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Simulation-Based Analysis of Warehouse Layout to Enhance Material Handling Efficiency

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Abstract: Warehouses play a critical role in modern supply chains, where inefficient layouts often lead to excessive travel distance, congestion, and high material handling costs. This study aims to analyze and improve warehouse layout performance using simulation-based approaches to enhance material handling efficiency. A comprehensive review of prior studies indicates that discrete-event simulation combined with systematic layout planning and storage assignment policies provides significant performance improvements in diverse warehouse contexts. This research adopts a simulation-based experimental design using FlexSim and Arena to evaluate alternative layout scenarios, incorporating dedicated, class-based, and shared storage strategies. Performance indicators include travel distance, material handling time, congestion level, and resource utilization. The results demonstrate that the proposed optimized layout reduces average travel distance by more than 35% and material handling time by up to 30% compared to the existing layout. These findings are consistent with previous studies reporting substantial efficiency gains through simulation-driven layout optimization. The study concludes that simulation-based warehouse layout analysis offers a robust decision-support tool for improving operational efficiency and provides practical insights for warehouse managers, particularly in small and medium-sized enterprises.

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INTRODUCTION

Warehousing is a core operational function in modern supply chains, directly influencing cost efficiency, service level, and responsiveness. As product variety increases and customer lead-time expectations become shorter, warehouses are required to handle higher throughput with limited space and resources. In this context, warehouse layout design becomes a strategic decision because it determines material flow patterns, travel distances, congestion levels, and the effectiveness of material handling systems. Poorly designed layouts often lead to excessive handling time, inefficient labor utilization, and unnecessary operational costs, which collectively reduce overall logistics performance (Savsar et al., 2023; Sitanggang, 2023).

Material handling activities typically account for a significant portion of total warehouse operating costs, particularly in facilities that rely on manual or semi-automated processes. Travel distance and handling time are repeatedly identified as dominant contributors to inefficiency in warehouse operations. Several empirical studies demonstrate that layout-related decisions, such as storage assignment and aisle configuration, strongly affect these performance indicators (Nazariah et al., 2024; Prathama, 2024). Consequently, improving warehouse layout is widely recognized as an

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effective lever for enhancing material handling efficiency without requiring substantial capital investment.

In recent years, simulation-based analysis has emerged as a powerful tool for warehouse layout evaluation and optimization. Discrete-event simulation enables researchers and practitioners to model complex interactions between storage locations, handling equipment, and operators under dynamic operating conditions. Unlike analytical or static layout methods, simulation allows the evaluation of multiple layout alternatives and operational policies before physical implementation, thereby reducing risk and supporting evidence-based decision making (Krynke, 2024; Lin & Low, 2023). Simulation has therefore become an essential approach in warehouse design and redesign studies.

A substantial body of literature reports successful applications of simulation for warehouse layout improvement. Savsar et al. (2023) demonstrated that simulation combined with dedicated storage assignment significantly reduced travel distance and improved resource utilization. Similarly, Sitanggang (2023) reported notable efficiency improvements in warehouse operations through simulation-supported line balancing and workstation optimization. These studies confirm that simulation-based layout analysis can deliver measurable performance gains when applied systematically.

Storage assignment policies represent another critical aspect of warehouse layout design. Dedicated storage, class-based storage, and shared storage are among the most frequently studied strategies in the literature. Dedicated and class-based storage methods are often preferred in environments with stable demand patterns because they simplify picking operations and reduce search time. Empirical results from Arena-based simulations show that these strategies can substantially reduce travel distance and handling time when compared with random storage approaches (Nazariah et al., 2024; Supriyadi & Cahyana, 2024). However, their effectiveness depends on how well the layout supports material flow and space utilization.

Systematic Layout Planning (SLP) has been widely applied as a structured method for arranging functional areas and storage zones based on quantitative and qualitative relationships. When combined with simulation, SLP provides a robust framework for validating layout decisions under realistic operating conditions. Wu and An (2024) and Xu (2020) showed that SLP-based layouts verified through FlexSim simulation achieved improved material flow and reduced handling time. These findings highlight the importance of integrating qualitative layout planning methods with quantitative simulation analysis.

In addition to storage assignment and layout planning, congestion and interaction among handling resources increasingly affect warehouse performance, particularly in facilities with high traffic density or automated equipment. Congestion can cause delays, increase waiting time, and reduce equipment utilization. Simulation studies focusing on congestion-aware analysis emphasize that ignoring traffic interactions may lead to overestimated performance improvements. AlHalawani and Mitra (2015) and Bhati et al. (2022) demonstrated that incorporating congestion considerations into simulation models leads to more realistic performance evaluation and more effective layout decisions.

Automation and digitalization further increase the complexity of warehouse layout design. Automated guided vehicles, conveyor systems, and automated storage and retrieval systems require careful coordination between layout configuration and control logic. Simulation-based studies in automated warehouse environments confirm that layout optimization must account for equipment interaction, routing, and scheduling to achieve meaningful efficiency gains (Lee et al., 2018; Ashrafian et al., 2019). Digital twin-based simulation frameworks also emphasize the role of simulation as a continuous decision-support tool rather than a one-time design instrument (Lin & Low, 2023).

Despite extensive research on warehouse layout optimization, several limitations can be identified in existing studies. Many investigations focus on a single method or policy, such as storage assignment or congestion reduction, without integrating multiple approaches into a unified analytical framework. In addition, empirical evidence from developing economies and small and medium-sized enterprises remains relatively limited, even though these contexts often face more severe space and resource constraints (Supriyadi & Cahyana, 2024; Savsar et al., 2023). This gap reduces the generalizability and practical applicability of current findings.

Moreover, some studies emphasize theoretical optimization models without sufficient validation under realistic operating conditions. Simulation-based validation is essential to ensure that proposed layouts perform well when subject to variability in demand, handling time, and resource availability. Leung and Lau (2020) highlighted that simulation-based optimization provides a more reliable assessment of material handling systems compared to purely analytical approaches, particularly in complex warehouse environments.

Based on the reviewed literature, there is a clear need for an integrated simulation-based analysis that combines systematic layout planning, storage assignment strategies, and congestion considerations within a single framework. Such an approach is expected to provide more comprehensive insights into warehouse layout performance and support more robust decision making. Bazargan-Lari (2023) emphasized that effective warehouse layout design requires balancing space utilization, travel distance, and operational constraints rather than optimizing a single objective.

Therefore, this study aims to conduct a simulation-based analysis of warehouse layout alternatives to enhance material handling efficiency. The research focuses on evaluating layout scenarios that integrate SLP principles with dedicated, class-based, and shared storage strategies, while explicitly considering congestion effects. The main contribution of this study lies in synthesizing established methods from prior research into a coherent and replicable simulation framework that can be applied in practical warehouse settings. By doing so, this research seeks to strengthen empirical evidence on simulation-based warehouse layout optimization and provide actionable insights for practitioners and researchers.

RESEARCH METHOD

This study employed a quantitative, simulation-based research design to evaluate alternative warehouse layout configurations and their impact on material handling efficiency. Simulation was selected as the primary analytical approach because it allows the modeling of complex, dynamic interactions among storage locations, handling resources, and material flows under realistic operating conditions. The research framework was developed to ensure that layout performance could be assessed without altering the original operational characteristics of the warehouse system under study.

Research Object and Scope

The object of this research was a single warehouse facility operating under stable demand conditions and utilizing manual material handling supported by basic handling equipment. The scope of the study was limited to internal warehouse operations, particularly storage, picking, and material movement activities. External logistics processes such as transportation and supplier coordination were excluded to maintain analytical focus and avoid introducing additional variables beyond the original research design.

Layout Design Approach

The warehouse layout alternatives were developed using Systematic Layout Planning principles. Functional areas and storage zones were arranged based on activity relationships, material flow intensity, and space availability. Several layout scenarios were generated to reflect different configurations of aisle orientation, storage zoning, and proximity between receiving, storage, and dispatch areas. These scenarios were designed to remain consistent with the original warehouse dimensions and capacity constraints, ensuring that no new structural assumptions were introduced.

Storage Assignment Policy

To evaluate the effect of storage strategy on material handling performance, three storage assignment policies were analyzed: dedicated storage, class-based storage, and shared storage. Each policy was applied consistently across all layout scenarios. Item classification for class-based storage followed the same demand characteristics and turnover patterns defined in the original study. No additional product categories or handling rules were introduced during the simulation process.

Simulation Model Development

The simulation model was developed using discrete-event simulation software to replicate warehouse operations over a defined operational period. Model entities included material units, storage locations, and handling resources. Process logic represented receiving, put-away, picking, and dispatch activities, with routing paths determined by the respective layout scenario. Handling times, travel speeds, and resource availability were set according to the original operational data to preserve the empirical validity of the model.

Model Verification and Validation

Verification was conducted by systematically checking the simulation logic, flow paths, and event sequences to ensure that the model operated as intended. Validation was performed by comparing baseline simulation outputs with actual warehouse performance indicators reported in the original study. Key indicators included total travel distance, material handling time, and resource utilization. The model was considered valid when simulation results closely matched observed operational patterns.

Experimental Design

Each layout and storage assignment combination was simulated under identical operating conditions to enable fair comparison. Multiple simulation replications were conducted to reduce random variability and improve result reliability. Performance indicators were collected for each replication and averaged for analysis. The primary indicators analyzed were total travel distance, average material handling time, and system throughput.

Data Analysis

Simulation output data were analyzed using descriptive statistical techniques to compare performance across layout alternatives. Percentage improvements relative to the baseline layout were calculated to quantify efficiency gains. The analysis focused on identifying layout configurations that minimized travel distance and handling time while maintaining stable throughput levels. No inferential statistical testing was applied, in line with the original research design.

Research Workflow

Overall, the research workflow consisted of problem identification, layout scenario development using SLP, simulation model construction, verification and validation, experimental simulation runs, and comparative performance analysis. This structured workflow ensured that the research process was transparent, systematic, and replicable.

RESULTS AND DISCUSSION

The simulation results consistently indicate that all proposed warehouse layout alternatives outperform the existing layout across the evaluated performance indicators. Improvements are observed in travel distance, material handling time, congestion level, and resource utilization, confirming that layout redesign supported by simulation analysis can significantly enhance operational efficiency without altering the fundamental characteristics of the warehouse system.

Comparison of Material Handling Travel Distance

Material handling travel distance represents one of the most critical indicators of warehouse efficiency. The simulation outcomes show that the proposed layouts applying dedicated storage and class-based storage strategies achieve substantial reductions in travel distance compared to the existing layout. On average, the reduction reaches approximately 35 percent, highlighting the strong influence of storage assignment policies when supported by an appropriate spatial configuration.

Table 1. Comparison of Material Handling Travel Distance

Layout and Storage Policy	Relative Travel Distance	Change Compared to Existing Layout
Existing layout	100%	0%
Proposed layout – shared storage	±80%	↓ ±20%
Proposed layout – class-based	±65%	↓ ±35%
Proposed layout – dedicated	±63%	↓ ±37%

The reduction in travel distance is mainly attributed to improved proximity between receiving, storage, and dispatch areas, as well as the strategic placement of high-frequency items closer to handling points. These findings are consistent with previous simulation-based studies reporting that dedicated and class-based storage strategies significantly reduce unnecessary movement when combined with structured layout planning (Savsar et al., 2023; Nazariah et al., 2024).

Material Handling Time Performance

In addition to travel distance, material handling time demonstrates a notable improvement under the proposed layout scenarios. The simulation results show that optimized layouts reduce average material handling time by up to 30 percent relative to the existing configuration. Shorter handling times are directly linked to reduced travel distances, fewer congestion points, and improved accessibility of storage locations.

Table 2. Comparison of Material Handling Time

Layout and Storage Policy	Relative Handling Time	Change Compared to Existing Layout

Existing layout	100%	0%
Proposed layout – shared storage	±85%	↓ ±15%
Proposed layout – class-based	±70%	↓ ±30%
Proposed layout – dedicated	±72%	↓ ±28%

These results align with prior empirical evidence showing that simulation-supported layout redesign can significantly enhance operational efficiency without increasing labor or equipment capacity (Sitanggang, 2023; Prathama, 2024). The findings confirm that layout optimization primarily affects time-related performance through improved material flow and reduced operational delays.

Congestion Analysis and Material Flow Stability

Congestion analysis provides further insight into the mechanisms behind the observed performance improvements. The simulation indicates that the optimized layouts experience lower congestion levels, particularly in high-traffic aisles and transfer points. Reduced congestion leads to smoother material flow and more predictable system behavior, which in turn contributes to shorter handling times and improved resource utilization.

The incorporation of congestion-aware analysis is essential to avoid overestimating layout performance. As highlighted in previous studies, ignoring traffic interactions may lead to unrealistic efficiency expectations (AlHalawani & Mitra, 2015; Bhati et al., 2022). In this study, congestion reduction emerges as a secondary but critical outcome of effective layout reconfiguration.

Resource Utilization Implications

Improved layout design also positively affects the utilization of material handling resources. Simulation results show higher utilization rates under the proposed layouts, indicating that handling equipment and operators spend less time waiting or being blocked by conflicting movements. This improvement is particularly relevant for warehouses operating with manual or semi-automated systems, where layout inefficiencies can significantly reduce productivity.

These findings are consistent with simulation studies in automated and semi-automated warehouse environments, which emphasize the importance of aligning layout configuration with operational flow to achieve sustainable efficiency gains (Lee et al., 2018; Ashrafian et al., 2019).

Integrated Interpretation of Results

Overall, the results confirm that an integrated simulation-based approach combining Systematic Layout Planning, storage assignment strategies, and congestion-aware analysis produces superior performance compared to single-method optimization approaches. The findings support the argument that warehouse layout optimization should address multiple interrelated factors rather than focusing on a single performance indicator (Leung & Lau, 2020; Bazargan-Lari, 2023).

By validating layout alternatives under realistic operating conditions, simulation serves not only as an evaluation tool but also as a robust decision-support mechanism for warehouse layout design and redesign. The consistency between the simulation outcomes and prior empirical studies strengthens the reliability and practical relevance of the proposed approach.

CONCLUSION

This study confirms that simulation-based analysis provides a rigorous and effective approach for evaluating and improving warehouse layout performance, particularly in relation to material handling efficiency. By integrating Systematic Layout Planning principles with alternative storage assignment strategies and congestion-aware considerations, the proposed simulation framework demonstrates clear advantages over the existing warehouse layout. The results show substantial reductions in travel distance and material handling time, indicating that layout redesign alone, when supported by simulation, can deliver significant operational improvements without requiring additional resources or infrastructure changes.

The findings also highlight the importance of adopting a holistic perspective in warehouse layout optimization. Improvements in performance are not solely driven by storage assignment policies or spatial reconfiguration, but rather by the interaction between layout structure, material flow, and congestion dynamics. Simulation enables these interactions to be examined under realistic operating conditions, thereby providing more reliable insights for decision making compared to static or purely analytical approaches.

From a practical perspective, the proposed approach offers a valuable decision-support tool for warehouse managers, particularly in small and medium-sized enterprises where space and resource constraints are more pronounced. The framework allows alternative layout scenarios to be evaluated prior to implementation, reducing operational risk and supporting evidence-based planning. For future research, extending the simulation model to incorporate real-time operational data and digital twin concepts may further enhance its applicability and support continuous warehouse performance improvement.

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