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Simulation-Based Assessment of Warehouse Logistics: A Case Study in Beverage Distribution

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Abstract

Recent worldwide disruptions, including supply chains, geopolitical tensions, and shifting trade policies, have underscored the strategic importance of effective and flexible warehouse logistics. This work outlines an approach that is transferable to multiple contexts for the design of warehouse configurations and storage policies using simulation, with the specific objective of maximizing the use of available areas, improving the efficiency of operations, and enabling responsiveness to seasonal fluctuations in demand during the year. The model takes into account the classification of items based on their rate of turn, strategic location of storage, and simulation modeling reinforced with key performance indicators (KPIs) to provide data-based decision support. An example is demonstrated through its application in an Italian warehouse, with the specific responsibility of distributing drinks in the geographically remote island of Sardinia, with the complications of seasonal fluctuations in demand patterns. Using the AnyLogic simulation, this study analyses multiple storage layouts and assesses a flexible, mobile rack system to enhance receiving efficiency, utilise floor space effectively, and reduce handling distances. Results emphasize the practical relevance and broad transferability of this new approach to multiple contexts of warehouse operation.

Keywords: Warehouse logistics; Storage allocation; Simulation; KPI analysis

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1. Introduction

Logistics is an integral aspect of modern supply chains, and it plays the role of an intermediary between consumption and production locations of materials and products [1–3]. Timely and economical assurance of logistics operations is especially important in cases of food and beverage supply chains, as any delay may suspend sales or block the production process [4–6]. Global trends that have affected the world in the recent past, including supply chain disruptions, geopolitical conflicts, and shifting trade policies, have enhanced the significance of efficient logistics management even further [7,8]. Warehouse operations that involve the receipt, storage, and dispatch of materials and products thus play an important role in the achievement of service level objectives while minimizing costs [9,10].

Optimizing storage assignment and warehouse layout is crucial in the realization of these goals. Storage assignment, which is the process of assigning products to storage locations, has a direct bearing on floor area efficiency, handling, and responsiveness to supply and demand variability fluctuations [10,11]. However, practically, most warehouses still resort to the use of heuristic, experience-based methods that underperform under the influence of seasonal fluctuations, large SKU variability, and shelf-life limitations, especially in the food and chemical industries that handle very perishable goods [12,13]. Thus, developing universally applicable, data-informed methodologies that optimize storage assignment and warehouse layout is an underlying area of focus both among researchers and practitioners.

This study addresses these challenges by proposing a simulation-based approach for warehouse layout and storage assignment optimization, integrating turnover-based product classification, strategic zoning, and dynamic modelling. The approach combines turnover-led product segmentation, strategic zone configuration, and dynamic modeling. It is optimized to achieve maximum use of available storage and increase economies of use while still being flexible with variations in seasonal demand levels. Though the approach has been proven with an exemplary application at the Sardinian, Italy, warehouse, it is developed as applicable to wider warehouse utilization and supply considerations, including the retail, food, and pharmaceutical supply chains.

The Sardinian warehouse exemplifies many of the operational challenges encountered in such environments. The facility stores and distributes beverages, a product category characterized by distinct seasonal demand patterns, frequent packaging changes, and shelf-life constraints [13–15]. Demand peaks during the summer months, requiring flexible space allocation to accommodate increased inbound flows, while off-peak periods risk underutilization of resources. Products are currently stored in bays labelled by zone and sequential number, without fixed assignments to specific product types, complicating the management of expiry dates and undermining FIFO (First-In, First-Out) principles [16]. Batches of the same product are often dispersed across distant bays, increasing handling times and inefficiencies [17,18]. Furthermore, the high SKU variety and frequent introduction of promotional items exacerbate the difficulty of strategic space allocation and inventory turnover [10,12].

Another issue frequently faced in such centers is the need to strike a balance between peak and off-peak month space allocation. Allocating space based on peak-month requirements assures service-level agreement compliance but leads to inefficiencies during off-peak months. Offering space based on off-peak amounts takes the risk of peak-month capacity shortfalls. These trade-offs imply that storage assignment and facility design must be carried out systematically, with the option to adapt flexibly based on data.

To that purpose, the current work outlines and enacts an integrated systematic procedure including: (i) the characterization of incoming product flows and turnover indices through ABC classification [12]; (ii) the prioritization of reception areas based on accessibility and prioritization of turns; (iii) the derivation of an interactive simulation model with consideration of real-world limitations; and (iv) the validation according to KPIs and iterative refinement of contingent configurations. The Sardinian warehouse of beverages is an appropriate validation case study, which shows the effectiveness of the method in terms of improving efficiency in reception, optimally utilizing the floorspace, minimizing pallet travel distance, and hence, its wider applicability under corresponding operational contexts.

2. Modeling Approach

The study utilizes simulation-based methods to explore warehouse configuration and storage allocation, with the design being suitable for application beyond the particular case being analyzed. This procedure incorporates dataintensive product classification, theoretical zoning, simulation modeling over multiple periods, and performance assessment based on KPIs. The approach is demonstrated in an Italian regional Sardinian beverage distribution warehouse, which is known to experience extreme variability in stock-keeping units (SKUs), seasonal demand variability, and storage capacity limitation.

The historical 2024 inbound data, consisting of product codes, dates, times of arrival, and pallet quantities, was examined to determine patterns and seasonal variations. Monthly trends revealed that the busiest periods of the year were the summer months, confirmed through aggregation into quarterly data to support simulation modeling. Furthermore, daily averages were determined to account for intra-quarter variances. A Pareto (ABC) analysis was performed to sort the products into three turn-over groups (A, B, C), which revealed six fast-turnover items that consumed almost 40% of pallet movements (Figure 4 – Pareto analysis of product turn-over groups (A, B, C) based on the total number of inbound pallets in the year). Owing to the resulting guidance, an in-warehouse zoning policy was developed, with fast-turnover products assigned the most convenient storage bays, and quarterly storage allocations made to accommodate the change in volumes with the seasons while avoiding inefficiencies during the off-peak months.

Figure 1 – Layout and location of pallets inside the bay

A simulation model of the warehouse was developed using AnyLogic software to properly reflect the physical configuration, movement of materials, and operational constraints. Optimization of the configuration was carried out based on field measurements taken on the premises to achieve accuracy, including bays' dimensions, stacking levels, and pallet positions (Figure 1 – Layout and configuration of a bay, showing pallet positions level and column-wise). One bay was represented in the simulation as groups of nodes that represent specific pallet positions along two or three stacking levels, depending on the type of product being handled. The logical sequence of pallet handling activity was integrated into the simulation to capture true operational sequences (Figure 2 – Logical schema of pallet flows during simulation modeling). This approach included inbound arrivals, specific storage locations, dwell time, picking activities, and dispatching activities. Material handling equipment, namely the fork-lift, was represented in the model, with speed of movement being changed according to actual schedules of warehouse operations to capture delays due to interference, non-uniform floor, and loading variability.

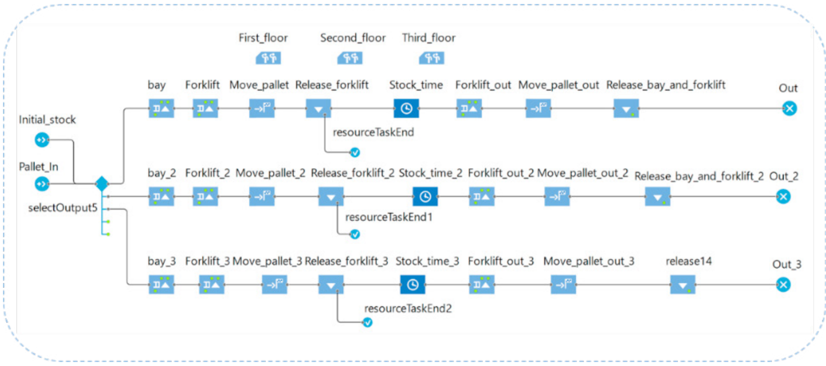

Figure 2 - Logical schema

The incoming pallets were simulated based on two different input streams: the first, modeling the opening inventory as of January 1, 2024, and the second, modeling the everyday incoming, which was dynamically taken from an Excel data set. Pallets were assigned to the rack levels proportionally to the available capacities, following specific constraints corresponding to the stacking rules. The seasonal shifting of racks was ideated as a quarterly shift in the product-to-rack mappings, running, for each scenario, as an autonomous model corresponding to the seasonal volumes documented. This approach allows the representation of the slow "domino effect" due to the reassignments over time (Figure 3 – Type of product assigned to each rack).

The model was then used to compute KPIs receiving efficiency, space occupancy rate, and distance travelled per pallet, to assess performance under the current configuration and proposed quarterly zoning adjustments. Temporary buffer zones were introduced to absorb excess pallets during peak periods without overcommitting permanent space.

It provides an unambiguous and adaptable structure for assessing warehouse performance, combining workable operating considerations with data-scenario-based analysis. Though optimization processes remain to be implemented, the simulation forms a sturdy foundation for future optimization studies and is developed to remain applicable for similar warehouses that are marked by product heterogeneity and seasonal variations in the patterns of demand.

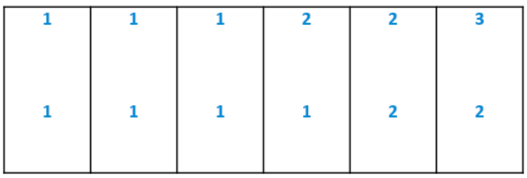

Figure 3 - Type of product assigned to each rack.

3. Results and Discussion

3.1. Analysis of Item Distribution

The detailed analysis of item turn is vital in developing optimal storage assignment strategies, as it helps prioritize the most impactful items and optimizes the use of available space. To achieve this goal, the items under consideration had their Pareto (ABC) analysis carried out, and they were segmented based on their share of the total annual inbound pallet volume. This segmentation is the basis of the zoning plan, which ensures that fast-moving items are allocated the most accessible storage locations, thereby reducing travel distances and handling times and enhancing throughput.

As seen in the example of Figure 4 – Pareto analysis of product types based on product turnover (A, B, C), the small percentage of Turnover A products accounts for the most pallet movements, with Turnover B and C items having increasingly smaller contributions. This is in agreement with the typical 80/20 rule often observed in warehouse management [9], thus supporting the necessity to focus on a few highly-turning items with prioritized storage. By placing Turnover A products closest to loading and picking locations and keeping lower-priority products away in peripheral or upper-level areas, an efficient and data-supported configuration may be developed that decreases excessive handling and reduces congestion.

Although demonstrated here in the context of a beverage warehouse, this turnover-based zoning approach is generalisable to other warehousing contexts where SKU heterogeneity and demand variability pose similar challenges. Quantitative analysis of item distribution thus represents a critical foundation for effective and adaptable warehouse layout planning.

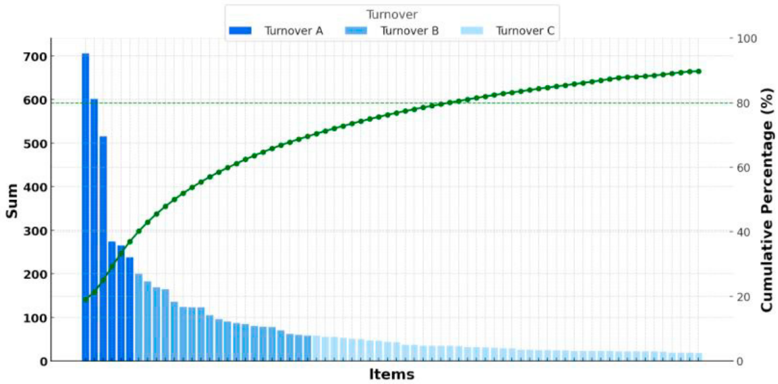

Figure 4 - Pareto analysis

3.2. As-Is

A simulation model was used to assess the current storage configuration and the warehouse's operational performance. The investigation considered two important performance indicators: the number of pallets queuing because of unavailable allocated free slots and the storage occupancy rate in the allocated storage area. They represent the trade-off between achieving slot utility efficiency optimally and countering peak-hour congestion.

The performance represented in Figure 5 – Waiting pallets number is that during the peak demand summer months, especially July, many fast-moving items experience significant waiting times due to the availability of their allocated slots. This leads to higher transient buffer zone use, which is marked with lowered efficiency and product storage in sub-optimal parts of the facility. Though the number of waiting pallets decreases in the following months as the demand decreases, the pattern shows the inability of the current allocation structure to handle the seasonal variations effectively.

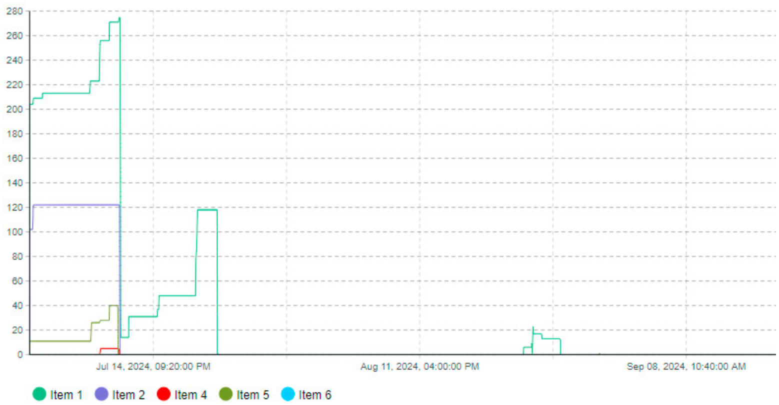

Figure 5 - Number of pallets that remain in a waiting state

The patterns of storage slot use, represented in Figure 6 – Utilisation Rate of Storage Slots, show an extreme peak utilisation and an extreme off-peak utilisation during off-peak periods. The utilisation rates show extreme differences between various product groups, corresponding to the extreme turnover patterns recognised in the Pareto analysis. The fact that this variability is present shows that the assigned fixed storage area is too limited to provide an optimal trade-off between responsiveness and spatial efficiency.

The findings of the research confirm the drawbacks of the conventional approach, which neither takes account of seasonal fluctuations nor the rate of product replacement. The revealed ineffectiveness underlines the importance of adopting an adaptive, turn-based storage allocation policy, such as the mobility-focused zone configuration pattern under consideration, to better match storage capacities with the shifting demand and achieve an optimal and stable storage utilisation of the existing areas.

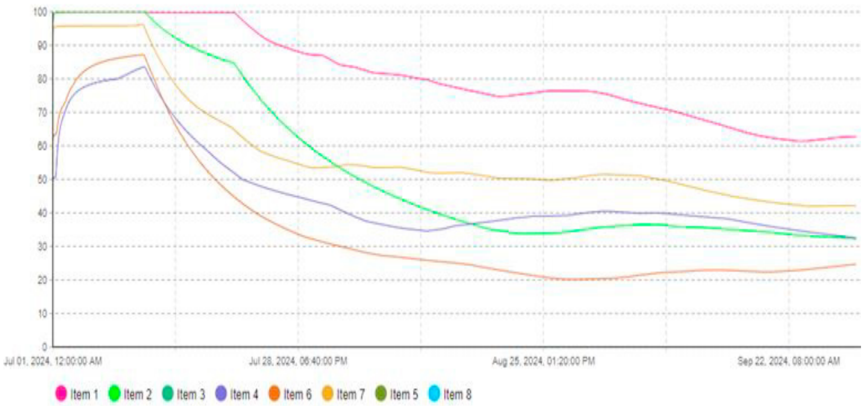

Figure 6. Utilization rate of the storage slots

3.3. KPI

To determine the current configuration of the warehouse and explore the effects of different storage allocation policies, three main KPI were defined and compared with the help of simulation modeling: receiving efficiency, area occupancy rate, and traveled pallet distance. They represent different aspects of performance during operation and are often cited in literature on warehouse management as important indicators used to assess both efficiency and resource use [19,20].

The first key performance indicator, receiving efficiency, measures the rate at which incoming pallets are received and stocked, expressed in terms of pallets handled per minute. As shown in Figure 7 – Receiving efficiency by product type, the analysis shows a strong relationship between the proximity of storage locations to the unloading zone. High-turnover products designated to bays nearest the unloading area show higher receiving rates, while products placed farther away are processed at a lower rate. This supports the argument that storage location decisions significantly influence inward movement, and that prioritizing high-turnover products in convenient locations has the potential to enhance receiving performance.

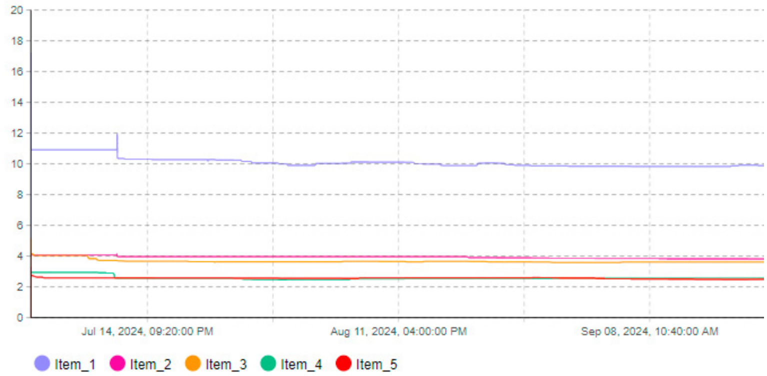

Figure 7- Receiving efficiency

The second KPI, space occupancy rate, quantifies the percentage of allocated storage capacity utilised over time. The time-series results in Figure 8 – Space occupancy rate by product type reveal distinct patterns across product categories. Occupancy peaks during high-demand periods, particularly for high-turnover products, but drops significantly during off-peak months, reflecting underutilisation of allocated space. Notably, low-turnover products maintain low occupancy throughout, suggesting that dedicated slots for these items could be better consolidated. These findings reinforce the need for dynamic allocation policies that adjust to seasonal demand fluctuations, such as the proposed mobile zoning strategy, to optimise space utilisation while maintaining responsiveness.

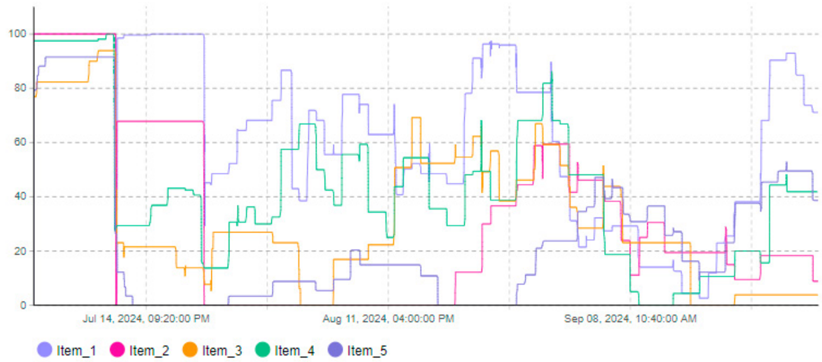

Figure 8 - Space occupancy rate

The third KPI, distance traveled per pallet, calculates the total material handling effort expended in storing and retrieving pallets, expressed in metres. From Figure 9 – Distance travelled per pallet, it is seen that the farther away the product is from the dispatch and unloading regions, the higher the travel costs, both in terms of time and energy consumption. The seasonal redeployment of racks injects variability into the distances, requiring tight management to avoid excessive travel during busy periods. This KPI brings into sharp focus the trade-off between optimal area use and optimal traveling, and the need for an equitable storage assignment strategy.

The individual KPIs, taken collectively, provide an in-depth view of warehouse performance under both existing and alternative configurations. They reveal the limitations of an exclusively static storage area allocation in coping with the seasonal variations and heterogeneous turnouts, which cause bottlenecks, underutilization, and increased handling efforts. Though there is neither an explicit measure of optimization yet at this phase, the KPI analysis gives an effective initial baseline from which specific inefficiencies may be identified and promotes future scenario testing designed to achieve continuous improvement. Furthermore, the indicators are transferable and may be applied to assess performance under different warehouse scenarios that face similar operational challenges.

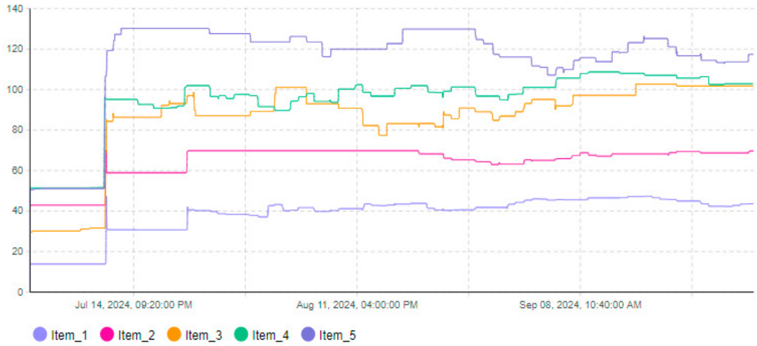

Figure 9 – Distance travelled per pallet

4. Conclusions and Future Work

This study demonstrates a simulation-based approach for the assessment of warehouse layout and storage assignment, integrating turnover-based product classification, conceptual zoning, dynamic modelling, and KPI-driven evaluation. While applied here to a beverage distribution warehouse in Sardinia, the approach is designed to be generalisable to other warehouse contexts characterised by high product variety, seasonal demand fluctuations, and constrained space.

The case study highlights how static storage assignments can lead to inefficiencies, including underutilised space in off-peak periods, increased handling distances, and congestion during peak demand. The proposed turnover-based zoning strategy, complemented by a mobile quarterly reassignment of storage space, was shown to improve the alignment between storage capacity and demand patterns. The KPI analysis measuring receiving efficiency, occupancy rate, and distance per pallet provided actionable insights into operational performance and identified areas for improvement.

The broader implication of this work is that data-driven, simulation-supported storage assignment policies can enhance warehouse responsiveness, space efficiency, and throughput, supporting organisations in adapting to increasingly volatile demand conditions. Such methodologies also enable decision makers to test alternative scenarios before implementation, reducing risks and improving planning robustness.

Future research will focus on extending the methodology by incorporating formal optimisation procedures, sustainability-related KPIs such as energy consumption and emissions, and real-time data integration through a digital twin. These enhancements will further strengthen the ability to balance operational efficiency, environmental impact, and service levels in line with Industry 4.0 and sustainability objectives.

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