Multi-Method Approaches for Simulation Modelling of Warehouse Processes

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Abstract: Efficient warehouse management is essential for business-to-business (B2B) operations, ensuring timely delivery, cost minimization, and operational efficiency. To meet these challenges, advanced modelling and simulation techniques are increasingly adopted. This paper shows the application of multi-method simulation approaches, specifically agent-based and discrete event simulation, applied to optimize warehouse processes and resource allocation for a leading sport brand retailer in the B2B sector. By combining these approaches, we aimed to capture the complexity of warehouse operations and identify opportunities for improvement. The simulation model developed using AnyLogic software, integrated agent-based modelling to represent entities such as packages, articles, orders, warehousemen, and trucks, along with discrete event simulation to model key events like order arrival and truck departure. The developed model has been used to optimize the resource allocation ensuring order fulfilment. Scenario analyses revealed varying resource requirements across different demand scenarios, highlighting the challenges posed by increasing demanded volumes. The study underscores the importance of strategic resource planning and proactive measures to address capacity limitations and ensure warehouse efficiency in meeting future demand. Our findings contribute to informed decision-making in warehouse management, guiding strategies for optimization and adaptation to evolving market demands.

1 INTRODUCTION

1.1 Context

In modern commerce, two primary transactional models prevail: Business-to-Consumer (B2C) and Business-to-Business (B2B), representing distinct paradigms for goods and services exchange. B2C transactions involve direct interactions with individual consumers, focusing on personalized experiences and brand loyalty. On the other hand, B2B transactions occur within corporate ecosystems, involving complex networks and multiple stakeholders to meet supply chain needs. Efficient warehouse management is crucial for B2B operations, ensuring timely delivery, cost reduction, and operational efficiency. To address these challenges, businesses increasingly employ advanced modelling and simulation techniques to optimize warehouse processes.

This paper discusses the use of multi-method simulation approaches, including agent-based and discrete event simulation, for modelling and optimizing B2B warehouse processes for a leading sport brand retailer. Through a detailed case study, we demonstrate the efficacy of simulation models in analysing and optimizing key processes, such as order fulfilment and inventory management, to improve overall efficiency in serving B2B clientele.

The main objective of this study was to create a simulation model to understand the warehouse's capacity to manage predicted volumes and identify opportunities for productivity enhancement and so to provide strategic decision-making support for

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resource allocation, workflow optimization, and infrastructure investments in the warehouse environment. The study conducted scenario analyses to identify potential capacity constraints and opportunities for process improvement, providing actionable recommendations for mitigating risks and enhancing resilience.

Ultimately, this study aimed to empower stakeholders with the tools and information needed to make informed decisions aligning with the organization's strategic goals, while laying the foundation for future-proofing the operation and positioning for long-term success and growth.

2 LITERATURE REVIEW

Warehouse optimization is a topic of significant interest in both academia and industry, with numerous studies exploring various approaches to enhance the efficiency and effectiveness of warehouse operations. In this section, we review the existing literature on simulation modelling in warehouse optimization, with a particular focus on multi-method approaches and their application in the context of B2B operations. Simulation modelling has emerged as a powerful tool for analysing, predicting, and optimizing warehouse operations. By replicating the behaviour of a real-world system within a model, simulation enables researchers and practitioners to experiment with different scenarios, test alternative strategies, and evaluate the performance of various configurations without disrupting actual operations. In the context of warehouse optimization, simulation models can highlight the intricate interactions between different processes, resources, and constraints.

Discrete Event Simulation (DES), System Dynamics, and Agent-Based Modelling (ABM) are three simulation methods commonly used in warehouse-oriented environments. DES (Rana, D. S., 2018, Gagliardi, J.-P., Renaud, J., & Ruiz, A. 2007, Saderova, J., Rosova, A., Behunova, A., Behun, M., Sofranko, M., & Khouri, S. 2022) allows for the modelling of discrete events, such as order entry, order processing, transport, and delivery, providing detailed insight into warehouse dynamics. System Dynamics (Ramirez-Malule, D., Jaén-Posada, J. S., & Villegas, J. G. 2021) analyses the interdependencies and feedback loops within a warehouse system, helping to understand its behaviour over time. Agent-based (Maka, A., Cupek, R., & Wierzchanowski, M. 2011) modelling is a methodology that focuses on modelling the behaviour of individual agents within a warehouse. This enables the analysis of emergent properties and the optimisation of warehouse operations. These methodologies are essential tools for improving efficiency, optimising resource utilisation, and addressing warehouse management challenges.

DES has several advantages in warehouse-oriented environments. Firstly, it helps to analyse system behaviour, identify bottlenecks, evaluate trade-offs, and optimize processes in logistics and supply chain management. Moreover, DES enables decision-makers to test multiple tactics in a virtual system without disrupting operations, thereby optimizing inventory management, transportation routing, and warehouse operations. However, while DES models can be useful, they often rely on simplified assumptions that may not fully capture the dynamics of real-world systems.

In contrast, System Dynamics offers valuable insights into complex warehouse systems by capturing the interactions between various actors and processes. Decision-makers can use System Dynamics to assess the impact of different variables on system performance and optimize procedures for increased efficiency. However, accurately modelling all variables in System Dynamics models can be challenging due to their complex interrelationships, which poses a limitation.

ABM provides a more realistic representation of how agents interact within the warehouse environment and adapt dynamically to changing conditions. This approach assists decision-makers in comprehending emergent behaviours, optimising resource allocation, and enhancing overall efficiency in warehouse operations. However, creating precise agent-based models can be a challenging and time-consuming task due to the requirement for detailed data and behavioural rules for individual agents.

2.1 Multi-Method Approaches in Simulation Modelling

Multi-method simulation approaches have gained popularity for their ability to provide a comprehensive understanding of complex systems. While traditional simulation methods like DES focus on system-level behaviours and resource utilization (Law and Kelton, 2018; Rossetti et al., 2019), they may overlook nuanced interactions among individual entities within warehouses. To overcome this limitation, researchers integrate multiple simulation methods, such as ABM and DES, to better understand warehouse dynamics (Macal and North, 2010). ABM models individual entities and their interactions, allowing for detailed analysis of decision-making processes (Bonabeau, 2002), while DES excels in representing system-level processes and events, facilitating the analysis of resource utilization (National Aeronautics and Space Administration, 1995). Integrating ABM and DES enables researchers to capture the complexity of warehouse operations, providing insights into system-level behaviours and individual agent interactions (Klügl and Bazzan, 2019). Studies have demonstrated the effectiveness of multi-method simulation approaches in optimizing warehouse processes (Heath et al., 2012).

In warehouse optimization, traditional simulation approaches like DES are widely used for modelling system-level behaviours (Law and Kelton, 2018). However, in complex warehouse systems, DES alone may not provide a complete understanding of dynamics due to pivotal interactions between individual entities (Rossetti et al., 2019; Meredith et al. 2023). To address this limitation, researchers integrate multiple simulation methods, such as ABM and DES, enhancing modelling capabilities. ABM focuses on modelling individual entities and their interactions within a system, allowing for a granular analysis of the system's complexity. This integration enables researchers to capture both macroscopic system-level behaviours and microscopic agent-level interactions, providing a comprehensive understanding of complex warehouse systems. Several studies have demonstrated the effectiveness of multi-method simulation approaches in warehouse optimization, highlighting the importance of considering both macroscopic and microscopic factors for achieving operational efficiency (Macal and North, 2010, Hafezalkotob et al., 2016).

2.2 Challenges and Opportunities

Multi-method simulation approaches offer promise in addressing the complexities of warehouse optimization, yet they present challenges and opportunities that require careful consideration. Integrating ABM and DES introduces complexity, requiring meticulous attention to model assumptions, data capture, and computational resources. Scaling the model amplifies these challenges in development and implementation. Parameter estimation in multi-method simulations demands sophisticated techniques, necessitating a deep understanding of system dynamics and iterative refinement for accuracy.

Validation of multi-method simulation models is inherently complex due to the stochastic nature of warehouse operations and the interplay between macroscopic and microscopic dynamics. Extensive validation against empirical data is essential to ensure accurate representation and reliable results, often involving comparisons with operational metrics and sensitivity analyses.

Despite challenges, multi-method simulation offers significant opportunities for advancing warehouse optimization by providing a comprehensive understanding of B2B operations. This holistic perspective uncovers inefficiencies, identifies optimization opportunities, and evaluates strategic interventions. Multi-method simulation facilitates scenario analysis and decision support, enabling stakeholders to explore alternative strategies, assess outcomes, and make informed decisions.

In conclusion, while multi-method simulation presents challenges in model complexity, parameter estimation, and validation, its benefits in capturing the intricacies of B2B warehouse operations justify further research and exploration. Leveraging the strengths of agent-based and discrete event simulation, multi-method approaches offer a powerful toolset for optimizing warehouse operations and enhancing efficiency in B2B supply chains.

3 SIMULATION MODEL DEVELOPMENT

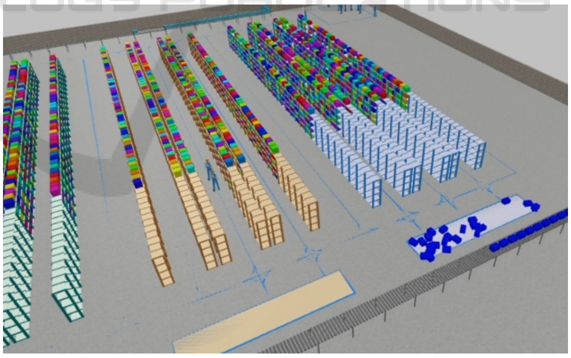

Figure 1: Warehouse environment.

The aim of developing the model was to simulate the flow of items through packaging, storage, picking, and delivery to trucks after preparation by warehouse staff. The process depends on the arrival of customer orders and the departure of trucks. When a customer order is received, the storekeeper prepares it for delivery by lorry. The preparation of orders involves organizing items into package, each containing a specific set of articles. The shop aims to maintain a stock of the majority of articles in the warehouse to ensure prompt fulfilment of most orders. All of these aspects must be managed accurately within the operation to ensure effective matching of demand and supply. The development has been done in the AnyLogic commercial software.

3.1 Overview of Anylogic

AnyLogic is a versatile simulation software that offers support for various modelling paradigms, including agent-based (Agent-Based Modelling), discrete event (Event-Based), and system dynamics. Its graphical interface and Java-based modelling language provide flexibility and ease of use, making it well-suited for complex simulation projects such as warehouse optimization. AnyLogic was chosen for its capabilities, which allowed us to craft a thorough multi-method simulation model proficient in capturing the complexities of both individual entities within the warehouse environment and overall warehouse operations. Our approach utilizes ABM to represent various elements within the warehouse environment, including packages, articles, orders, warehousemen involved in different processes, and trucks. Additionally, we incorporate discrete event simulation to model events that occur at different moments during the simulation, such as the arrival of orders and the departure of trucks.

3.2 Agent-Based Modelling

ABM forms the cornerstone of our simulation approach, allowing us to represent individual entities (agents) within the warehouse environment with high granularity. Each agent is endowed with specific properties, behaviours, and decision-making capabilities to accurately simulate their interactions within the warehouse ecosystem. The implemented agents include:

- Packages and Articles, packages represent the containers in which articles are stored and transported within the warehouse. Each package agent is characterized by properties such as size, weight, destination, and contents. Articles, on the other hand, represent the individual items stocked in the warehouse and objects of the orders.
- Orders represent the requests placed by customers for specific articles. Each order agent contains information such as customer details, order quantity, truck and the related warehouse bay. Orders may consist of multiple articles and packages, depending on the customer's requirements.
- Trucks represent the vehicles used for transporting goods to and from the warehouse. Each truck agent is characterized by properties such as capacity and destination. Trucks are responsible for transporting packages and orders between the warehouse and customer locations.
- Warehousemen represent the workers responsible for performing various tasks within the warehouse, such as inbound receiving, stocking shelves, picking items for orders, and loading/unloading trucks. Each warehouseman agent is associated with properties related to their productivity capacity, such as articles processed per hour. By modelling warehousemen with different productivity capacities, we can accurately simulate the impact of workforce variability on overall warehouse performance.

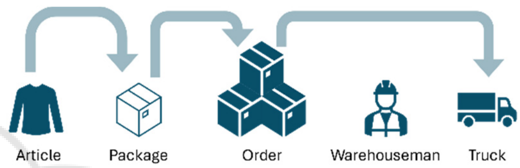

Figure 2: Agents of the model.

3.3 Event-Based Modelling

In integration and support to the ABM approach, our simulation model incorporates event-based simulation to capture key events that occur at different moment of the simulation. ABM enables the simulation of the behaviours and interactions of individual entities within the warehouse environment. Event-based simulation, in contrast, allows the modelling of the occurrence of specific events and the subsequent impact on workflow dynamics.

- Order Arrival: one of the key events we model in our simulation is the arrival of orders from customers. Orders arrive at the warehouse according to predefined arrival patterns or distribution functions. The timing, quantity, and characteristics of incoming orders influence warehouse workload, resource utilization, and order fulfilment processes. By simulating order arrival events, we can replicate the dynamic nature of customer demand and evaluate the warehouse's ability to meet service level agreements and customer expectations.
- Truck Departure: another key event we capture in our simulation is the departure of trucks transporting goods to delivery destinations. Once orders are picked and packaged, trucks are dispatched from the warehouse to deliver the goods to customer locations. By simulating truck

departure events, we can assess the efficiency of delivery operations, optimize routing decisions, and minimize transportation costs. Additionally, truck departure events may trigger subsequent events within the simulation, such as updating inventory levels and initiating replenishment processes.

Therefore, by integrating event-based simulation with agent-based modelling, we create a dynamic simulation environment that accurately reflects the real-world dynamics of warehouse operations. Events drive changes in system state, trigger agent behaviours, and influence decision-making processes, resulting in emergent behaviours and system-wide effects. This integrated approach allows us to capture the complexity and uncertainty inherent in warehouse operations and provides valuable insights into system performance under various conditions.

4 WAREHOUSE PROCESSES SIMULATION

4.1 Warehouse Processes

The warehouse chain can be divided into 4 main phases: inbound, stocking, picking, and outbound. Inbound operations include receiving, sorting, and storing incoming goods at a warehouse or distribution centre. Stocking involves arranging and organizing items within the warehouse for easy accessibility during subsequent picking. Picking involves retrieving individual items or specific orders from warehouse shelves in preparation for shipment or delivery. Outbound encompasses all operations related to shipping the stocked items from the warehouse to customers, stores, or other final destinations. These processes are essential for ensuring efficient inventory management and timely delivery of goods.

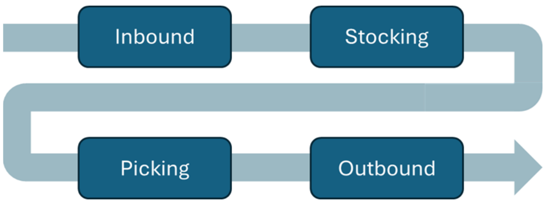

Figure 3: Warehouse intralogistics processes.

This section provides an overview of the simulation model developed to replicate the key processes within the warehouse environment. The model aims to replicate the real-world workflows and interactions observed in the warehouses of the sport brand retailer.

The inbound process begins with the arrival of trucks carrying packages containing goods destined for the warehouse. Upon arrival, packages are unloaded, and goods with standard-sized packages are directed to an intricate conveyor system for distribution to the shelves. Warehousemen stationed at this destination sector receive these packages and proceed to stock them on the shelves, recording their positions in the Warehouse Management System (WMS). This process ensures accurate inventory management and facilitates efficient retrieval during order fulfilment.

In the stocking process, warehousemen retrieve packages from the conveyor system and place them on designated shelves according to product categories. The WMS guides warehousemen to the appropriate shelf locations, ensuring optimal storage organization and minimizing retrieval times during picking operations. Warehousemen record the stocking of packages in the WMS, updating inventory levels and ensuring real-time visibility of available stock.

The picking process starts when an order is received on the WMS. The warehousemen in charge of order processing go through the shelves to pick the individual items needed to fulfil the order. In contrast to traditional bulk picking, in which entire parcels are dispatched, in this area, packages filled with a few units of heterogeneous items are prepared (generally the contents correspond to about 20 items). Then the warehousemen systematically retrieve the articles and place them in the new packages until the order is completed.

Finally, in the outbound process, completed orders are conveyed to the outbound area where packages are collected and palletized for loading onto trucks. Warehousemen ensure that packages are correctly labelled, sealed, and prepared for shipment. Once palletized, packages are loaded onto trucks for transportation to customer destinations.

4.2 Integration of Processes

The simulation model integrates these warehouse processes to replicate the dynamic flow of goods and activities within the warehouse environment. We adopted a high-level approach to modelling each process for standard packages, encompassing inbound, stocking, picking, and outbound operations. To ensure accuracy, we created a 2D model based on the warehouse plans and the structure of conveyors. This enabled us to account for distances and the time required to move packages between different areas of the warehouse.

In addition, we developed a detailed microscopic model for the picking area to analyse operations in relation to the number of warehousemen present. This microscopic analysis was crucial for identifying inefficiencies and understanding the impact of workforce allocation on overall performance, a topic that will be explored further in the Results chapter. By simulating the intricate details of the picking process, such as the movement of warehousemen, the retrieval of individual items, and the organization of packages, we were able to capture the complexities of real-world operations and assess the effectiveness of different staffing levels and strategies.

To implement the logic of the models, we utilized flowcharts made available by the logical blocks present in AnyLogic libraries. These blocks were customized to incorporate functions capable of replicating the algorithms and logic adopted by the WMS.

Through the integration of these processes, our simulation model provides valuable insights into system performance, resource utilization, and operational efficiency, facilitating informed decision-making and strategic planning for warehouse management. The comprehensive nature of our model allows to explore various scenarios, experiment with different strategies, and identify opportunities for improvement. By leveraging simulation technology, businesses can optimize warehouse operations, improve customer service, and adapt to changing market demands with confidence and agility.

4.3 Model Validation

The validation phase played a crucial phase of our work and involved a thorough comparison of simulation results with real-world and well-known situations occurred in the past. The validation procedure involved gathering real-world data and outlining reference scenarios that encompassed various operational conditions and challenges typically encountered. The available real-world data was leveraged to input the parameters into the model to generate output data comparable with the reference scenarios. This process was iterative in order to recalibrate the model and minimize the error degree.

These scenarios provided valuable insights into the complexities of warehouse operations, allowing to validate the performance of the simulation model under various conditions.

We specifically focused on historical data representing both off-peak and peak conditions in the sport brand retailer's warehouse, respectively the scenarios n. 0a and 0b reported in Table 1. Executing the simulation involved closely mimicking real-world parameters and configurations. This included replicating staffing levels, equipment capacities, order volumes, and workflow processes to accurately simulate the operational dynamics.

Comparing simulation results to real-world observations involved a meticulous analysis of key performance metrics such as throughput, order fulfilment rates, inventory levels, and resource utilization.

Through this validation process, we were able to estimate the magnitude of model error and identify specific components or processes within the model that contributed to inaccuracies. This iterative refinement process allowed to adjust parameters, refine algorithms, and incorporate additional details or complexities into the model to minimize discrepancies and improve alignment with real-world observations. The validation campaign performed on the latest version of the model returned the results shown in the table below. The model's error shows high reliability overall. On the peak scenario in particular, the model has a lower average error (2,8%) than the off-peak scenario (5,6 %). With the use case, it was determined that the error obtained is still acceptable. In fact, there are several factors, external and psychological, which the model does not take into account and which play a non-negligible role on resource efficiency. For example, when the workload is not particularly high, people tend to work not to their full capacity, which slows down operations. In addition, there may be unexpected events that often slow down the smooth running of warehouse operations, which means that at such times there is a surplus of resources to make up for lost time.

Table 1: Comparison of simulation results with real implementation.

Scen. n.	Volumes [packages/ day]	Total number of resources (real)	Total Number of Resources (simulated)	Error
0a	5.828	28	26,5	5,6%
0b	7.576	35	34	2,8%

Therefore, the validation process provided valuable insights into the accuracy and reliability of our simulation model. By ensuring that simulation results were comparable to real-world situations and configurations encountered in the sport brand retailer's warehouses, we enhanced the reliability of the model and gained confidence in its predictive capabilities.

5 RESULTS

Following the rigorous validation process aligning the simulation model with real-world warehouse performances, the study delved into various scenario analyses to assess the warehouse's capacity to handle forecasted volumes over the coming years, as outlined in Section 1. The primary focus was on optimizing the allocation of resources to effectively meet the increasing demand while maintaining operational efficiency.

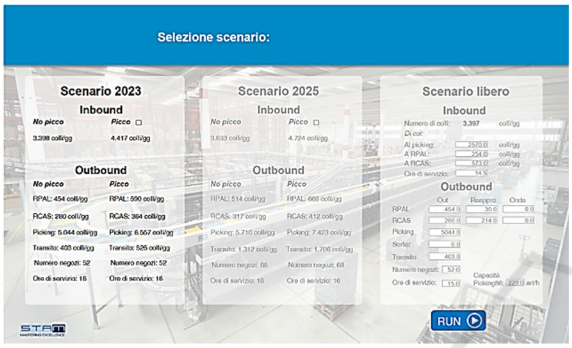

Figure 4: Model UI for scenario setting.

The simulation model was subjected to multiple scenario tests based on different demand projections and operational conditions. These scenarios were categorized into optimistic and pessimistic scenarios, each with variations in peak and off-peak demand conditions. The aim was to evaluate how the warehouse performed under various demand scenarios and to identify resource requirements for each scenario.

The simulation model analysed the number of warehousemen and machines needed in different sectors to handle the projected volumes effectively. This optimization process involved fine-tuning resource allocation to ensure efficient workflow management while meeting customer demands. By identifying the optimal number of resources required in each scenario, the model provided valuable insights for strategic resource planning and allocation.

Results from the scenario analyses revealed varying resource requirements across different demand scenarios. In the optimistic off-peak scenario (1a), which corresponds to the average demand for the year, volumes increased by 6% compared to the baseline (0a). The resource requirement in this case has already increased significantly compared to the current operating set-up (+66%).

In the peak optimistic scenario (1b), where demand surged during peak periods, the model indicated a notable increase in resource requirements, particularly in manpower compared to 0b (+176%).

The challenges intensified in scenarios 2a and 2b, the pessimistic off-peak and peak scenarios, respectively. In these scenarios, characterised by significantly higher demand than at present, the simulation model predicted a significant increase in resources. In particular, the most drastic increase was in the number of warehousemen.

The Table 2 shows the key results on which the assessments were made, i.e. for each scenario, the volumes and the corresponding required resources are indicated.

Table 2: Simulation campaign results.

Scenario n.	Volumes [packages/day]	Total Number of Resources (simulated)
0a	5.828	26.5
0b	7.576	34
1a	6.181	44
1b	11.434	94
2a	7.853	54
2b	15.495	128

Our study emphasizes the critical role of strategic resource planning and allocation in warehouse management. While our simulation model provided valuable insights into resource requirements under varying demand scenarios, it also highlighted the imperative for proactive measures to overcome capacity limitations and ensure the warehouse's resilience in meeting future demand effectively. Integrating simulation results with practical considerations and strategic decision-making enables the sport retailer to devise robust strategies for optimizing warehouse operations and navigating evolving market demands adeptly.

However, discussions with sport retailer management revealed a crucial consideration regarding the feasibility of implementing the recommended resources. The projected volumes could potentially strain the warehouse, particularly in the picking process, due to space constraints and congestion issues. The warehouse's physical limitations, including limited space and infrastructure, pose challenges to scaling up resources beyond a certain threshold.

In response, it is essential to explore additional measures beyond resource allocation to mitigate potential crises in warehouse operations. Strategies such as layout optimization, process redesign, automation implementation, and facility expansion offer promising avenues to enhance the warehouse's capacity to handle increasing volumes while sustaining operational efficiency. These proactive measures are essential for ensuring the warehouse's adaptability and competitiveness in an ever-evolving business landscape.

6 CONCLUSIONS

Warehouse management is crucial for supply chain operations, ensuring efficient goods movement and order fulfilment. This study explores warehouse optimization using advanced modelling and simulation techniques, focusing on challenges faced by B2B businesses. We aimed to develop a simulation model to forecast warehouse capacity and provide strategic insights to the sport brand retailer for managing increasing demand. Integrating agent-based and discrete event simulation methodologies enabled us to capture both macroscopic and microscopic aspects of warehouse operations.

Challenges encountered included model development, estimation, and validation, particularly in integrating simulation methods and parameter estimation. Validation was rigorous but essential, comparing simulation outputs with empirical data to ensure accuracy. Scenario analyses identified resource allocation strategies for different demand scenarios, aiding strategic decision-making. Our study highlights the significance of strategic decision-making and proactive planning in B2B warehouse management. Multi-method simulation approaches offer promising opportunities for optimizing operations and adapting to market demands.

Future work involves developing new models to analyse the automatic systems that will be implemented in the warehouses, enhancing the capability to predict and optimize operations further. This will enable businesses to stay ahead of evolving market trends and maintain competitiveness in the dynamic landscape of warehouse management.

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