzer & Lasch, 2019).

Despite the substantial progress achieved in warehouse optimization research, improving warehouse operational performance remains a challenging issue because warehouse efficiency is influenced by multiple interrelated factors rather than a single operational aspect. Among these factors, facility layout planning has consistently been recognized as one of the most influential determinants of warehouse performance. Systematic facility planning approaches, particularly Systematic Layout Planning (SLP), have been widely adopted because they systematically consider activity relationships, material flow, and space requirements to produce efficient facility configurations. Recent studies have further demonstrated that integrating SLP with Activity Relationship Charts (ARC) enables warehouse layouts to better reflect operational interactions among functional areas, thereby reducing unnecessary travel distance and improving workflow continuity. Compared with conventional layout design methods, these approaches have been shown to significantly improve space utilization and transportation efficiency in manufacturing warehouses (Erik & Kuvvetli, 2024; Hu & Chuang, 2023; Klausnitzer & Lasch, 2019).

While facility layout determines the physical arrangement of warehouse operations, its effectiveness is highly dependent on the efficiency of the associated material handling system. Material handling activities account for a substantial proportion of warehouse operating costs because they directly affect transportation distance, processing time, labor productivity, and equipment utilization. Consequently, recent research has increasingly emphasized the integration of layout design with material handling analysis rather than optimizing each aspect independently. Such integrated approaches enable more comprehensive evaluations of warehouse performance by

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simultaneously considering transportation routes, material flow patterns, and operational costs. Previous studies consistently report that coordinated optimization of facility layout and material handling produces greater operational improvements than isolated optimization strategies, particularly in warehouses characterized by high-frequency material movement and complex internal logistics (Czerniachowska et al., 2023; Görener, 2025; Klausnitzer & Lasch, 2019; Zhen & Li, 2022)

Although optimizing facility layout and material handling substantially improves operational efficiency, these approaches primarily focus on reducing transportation waste and enhancing workflow continuity, while giving relatively limited attention to operational reliability and human error prevention. To address these issues, Failure Mode and Effects Analysis (FMEA) has been extensively employed as a structured risk assessment tool for identifying, prioritizing, and mitigating potential operational failures. Concurrently, Poka-Yoke has evolved from a manufacturing error-proofing technique into a broader operational improvement approach capable of preventing human errors through systematic process design. Recent developments have further expanded Poka-Yoke by incorporating digital technologies, including computer vision, deep learning, and intelligent sensing systems, thereby improving operational accuracy and process reliability. Nevertheless, existing studies generally apply FMEA and Poka-Yoke independently from warehouse layout planning, with most implementations focusing on manufacturing processes rather than warehouse operations. Consequently, the potential of integrating operational risk management and error-proofing into warehouse redesign remains insufficiently explored (Faveto et al., 2024; Martinelli et al., 2022; Rodbundith et al., 2026; Trojanowska et al., 2023; Vergara et al., 2025).

Despite the significant advances in warehouse layout optimization and operational improvement, the existing body of knowledge remains fragmented. Although previous studies have successfully improved warehouse performance through facility layout optimization, material handling analysis, operational risk assessment, or error-proofing techniques, these approaches have generally been implemented independently. Consequently, limited attention has been given to developing an integrated warehouse redesign methodology capable of simultaneously improving operational efficiency, process reliability, and risk prevention. Conversely, studies employing FMEA primarily concentrate on identifying and prioritizing operational risks, while Poka-Yoke applications are predominantly implemented in manufacturing and assembly systems to reduce human errors. As a result, the interaction between facility layout design, material handling efficiency, operational risk management, and error prevention has received relatively limited attention within warehouse redesign research. This fragmented perspective restricts the ability of existing approaches to simultaneously improve operational efficiency, process reliability, and warehouse robustness, particularly in manufacturing environments characterized by intensive material movement and complex operational interactions (Albert et al., 2023; Erik & Kuvvetli, 2024; Faveto et al., 2024; Julião et al., 2025; Zhen & Li, 2022).

The identified research gap provides the basis for developing a more comprehensive warehouse improvement strategy. To address the identified research gap, this study develops an Integrated Warehouse Redesign Framework that systematically links warehouse diagnosis, facility layout planning, material handling analysis, operational risk assessment, and error-proofing within a single improvement methodology. Accordingly, this study proposes an Integrated Warehouse Redesign Framework that combines Systematic Layout Planning (SLP), Activity Relationship Chart (ARC), Material Handling Analysis, Failure Mode and Effects Analysis (FMEA), and Poka-Yoke within a unified methodological framework. Unlike previous studies that

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apply these approaches independently, the proposed framework establishes a sequential decision-making process in which SLP and ARC are employed to redesign warehouse layout according to activity relationships and space requirements, Material Handling Analysis quantitatively evaluates operational performance, FMEA identifies and prioritizes critical operational risks, and Poka-Yoke translates the identified risks into preventive improvement actions. By integrating these complementary approaches, the proposed framework extends conventional warehouse layout optimization beyond transportation efficiency toward a more holistic improvement strategy that simultaneously enhances operational efficiency, process reliability, and error prevention. This integrated perspective constitutes the principal novelty of the present study and provides a methodological foundation for systematic warehouse redesign in manufacturing environments.

Based on the identified research gap, this study aims to propose, implement, and validate an Integrated Warehouse Redesign Framework for improving warehouse operational efficiency in a manufacturing environment. The proposed framework integrates Systematic Layout Planning (SLP), Activity Relationship Chart (ARC), Material Handling Analysis, Failure Mode and Effects Analysis (FMEA), and Poka-Yoke into a unified improvement methodology that systematically links facility layout redesign, material flow optimization, operational risk assessment, and error-proofing. The framework is validated through an industrial case study in which warehouse operational performance is evaluated using quantitative indicators, including material travel distance, material handling time, material handling cost, backtracking movements, space utilization, and overall material handling efficiency. Through this integrated evaluation, the study seeks to demonstrate that warehouse redesign should not be limited to physical layout optimization but should simultaneously consider operational reliability and process quality as complementary dimensions of warehouse performance.

This study contributes to the Industrial Engineering literature in two important ways. **First**, it proposes an integrated methodological framework that bridges facility layout planning, material handling analysis, operational risk management, and error-proofing into a coherent decision-making process for warehouse redesign, thereby extending the conventional scope of warehouse layout optimization beyond transportation efficiency alone. **Second**, the study provides empirical evidence demonstrating the effectiveness of the proposed framework through its implementation in a real manufacturing warehouse, thereby strengthening its practical applicability. From a managerial perspective, the framework offers manufacturing companies a systematic and replicable guideline for redesigning warehouse operations to reduce transportation waste, improve material flow continuity, mitigate operational risks, and enhance process reliability without requiring major facility expansion. Consequently, the proposed framework provides both a theoretical advancement for warehouse redesign research and a practical decision-support tool for improving warehouse operational performance in manufacturing industries.

MATERIALS AND METHODS

This study proposes and validates an Integrated Warehouse Redesign Framework to enhance warehouse operational efficiency by systematically integrating facility layout planning, operational performance evaluation, operational risk assessment, and error-proofing within a unified improvement methodology. The framework was developed to overcome the limitations of conventional warehouse improvement approaches, which generally emphasize physical layout optimization while giving limited attention to operational risks and process reliability. As illustrated in Figure 1, the framework consists

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of six sequential stages: warehouse diagnosis, facility layout planning, operational performance evaluation, operational risk assessment, error-proofing strategy development, and framework validation.

The framework was validated through a case study conducted in the finished goods warehouse of a manufacturing company in Indonesia, hereafter referred to as Company XYZ for confidentiality purposes. The warehouse supports receiving, storage, order picking, packing, staging, and shipping activities. Preliminary observations indicated several operational inefficiencies, including excessive material travel distances, backtracking movements, cross-traffic, inefficient space utilization, and prolonged material handling processes. These issues negatively affected warehouse productivity and therefore provided the basis for implementing the proposed framework.

Both primary and secondary data were collected to support the implementation of the framework. Primary data were obtained through direct observations, field measurements, and semi-structured interviews with warehouse supervisors and operators to identify workflow characteristics, material movement patterns, operational constraints, and potential failure modes. Secondary data included warehouse layout drawings, inventory records, material flow data, standard operating procedures (SOPs), and historical warehouse operational reports. These datasets were used throughout the framework to support layout redesign, operational performance evaluation, risk assessment, and validation. The collected data are summarized in Table 1.

The first stage of the framework focused on facility layout planning using Systematic Layout Planning (SLP). The existing warehouse layout was analyzed to identify inefficient material flows, unnecessary transportation activities, and space utilization problems. Activity relationships among warehouse functions were evaluated using the Activity Relationship Chart (ARC), while space requirements were determined based on storage capacity, operational activities, equipment dimensions, and aisle requirements. These analyses were integrated to generate alternative warehouse layouts, from which the most feasible layout was selected according to operational workflow, accessibility, and material flow continuity.

The proposed warehouse layout was subsequently evaluated using Material Handling Analysis (MHA) to quantify its operational performance. The evaluation compared the existing and proposed layouts using several key performance indicators, including total material travel distance, material handling time, material handling cost, space utilization, backtracking movements, cross movements, and overall material handling efficiency. The total material travel distance (TD) was calculated using Equation (1).

$$TD = \sum_{i=1}^{n} (F_i \times D_i)$$

Where:

- **TD** = Total material travel distance (m)
- **Fi** = Frequency of material movement
- **Di** = Travel distance of movement *i* (m)

where TD is the total material travel distance, F_i is the frequency of material movement, and D_i is the corresponding travel distance.

E-ISSN : 2962-9713
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Following the operational performance evaluation, an operational risk assessment was performed using Failure Mode and Effects Analysis (FMEA). Potential failure modes associated with warehouse activities were identified through observations, interviews, and operational records. Each failure mode was evaluated using the standard FMEA criteria of Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) was calculated to prioritize critical operational risks requiring improvement, as expressed in Equation (2).

$$\boxed{RPN = S \times O \times D}$$

Where:

- **S** = Severity
- **O** = Occurrence
- **D** = Detection

Failure modes with the highest RPN values were selected as priorities for improvement.

Based on the prioritized risks, Poka-Yoke principles were employed to develop error-proofing strategies aimed at preventing recurring operational failures. The proposed improvements focused on minimizing human errors, improving operational consistency, simplifying material handling activities, and strengthening process reliability. Rather than functioning as independent corrective actions, the error-proofing strategies complemented the redesigned warehouse layout by ensuring that operational improvements were sustainable under routine warehouse operations.

Finally, the effectiveness of the Integrated Warehouse Redesign Framework was validated through a comparative analysis of warehouse operational performance before and after implementation. The validation considered improvements in travel distance, material handling time, material handling cost, space utilization, backtracking movements, cross movements, and overall material handling efficiency. The percentage improvement for each performance indicator was calculated using Equation (3).

$$\boxed{Improvement(\%) = \frac{P_{before} - P_{after}}{P_{before}} \times 100}$$

Where:

- P_{before} = Performance before implementation
- P_{after} = Performance after implementation

The integrated evaluation of these quantitative indicators was used to determine the capability of the proposed framework to enhance warehouse operational efficiency while simultaneously improving operational reliability and reducing process-related risks.

Table 1. Research Data Collection

Data Type	Data Collected	Purpose
Primary	Direct observations	Identify operational problems and workflow characteristics
Primary	Field measurements	Determine warehouse dimensions and travel distances
Primary	Interviews with warehouse personnel	Identify activity relationships and operational risks

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P-ISSN : 2963-928X

Secondary	Existing warehouse layout	Analyze current facility layout
Secondary	Material flow records	Evaluate transportation activities
Secondary	Inventory and storage data	Determine space requirements
Secondary	Standard Operating Procedures (SOPs)	Verify operational processes
Secondary	Historical warehouse performance reports	Establish baseline operational performance

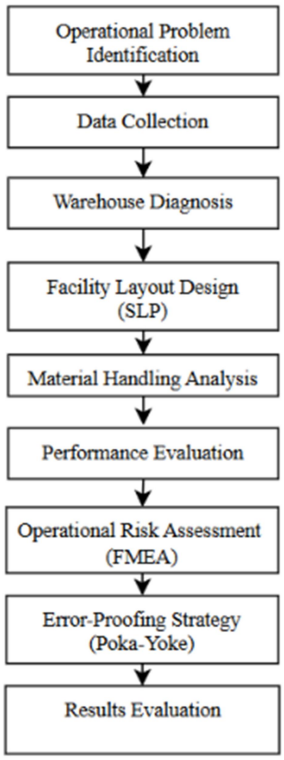


Figure 1. Integrated Warehouse Redesign Framework

Figure 1 illustrates the logical sequence of the proposed Integrated Warehouse Redesign Framework. Unlike conventional warehouse improvement methods that focus primarily on layout optimization, the proposed framework integrates facility planning, operational performance evaluation, risk assessment, and error-proofing into a continuous improvement process. Each stage generates outputs that serve as inputs for the subsequent stage, thereby establishing a systematic decision-making procedure for warehouse redesign.

RESULT AND DISCUSSION

3.1 Warehouse Diagnosis

The first stage of the Integrated Warehouse Redesign Framework involved conducting a comprehensive diagnosis of the existing warehouse to identify operational inefficiencies that adversely affected material handling performance. The diagnosis was performed through direct field observations, warehouse layout measurements, analysis of material movement patterns, and interviews with warehouse personnel. This assessment focused on evaluating the arrangement of functional areas, workflow continuity, transportation routes, and the utilization of available warehouse space.

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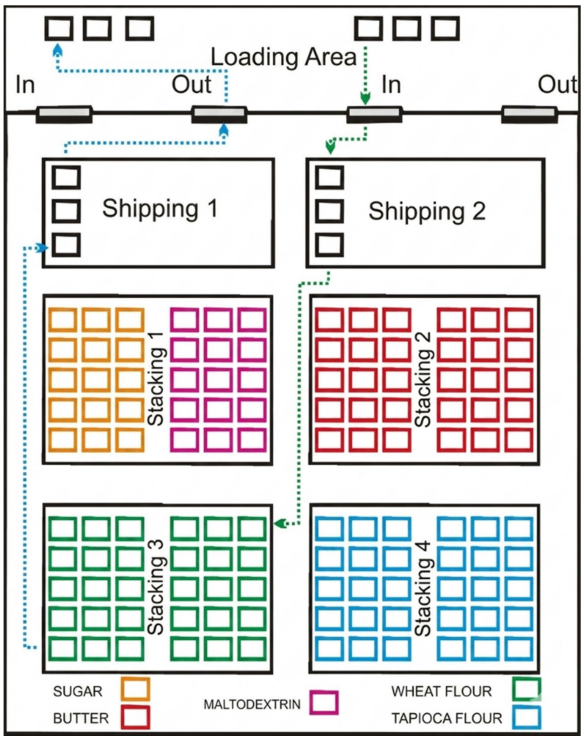


Figure 2. Existing Warehouse Layout and Material Flow

Figure 2 shows that the existing warehouse layout was characterized by long travel distances, several intersecting material flow paths, and inefficient utilization of available storage space. The arrangement of receiving, storage, and dispatch areas required operators to perform unnecessary backtracking movements, thereby increasing transportation time and material handling effort.

The diagnosis revealed that the existing warehouse layout generated unnecessarily long transportation routes between operational areas. Material movement frequently involved backtracking and intersecting travel paths, particularly between storage, picking, packing, and dispatch activities. These inefficient movement patterns increased transportation effort, prolonged material handling processes, and reduced workflow continuity. Furthermore, several operational areas experienced congestion due to insufficient working space, whereas other areas were underutilized, indicating an imbalance in space allocation across warehouse functions.

To support the redesign process, a detailed space requirement analysis was conducted by comparing the existing floor allocation with the operational space required for each warehouse function. The analysis considered storage capacity, material flow characteristics, equipment dimensions, operational activities, and accessibility requirements. The results, presented in Table 2, indicate that although the total warehouse area remained unchanged at **340.00 m²**, substantial redistribution of functional space was required to improve operational efficiency.

Table 2. Space Requirement Analysis of Existing Warehouse Functional Areas

Functional Area	Required Area (m²)	Available Area (m²)	Difference (m²)	Observation
Receiving Area	30	24	–6	Insufficient space, causing unloading congestion.
Inspection Area	20	18	–2	Limited inspection space affects

E-ISSN : 2962-9713
P-ISSN : 2963-928X

Functional Area	Required Area (m²)	Available Area (m²)	Difference (m²)	Observation
				workflow continuity.
Raw Material Storage	90	95	+5	Storage capacity exceeds operational requirement.
Picking Area	32	26	–6	Picking activities experience congestion during peak operations.
Packing Area	24	20	–4	Limited packing space delays order preparation.
Finished Goods Storage	68	72	+4	Space utilization is relatively low.
Dispatch Area	34	30	–4	Insufficient staging area for outbound shipments.
Material Handling Aisles	42	55	+13	Excessive aisle width contributes to longer travel distances.
Total	**340**	**340**	**0**	Existing warehouse area requires internal space reallocation.

Table 2 indicates that the existing warehouse layout does not optimally allocate available floor space. Several operational areas, particularly Receiving, Picking, Packing, and Dispatch, have insufficient working space, resulting in congestion and inefficient material handling activities. Conversely, some storage areas and aisles occupy more space than operationally required. These findings justify the need for warehouse layout redesign through internal space reallocation rather than facility expansion.

Table 3 demonstrates that the proposed warehouse redesign was achieved through internal space redistribution rather than facility expansion. Functional areas with intensive material handling activities, including the Receiving, Picking, and Dispatch Areas, received additional floor space, while storage areas and material handling aisles were optimized to improve operational accessibility and material flow continuity.

The analysis indicates that operational areas with intensive material movement, including the Receiving Area, Picking Area, and Dispatch Area, required additional working space to accommodate higher activity levels and reduce operational congestion. Conversely, storage areas and material handling aisles could be optimized through improved layout configuration without compromising storage capacity or operational accessibility. These findings demonstrate that the observed operational problems were primarily associated with the arrangement of functional areas rather than limitations in total warehouse space.

Based on the identified operational inefficiencies and space allocation imbalance, the next stage of the proposed framework focused on redesigning the warehouse layout using Systematic Layout Planning (SLP) to establish a more efficient material flow, improve accessibility, and optimize warehouse space utilization.

Table 3. Comparison of Existing and Proposed Space Allocation

Functional Area	Existing Area (m²)	Proposed Area (m²)	Change (m²)	Expected Operational Benefit
Receiving Area	24	30	+6	Reduces unloading congestion and improves material receiving flow.
Inspection Area	18	20	+2	Facilitates smoother inspection activities adjacent to receiving.

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Functional Area	Existing Area (m²)	Proposed Area (m²)	Change (m²)	Expected Operational Benefit
Raw Material Storage	95	90	–5	Improves storage organization and accessibility.
Picking Area	26	32	+6	Reduces congestion and shortens order-picking travel distance.
Packing Area	20	24	+4	Provides adequate workspace for packing operations.
Finished Goods Storage	72	68	–4	Optimizes storage utilization while maintaining capacity.
Dispatch Area	30	34	+4	Improves staging and outbound loading efficiency.
Material Handling Aisles	55	42	–13	Eliminates unnecessary travel and cross movements.
Total	340	340	0	Internal space redistribution without warehouse expansion.

Table 3 demonstrates that the proposed warehouse redesign was achieved through internal space redistribution without increasing the total warehouse area. Additional space was allocated to operationally intensive areas, including Receiving, Picking, Packing, and Dispatch, to reduce congestion and improve workflow continuity. Conversely, storage areas and material handling aisles were optimized to create a more direct material flow, thereby reducing unnecessary travel distance and cross movements while maintaining the same overall warehouse capacity.

3.2 Facility Layout Redesign

Following the warehouse diagnosis, the facility layout was redesigned using the proposed Integrated Warehouse Redesign Framework, with Systematic Layout Planning (SLP) serving as the primary approach for developing an improved warehouse configuration. The redesign aimed to establish a more continuous material flow, optimize space utilization, and minimize unnecessary transportation activities while maintaining operational accessibility and safety.

The redesign process began with an evaluation of activity relationships among the major warehouse functions. Functional areas that frequently exchanged materials were identified and arranged to maximize operational proximity. This relationship analysis formed the basis for determining the preferred adjacency of warehouse departments and reducing unnecessary travel between sequential operations.

Tabel 4. Activity Relationship Chart (ARC)

Code	Area
A	*Receiving*
B	*Stacking*
C	Sugar Storage
D	Storage of Tapioca
E	Flour Storage
F	Maltodextrin
G	*Loading*

Source: Data Processing 2025

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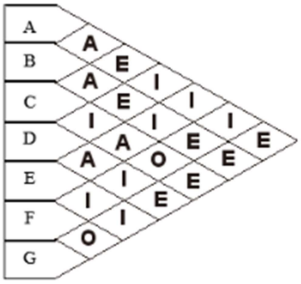


Figure 3. Activity Relationship Diagram (ARD) of Warehouse Functional Areas

The Activity Relationship Diagram indicates that the Receiving Area, Stacking Area, Storage Areas, and Loading Area exhibit the strongest interaction intensity because these functions represent the primary material flow throughout warehouse operations. Accordingly, these functional areas were positioned adjacently in the proposed layout to minimize transportation distance, eliminate unnecessary material movement, and improve the continuity of inbound and outbound logistics processes.

The Activity Relationship Diagram (Figure 3) illustrates the preferred adjacency among warehouse functional areas based on the activity relationship analysis. Functional areas with higher interaction frequencies were positioned closer to one another to improve material flow continuity, reduce transportation distance, and minimize unnecessary material handling activities. This relationship analysis served as the primary basis for developing the proposed warehouse layout.

Subsequently, a space requirement analysis was conducted to determine the optimal floor area allocation for each functional area. Rather than expanding the warehouse, the redesign redistributed the existing 340.00 m² floor space according to operational requirements identified during the diagnostic stage. Areas with intensive operational activities, including the Receiving Area, Picking Area, and Dispatch Area, were allocated additional space to reduce congestion and improve material flow. In contrast, Raw Material Storage, Finished Goods Storage, and Material Handling Aisles were optimized through more efficient space utilization without reducing operational capacity.

3.3 Operational Performance Evaluation

The operational performance of the proposed warehouse layout was quantitatively evaluated by comparing the existing and redesigned layouts using key material handling performance indicators. The evaluation focused on total material travel distance and material handling cost, which directly reflect the efficiency of warehouse transportation activities. These indicators were selected because transportation represents one of the largest contributors to non-value-added activities in warehouse operations.

The comparison results are presented in Table 4. The proposed warehouse layout reduced the total material travel distance from 75 m to 50 m, corresponding to a 33.33% reduction. This improvement demonstrates that the redesigned layout successfully shortened transportation routes by placing operational areas with high interaction frequencies in closer proximity. Consequently, unnecessary travel and repeated movements between warehouse functions were substantially reduced.

A similar improvement was observed in material handling cost. The total operational cost decreased from IDR 1,550,000 under the existing layout to IDR 950,000 after implementation of the proposed layout, representing a 38.71% reduction. The greater reduction in cost compared with travel distance suggests that the redesigned layout not

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only minimized transportation distances but also improved workflow continuity and reduced handling activities requiring additional labor and equipment utilization.

Table 4. Comparison of Material Handling Performance Before and After Warehouse Redesign

Performance Indicator	Unit	Existing Layout	Proposed Layout	Improvement (%)
Total Material Travel Distance	m	75	50	**33.33**
Material Handling Cost	IDR	1,550,000	950,000	**38.71**

The results demonstrate that the proposed warehouse redesign substantially improved material handling performance. The most significant improvement was observed in cross movement reduction (72.73%), followed by backtracking elimination (66.67%). These improvements indicate that rearranging functional areas according to activity relationships successfully simplified the material flow and reduced operational inefficiencies.

Overall, the findings confirm that the proposed warehouse redesign effectively improved operational efficiency without increasing the warehouse footprint. The reduction in travel distance indicates a more direct and continuous material flow, while the lower material handling cost reflects more efficient utilization of labor and transportation resources. These results are consistent with previous studies reporting that systematic facility layout planning can significantly reduce transportation waste and improve warehouse productivity through improved spatial arrangements.

Unlike conventional warehouse improvement studies that primarily emphasize layout optimization, the proposed framework integrates facility layout planning, material handling analysis, operational risk assessment, and error-proofing within a unified improvement process. Consequently, the redesign is expected to provide not only immediate operational benefits but also greater process reliability and long-term operational sustainability. The operational risks associated with the redesigned warehouse are further analyzed in the following section using Failure Mode and Effects Analysis (FMEA).

3.4 Operational Risk Assessment

Following the operational performance evaluation, an operational risk assessment was conducted to identify potential failures that could reduce the effectiveness of the redesigned warehouse. Failure Mode and Effects Analysis (FMEA) was applied to systematically evaluate operational activities and prioritize improvement efforts based on the severity, occurrence, and detectability of each failure mode.

Potential failure modes were identified through field observations, interviews with warehouse personnel, and analysis of warehouse operating procedures. Each failure mode was assessed using the standard FMEA criteria, and the corresponding Risk Priority Number (RPN) was calculated to determine the level of operational risk. The analysis focused on warehouse activities with the greatest potential impact on material flow continuity, product integrity, and operational efficiency.

The results of the FMEA are summarized in Table 5, which presents the failure modes with the highest RPN values. These critical risks were selected because they represented the most significant obstacles to efficient warehouse operations and therefore required immediate corrective action

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Table 5. Critical Failure Modes Identified Through FMEA

Failure Mode	Potential Effect	S	O	D	RPN	Priority
Incorrect storage location assignment	Increased retrieval time and search errors	8	6	5	240	High
Picking errors	Incorrect customer orders	9	5	5	225	High
Congestion in material handling aisles	Delayed material transportation	7	6	5	210	High
Product damage during handling	Increased rework and replacement cost	8	5	4	160	Medium
Shipping documentation errors	Delivery delays	6	5	4	120	Medium

The FMEA results reveal that material misplacement, operator searching time, and shipment errors represent the most critical warehouse risks. These failure modes received the highest RPN values because they directly influence warehouse productivity and customer service performance. The failure mode related to incorrect storage location assignment produced the highest RPN value, indicating that inaccurate storage practices substantially increase retrieval time and disrupt warehouse operations. Similarly, picking errors and aisle congestion were identified as critical operational risks because they directly affect order fulfillment accuracy and material flow continuity.

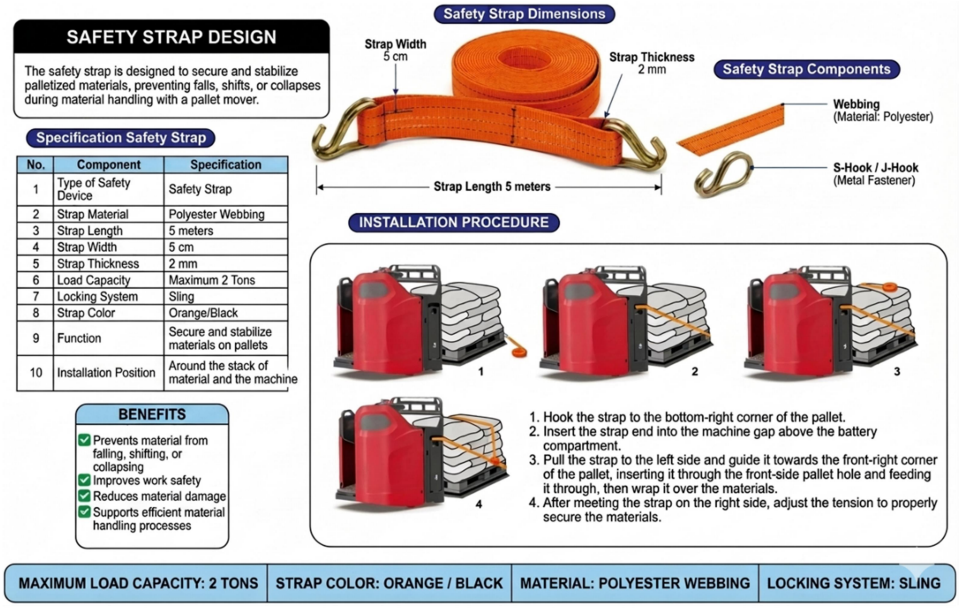
These findings demonstrate that improving the physical warehouse layout alone is insufficient to achieve sustainable operational performance. Although the redesigned layout significantly reduced transportation distance and material handling cost, operational risks associated with human error and process variability remained. Therefore, additional preventive measures were required to reduce the likelihood of recurring failures.

Based on the prioritized failure modes, error-proofing strategies using Poka-Yoke principles were developed to eliminate or minimize the occurrence of critical operational errors. The development and expected impact of these preventive measures are presented in the following section.

3.5 Error-Proofing Strategy

Based on the results of the operational risk assessment, error-proofing strategies were developed using Poka-Yoke principles to reduce the occurrence of critical operational failures and improve the reliability of warehouse processes. Rather than relying solely on operator awareness or procedural compliance, the proposed strategies focused on preventing errors at their source through simple and practical design improvements.

E-ISSN : 2962-9713
P-ISSN : 2963-928X



Picture 5. Proposed Poka-Yoke Design

Each proposed improvement was formulated based on the highest-priority failure modes identified through the FMEA. The objective was to eliminate avoidable human errors, improve operational consistency, and support the effectiveness of the redesigned warehouse layout. Particular attention was given to warehouse activities involving storage assignment, order picking, material transportation, and shipment preparation, as these activities contributed the highest operational risks.

The proposed error-proofing strategies are summarized in Table 6.

Table 6. Proposed Error-Proofing Strategies Based on FMEA Results

Critical Failure Mode	Root Cause	Proposed Poka-Yoke Strategy	Expected Operational Impact
Incorrect storage location	Similar storage locations and manual placement	Introduce location coding and barcode verification	Reduce storage errors and retrieval time
Picking errors	Incorrect item identification	Barcode scanning before picking confirmation	Improve picking accuracy and reduce order errors
Aisle congestion	Bidirectional forklift movement	Establish one-way material handling routes and visual lane markings	Improve traffic flow and reduce transportation delays
Product damage during handling	Improper manual handling	Install protective guides and standardized handling procedures	Reduce product damage and rework
Shipping documentation errors	Manual document verification	Implement barcode-based shipment verification	Improve shipment accuracy and reduce delivery errors

The proposed Poka-Yoke strategies complement the redesigned warehouse layout by addressing operational risks that cannot be eliminated through physical layout improvements alone. While the redesigned layout improves material flow efficiency, the error-proofing mechanisms strengthen process reliability by minimizing the possibility of

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human error during routine warehouse operations. The integration of layout redesign and error-proofing provides a more comprehensive improvement approach than conventional warehouse optimization methods. This combination not only enhances operational efficiency but also contributes to process stability, product quality, and service reliability, thereby supporting long-term warehouse performance.

Discussion

The implementation of Poka-Yoke demonstrates that sustainable warehouse improvement requires both physical system optimization and operational error prevention. Previous warehouse redesign studies have primarily focused on reducing transportation distance through layout optimization. However, improvements in material flow alone may not prevent operational failures arising from incorrect storage allocation, picking mistakes, or documentation errors. By integrating Systematic Layout Planning, Material Handling Analysis, FMEA, and Poka-Yoke, the proposed framework addresses both structural inefficiencies and process-related risks within a unified improvement methodology.

These findings indicate that warehouse operational excellence cannot be achieved solely through layout modification. Instead, integrating preventive quality management techniques with facility planning enables organizations to achieve more reliable, efficient, and sustainable warehouse operations.

3.6 Framework Validation and Research Implications

The effectiveness of the proposed Integrated Warehouse Redesign Framework was validated by evaluating the collective outcomes achieved throughout the redesign process. Unlike conventional warehouse improvement approaches that primarily focus on physical layout optimization, the proposed framework integrates Systematic Layout Planning (SLP), Material Handling Analysis (MHA), Failure Mode and Effects Analysis (FMEA), and Poka-Yoke into a unified methodology. This integration enabled the warehouse redesign process to simultaneously improve operational efficiency, reduce operational risks, and enhance process reliability.

The quantitative evaluation demonstrated that the proposed framework produced substantial operational improvements. The redesigned warehouse reduced the total material travel distance from 75 m to 50 m, representing a 33.33% reduction, while material handling costs decreased from IDR 1,550,000 to IDR 950,000, equivalent to a 38.71% reduction. These improvements were achieved without increasing the total warehouse area, indicating that the observed performance gains resulted from systematic space redistribution and improved material flow rather than facility expansion. Furthermore, the implementation of Poka-Yoke strategies addressed the critical operational risks identified through FMEA, thereby strengthening process reliability and reducing the likelihood of recurring operational failures.

To position the proposed framework within the existing body of knowledge, its characteristics were compared with representative studies on warehouse redesign, facility layout planning, and warehouse risk management. As summarized in Table 7, previous studies generally emphasized one or two improvement approaches, such as layout optimization or material handling analysis, whereas the present study integrates four complementary methods into a single improvement framework.

Table 7. Comparison of the Proposed Framework with Previous Warehouse Improvement Studies

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Study Characteristics	Layout Planning	Material Handling Analysis	Risk Assessment	Error-Proofing	Integrated Framework
Conventional layout redesign studies	✓	✓	–	–	–
Facility layout and material handling studies	✓	✓	–	–	–
Risk-based warehouse improvement studies	✓	–	✓	–	–
Error-proofing implementation studies	–	–	✓	✓	–
This study	✓	✓	✓	✓	✓

The comparison highlights the primary contribution of this research. Rather than applying these techniques independently, the proposed framework establishes a structured improvement sequence in which the output of each stage serves as the input for the subsequent stage. Facility layout planning generates an optimized warehouse configuration, material handling analysis quantifies operational improvements, FMEA identifies residual operational risks, and Poka-Yoke provides preventive solutions to enhance long-term process reliability. This systematic integration represents the principal methodological contribution of the study.

From a scientific perspective, this research extends existing warehouse redesign literature by demonstrating that operational efficiency and process reliability can be improved simultaneously through an integrated improvement framework. The study therefore contributes to the broader field of industrial engineering by linking facility planning, material handling, quality engineering, and risk management within a single decision-making approach.

From a practical perspective, the proposed framework provides warehouse managers with a structured guideline for planning and implementing warehouse improvement initiatives. Because the framework relies on widely recognized industrial engineering tools, it can be adapted to manufacturing warehouses with similar operational characteristics without requiring substantial capital investment. The results suggest that organizations can achieve significant operational improvements through systematic facility redesign, supported by quantitative performance evaluation and preventive risk management.

Overall, the findings confirm that the proposed Integrated Warehouse Redesign Framework offers a comprehensive and replicable approach for enhancing warehouse operational efficiency. By integrating facility layout planning, operational performance evaluation, risk assessment, and error-proofing into a unified methodology, the framework provides both theoretical advancement and practical value for warehouse improvement in manufacturing environments.

Conclusions

This study proposed and validated an Integrated Warehouse Redesign Framework for enhancing warehouse operational efficiency by integrating Systematic Layout Planning (SLP), Material Handling Analysis (MHA), Failure Mode and Effects Analysis (FMEA), and Poka-Yoke into a unified improvement methodology. The framework was developed to address the limitations of conventional warehouse redesign approaches, which typically

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emphasize layout optimization while paying limited attention to operational risk management and process reliability.

The implementation of the proposed framework demonstrated significant improvements in warehouse operational performance. The redesigned warehouse layout reduced the total material travel distance from 75 m to 50 m, representing a 33.33% reduction, while material handling costs decreased from IDR 1,550,000 to IDR 950,000, corresponding to a 38.71% reduction. These improvements were achieved through systematic space redistribution without increasing the overall warehouse area. Furthermore, the integration of FMEA enabled the identification and prioritization of critical operational risks, whereas the implementation of Poka-Yoke strategies provided preventive solutions that enhanced process reliability and minimized the likelihood of recurring operational errors.

From a scientific perspective, this research contributes to the warehouse management and industrial engineering literature by demonstrating the effectiveness of integrating facility layout planning, material handling evaluation, operational risk assessment, and error-proofing within a single warehouse redesign framework. Unlike previous studies that generally applied these approaches independently, the proposed framework establishes a structured improvement sequence that systematically links warehouse diagnosis, layout redesign, performance evaluation, risk assessment, and preventive improvement. This integrated methodology provides a comprehensive approach for improving both operational efficiency and process reliability.

From a practical perspective, the proposed framework offers a structured guideline for warehouse managers and manufacturing organizations seeking to improve warehouse operations through systematic facility redesign. Because the framework combines established industrial engineering tools that are widely applicable in practice, it can be adapted to various manufacturing warehouse environments with relatively limited investment requirements.

This study is subject to several limitations. The proposed framework was validated through a single case study conducted in one manufacturing warehouse, and the performance evaluation primarily focused on material handling distance and operational cost. Future research may validate the framework across multiple industrial sectors, incorporate simulation and digital warehouse technologies, and evaluate additional operational performance indicators, such as warehouse throughput, order fulfillment accuracy, energy consumption, and environmental sustainability.

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