*Proceedings of the International Conference on Industrial Engineering and Operations Management*

Publisher: IEOM Society International, USA DOI: 10.46254/SA6.20250116
Published: May 12, 2025

# Analyzing the Scalability of Autonomous Guided Vehicles in Dynamic Classical Warehousing Environments for the GTS Systems

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## Abstract

The rapid growth of e-commerce has increased pressure on warehouses to efficiently manage a rising number of products and organize them onto shelves with speed and accuracy. In this scenario, automation has become crucial, especially with the implementation of goods-to-shelf (GTS) systems that reduce the need for human movement and enhance picking efficiency. Among these advancements, Autonomous Guided Vehicles (AGVs) emerge as a versatile and scalable option that can revolutionize traditional warehouse operations. This study examines the performance and scalability of AGVs by creating a detailed simulation model using FlexSim 25.0.2. The model reflects real-world classical warehouse dynamics through visually adaptable shelving systems, comprehensive order lists, advanced process flows, and dynamic rules for resource allocation that dictate robot actions. The simulation investigates various AGV deployment strategies and assesses key performance metrics such as order fulfillment time, robot usage, travel distance, and overall system throughput. The results indicate that employing the right number of AGVs significantly boosts warehouse efficiency by minimizing manual tasks, enhancing task distribution, and improving the system's overall responsiveness. Single-load robots demonstrated a balanced performance, while double-load robots provided greater capacity but risked creating bottlenecks when handling heavier loads. This research highlights the promise of AGV-driven automation in contemporary warehousing while also addressing the challenges of scaling these systems in intricate environments. The simulation-based methodology discussed here offers valuable insights for warehouse designers, managers, and researchers aiming to enhance logistics performance and move towards smarter, automated fulfillment systems.

## Keywords
Autonomous Guided Vehicles, Warehouse Operations, Goods-to-Shelf System, Simulation, FlexSim

## 1. Introduction
The emergence of warehouse automation technologies has greatly changed traditional material handling systems, focusing more on improving operational efficiency and reducing the need for human involvement. One of the most exciting developments is the use of Autonomous Guided Vehicles (AGVs) in goods-to-shelf (GTS) systems, where robots fetch and deliver items directly to pickers, cutting down on travel time and labor needs. These systems are especially important in e-commerce and large distribution centers, where the speed and volume of orders are crucial. Bozer et al. (2018) conducted a thorough simulation-based comparison of two key GTS order-picking systems: the Mini-load system and the Kiva system. Their research pointed out the structural and operational trade-offs between these systems and highlighted the benefits of robotic GTS solutions in fast-paced retail environments. Building on this work, Peter et al. (2008) investigated the Kiva warehouse management system, showing that productivity could be significantly increased when robots autonomously moved goods to workers, thus removing the need for manual travel. Bauters et al. (2016) further looked into how autonomous vehicle storage systems performed compared to traditional Automated Storage and Retrieval Systems (AS/RS), confirming the flexibility and performance advantages of AGV-based solutions. Zou et al. (2021) expanded on this by testing different robot-to-docking station assignment strategies, finding that smart assignments could reduce overall operational costs and enhance throughput, depending on the layout and design of the system. Even

with the notable progress in integrating AGVs, there are still challenges in achieving scalable coordination, intelligent routing, and real-time resource allocation in increasingly complex warehouse settings. To tackle these issues, this study presents a simulation model created in FlexSim 25.0.2, aimed at assessing the performance and scalability of AGVs in contemporary warehouse operations. The initial inspiration for this study was drawn from (FlexSim Simulation Software, 2021), in which the narrator demonstrated a general way of modeling AGVs in a warehouse environment using the FlexSim tool. The model in this study focuses on quickly picking items and delivering them directly to picker stations using advanced process flows, global order management lists, and dynamic resource assignment strategies. A key feature of this model is its visual and modular design. Flow storage elements on the simulation floor resemble real-world shelving, while process flows dictate how robots behave and navigate. The model also features a global list-based order management system with visual cues to aid in real-time order generation and routing decisions. Furthermore, it incorporates scalability through a template-based design, enabling the replication of multiple robots and stations, with a prioritization system that directs robots to the least busy stations first. This paper presents a simulation-based framework that can help both researchers and practitioners assess the effectiveness of autonomous robots in the GTS systems. By simulating and analyzing various operational scenarios, this research provides valuable insights into the design and management of smart warehouse systems that utilize autonomous robotics to enhance logistics performance for the future.

### 1.1 Objectives

This study focuses on creating a simulation-based framework to evaluate the performance of AGVs in a classical GTS warehouse system. The main goals are to:

- Assess how AGVs affect picker travel time and overall operational efficiency.
- Explore strategies for dynamic resource allocation and real-time prioritization of robots to stations.
- Investigate how scalable AGV deployment can be achieved through modular and template-based system designs,
- Provide practical insights for warehouse designers and practitioners by simulating different scenarios

By achieving these goals, the study aims to enhance our understanding of how smart automation technologies can transform warehouse operations, especially regarding throughput, flexibility, and system responsiveness.

## 2. Literature Review

The field of warehouse management has been transformed into smart warehouse management by the introduction of advanced Automation Technologies and the incorporation of AGV. A joint approach to order allocation and movable rack assignment for pickers in Kiva systems has been discussed in Hu, L. (2021). The heuristic algorithm for balancing picker workloads has also been proposed to ensure that pickers receive all required items. Bauters et al. A control architecture for warehouse automation performance evaluation is presented by Miklic et al. (2011). This involves multiple AGVs transporting packages from the originating location to one of multiple destinations in an unorganized warehouse environment. AGVs are equipped with wheel encoders, laser range finders, and RFID tag readers. At the lowest level, controllers monitor intermediate points to ensure task execution. Draganjac et al. (2016) introduce a methodology for the decentralized control of multi-AGV systems in performing transportation tasks in commercial and warehousing environments. The methodology, which works on every vehicle in the system, is strengthened by the vehicles' self-managing trajectory planning and movement synchronization capabilities. The robustness of the presented methodology is analyzed, and the absence of deadlock and live lock features is discussed. Winkelhaus et al. (2022) introduce that hybrid order picking in most companies is still done manually by human operators. Technology is available to automate order-picking processes or support human order pickers. The results show that hybrid order-picking generally has the capacity to improve pure manual or automated order-picking operations in terms of production and total cost. Based on the simulation results, promising research potentials are discussed. Qi et al. (2018) describe an automated guided vehicle system (AGVS) as an advanced material handling system widely utilized in various automated systems, particularly in e-commerce storehouses. To accommodate more intricate situations, diverse kinds of storehouse configurations are experimented with. Extensive simulations are conducted to scrutinize the impacts of policies, storehouse configurations, task densities, and timing of an AGV to solicit a resource on the evaluation of the AGVS-based warehouse operation performance, which provides guidelines for warehouse designers. The problem of storage allocation and grouping of orders in the Kiva mobile fulfillment system has been examined by Li et al. (2020). The storage allocation model aims to determine the optimal assignment of products to bins to maximize product similarity. This approach is further enhanced by the use of variable neighborhood search. Computational experiments are conducted to verify the performance of the proposed model and algorithm. Inam et al. (2018) examine a collaborative environment, where humans and robots work together, expected to increase both safety and reliability. An automated warehouse is presented where AGV loads products onto trucks and share the same environment with human employees. It generates different alerts or actions performed according to security levels and is responsible for changing the size of dynamic areas. Warehouse operations require a lot of manpower and physical space. Currently, companies with large warehouses are investing in AGVs to save time and effort and prevent human error. Bolu et al. (2019) provide a complete and error-free solution to the path planning problem and describe its performance in different warehouse scenarios with multiple mobile robots and different design considerations. This study's main goal is to provide a thorough knowledge of the function and effectiveness of AGV concerning contemporary warehouse operations. The following main goals are addressed by this study. The objective of this study is to assess the effectiveness and function of AGV in present-day warehouse operations. The research entails simulating diverse scenarios of warehouse functions, specifically focusing on the interaction between the GTS system employing AGV. Utilizing FlexSim's simulation features, this study aims to construct models, assess performance, and scrutinize the scalability of AGV within warehouse settings. AGVs have emerged as a prominent feature within contemporary warehousing, primarily in material handling tasks. This study seeks to explore the influence of automation on the GTS process in modern warehouse management, aiming to comprehensively understand its impact on operational efficiency.

## 3. Methodology

### 3.1 Simulation Tool

FlexSim, a highly powerful discrete-event simulation software that is commonly utilized for modeling, analyzing, and optimizing dynamic systems across various sectors, including manufacturing, logistics, and healthcare. With its user-friendly drag-and-drop interface, impressive 3D visualization capabilities, and a powerful scripting language known as FlexScript, it facilitates the efficient simulation of intricate processes. FlexSim aids in real-world decision-making by enabling users to explore "what-if" scenarios, pinpoint bottlenecks, and enhance overall system performance. In this study, this simulation tool was employed to model and analyze the classical warehouse system integrated with AGVs within the context of GTS systems. A visual representation of the simulated warehouse layout with Floor Storage and AGVs is presented in Figure 1.

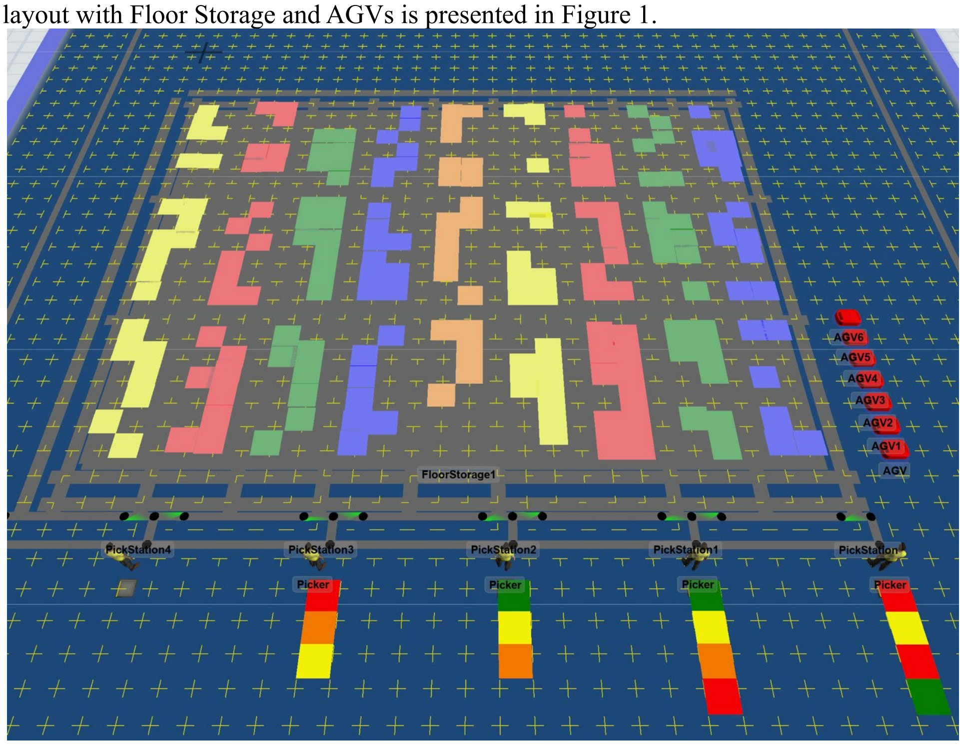


Figure 1. Floor Storage Process

### 3.2 Simulation Process Flow

The simulation flow was designed to replicate real-time AGV operations in a dynamic warehouse setting. The movement of these AGVs on the floor storage can be seen in Figure 1. In this model, products of different categories come to the warehouse randomly, and it is important to ensure that each product is placed at its designated category locations on the floor storage. To facilitate this process, each product and its corresponding location are color-coded for easy identification. On the arrival of the product, it needs to be assigned to an available AGV, which retrieves the necessary items from the pick-up stations and facilitates their delivery. After delivering the product to its assigned area, each AGV either goes back to its home position or moves back to the pick stations for its next assigned job. The structure of this whole simulation methodology is implemented through several development stages, some of which are elaborated upon below, accompanied by the illustration in Figure 2.

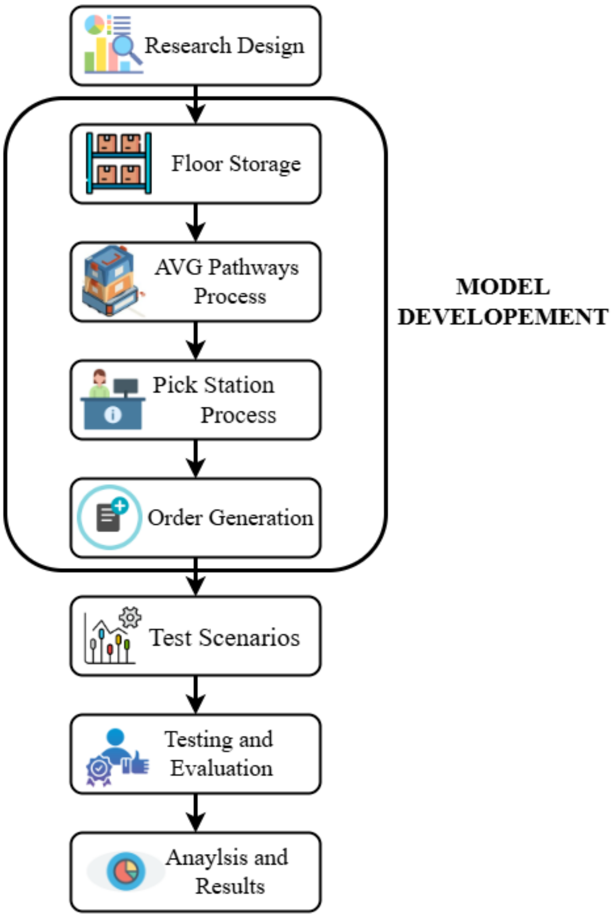


Figure 2. Methodology of the Study

### *3.2.1 Model Development*

#### *3.2.1.1 Floor Storage Process*

This module emulates the actual classical warehouse layout of 26x20 grids, with pathways marked in black and storage areas in gray. The process initiates with a Source block that triggers cart creation. Each of these carts is generated and given a unique color according to the product for easy identification. A custom code block has been added to define specific behavior attributes or operational rules for each cart. This design simulates the cyclical nature of resource generation and disposal within warehouse logistics, as shown in Figure 3.

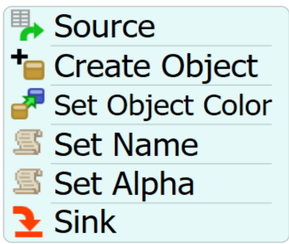


Figure 3. Floor Storage Process

#### 3.2.1.2 AGVs Pathways Process

This flow governs the full lifecycle of an AGV fulfilling an order. The flowchart of the whole pathway process can be seen in Figure 4. The process starts by locating each AGV's location. The system continuously checks for new cart requests; when a request is detected, an available AGV is assigned the task and returns to its home position to initiate the assignment.

The process includes:

- Identifying the requested item and its storage location.
- Navigating to the item using pathfinding logic.
- Loading the item onto the AGV.
- Delivering it to the assigned pick station.
- Returning to the warehouse and resetting for future tasks.

Real-time monitoring of system variables such as DeliveredCarts, CartRequests, and ReleasedRobots enables effective task tracking. The system also incorporates a dynamic barrier management model, which prevents path conflicts in real-time through a live update mechanism. Under this dynamic obstacle avoidance mechanism, if a path becomes blocked, the system marks it accordingly and reroutes the AGV using an updated set of navigation rules, primarily managed by the A* algorithm. This mechanism is essential for ensuring uninterrupted flow in multi-AGV environments.

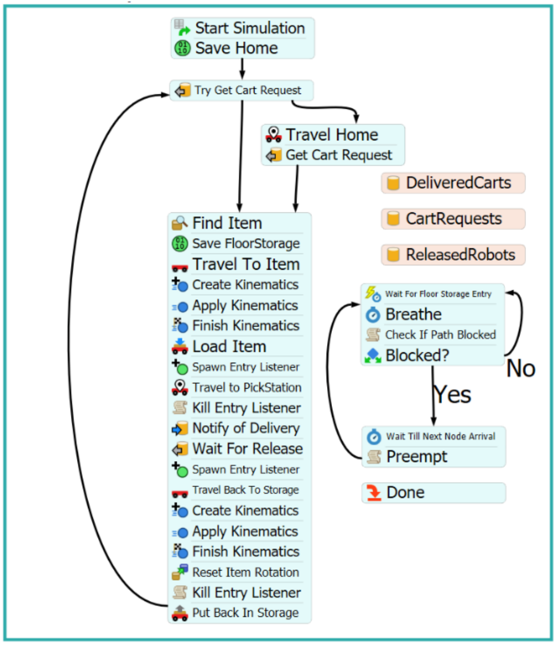


Figure 4. AGVs Pathways Process

### 3.2.1.3 Pick Stations Process

The Pick Station Process mimics how tasks are handled in a warehouse, from when an order is received to when a robot completes its job. It all begins with a Source block that introduces a token for a new task. The Reset Assign Robots block then clears any previous assignments and adds a small random delay to ensure that robots are assigned fairly. An order is retrieved through the Get an Order function, and an object related to that order is created and visually identified using the Create Object and Color Object blocks. A transport cart is requested (Request Cart), and the assignment of robots is monitored with the Inc Assigned Robots function. The robot waits for the cart to arrive (Wait For Delivery), and once it does, the robot carries out the picking operation using Run Animation, Perform Picking, and Stop Animation. These actions represent the robot physically retrieving items. After the task is done, the robot is released (Release Robot), and the object is removed and destroyed (Move Object Into Model, Destroy Object), signalling the end of the process. This organized method ensures that robots are used efficiently, tasks are handled in sync, and the overall system operates smoothly. The flowchart of the of whole Pick Station Process can be seen in Figure 5.

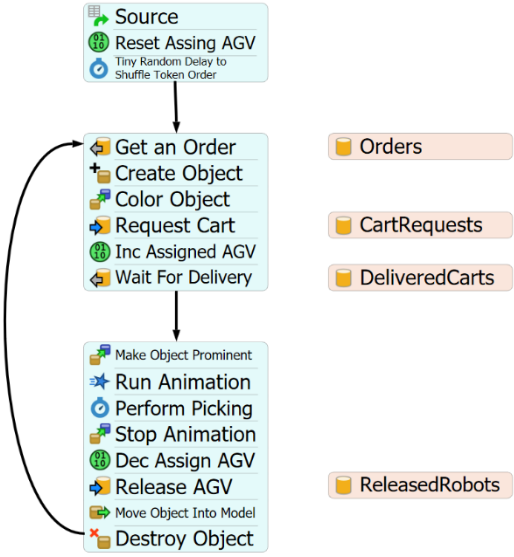


Figure 5. Pick Stations Process

#### 3.2.1.4 Order Generation Process

The process of creating an order starts at random intervals set by the system. Once triggered, the system carefully chooses the type of order, which could include AGVs of various colors or sizes. After that, a suitable order is created based on the chosen type, and it gets recorded in the system under "Orders," completing the whole process.

### 3.2.2 Test Scenarios

A total of 200 products of 5 distinct types are created, with their types distinguished by a random color. To comprehensively evaluate the performance and scalability of the AGVs on a classical warehouse system in that setting, a structured set of simulation scenarios was developed by varying four critical operational parameters. These operational parameters are *the number of product types stored on the warehouse floor*, *the number of AGVs deployed*, *the number of pick-up stations*, and *the number of products retrieved per AGV per visit*. Each scenario is represented in the format **P-A-S-V**, where:

- **P** refers to the number of distinct product types arranged in the floor storage area (set to 5 in all scenarios),
- **A** is the number of AGVs operating within the system,
- **S** denotes the number of active pick-up stations,
- **V** represents the number of products an AGV is assigned to collect per trip.

A total of 18 scenarios were simulated to observe how these variations influence key performance metrics such as average waiting time, travel distance, AGV utilization rate, and overall throughput. The distribution logic was governed by the *duniform(1, 5, getstream(activity))* function, representing five independent activity streams simulating real-time warehouse dynamics. The detailed configuration of each scenario is summarized in **Table 1** below.

Table 1. Scenario Configuration Based on Product Type, AGVs, Stations, and Visit Load

| Scenario P-A-S-V | Number of AGV (A) | Number of Pick Stations (S) | Number of Products/Visit (V) |
|---|---|---|---|
| 5-3-2-1 | 3 | 2 | 1 |
| 5-3-2-2 | 3 | 2 | 2 |
| 5-3-4-1 | 3 | 4 | 1 |
| 5-3-4-2 | 3 | 4 | 2 |
| 5-3-6-1 | 3 | 6 | 1 |
| 5-3-6-2 | 3 | 6 | 2 |
| 5-5-2-1 | 5 | 2 | 1 |
| 5-5-2-2 | 5 | 2 | 2 |
| 5-5-4-1 | 5 | 4 | 1 |
| 5-5-4-2 | 5 | 4 | 2 |
| 5-5-6-1 | 5 | 6 | 1 |
| 5-5-6-2 | 5 | 6 | 2 |
| 5-7-2-1 | 7 | 2 | 1 |
| 5-7-2-2 | 7 | 2 | 2 |
| 5-7-4-1 | 7 | 4 | 1 |
| 5-7-4-2 | 7 | 4 | 2 |
| 5-7-6-1 | 7 | 6 | 1 |
| 5-7-6-2 | 7 | 6 | 2 |

## 4. Results and Discussion

A set of 18 scenarios was tested to evaluate the impact of different AGVs and Pick Stations' configurations on waiting time, travel distance, and utilization at a constant speed of 2.0 m/s. As seen in Table 2, scenarios with single-transport loads (e.g., 5-3-4-1) generally resulted in shorter waiting times and moderate utilization, offering a balanced operational performance. In contrast, double-transport scenarios showed higher utilization rates—often above 86%—but also led to increased waiting times, highlighting a trade-off between throughput and efficiency. The least efficient configuration was observed in scenario 5-7-2-1, where low utilization and high waiting time pointed to poor resource coordination.

Table 2. Performance Metrics by Scenario (AGV speed = 2.0 m/s)

| Scenario | Average Waiting Time Robots (min) | Average Distance (m) | % Utilization per hour |
|---|---|---|---|
| 5-3-2-1 | 80.32 | 26,413 | 48.7 |
| 5-3-2-2 | 105.91 | 46,632 | 88.6 |
| **5-3-4-1*** | **71.67** | 28,225 | 52.3 |
| 5-3-4-2 | 102.44 | 46,21 | 88.4 |
| 5-3-6-1 | 72.27 | 28,444 | 52.5 |
| 5-3-6-2 | 103.10 | 46,523 | 88.0 |
| 5-5-2-1 | 92.79 | 24,062 | 44.3 |
| 5-5-2-2 | 108.25 | 45,849 | 87.5 |
| 5-5-4-1 | 74.05 | 27,569 | 51.3 |

| Scenario | Average Waiting Time Robots (min) | Average Distance (m) | % Utilization per hour |
|---|---|---|---|
| 5-5-4-2 | 103.36 | 45,402 | 87.0 |
| 5-5-6-1 | 72.11 | 28,06 | 52.8 |
| 5-5-6-2 | 104.20 | 45,995 | 87.5 |
| **5-7-2-1*** | **111.87** | 20,423 | 37.5 |
| 5-7-2-2 | 108.31 | 44,856 | 86.4 |
| 5-7-4-1 | 79.21 | 25,932 | 48.2 |
| 5-7-4-2 | 104.74 | 45,654 | 87.8 |
| 5-7-6-1 | 73.87 | 28,104 | 51.8 |
| 5-7-6-2 | 106.37 | 46,373 | 88.7 |

### 4.1 Comparative Performance Analysis of Simulated AGV Scenarios

Among the tested scenarios, 5-3-4-1 demonstrated the most balanced performance with the lowest average waiting time (71.67 minutes), indicating efficient queue and transport coordination. In contrast, 5-7-2-1 showed the highest waiting time (111.87 minutes) and the lowest utilization (37.5%), reflecting poor resource allocation. Scenario 5-3-2-2 recorded the longest travel distance (46,632 units), highlighting the operational cost of dual-transport systems. The highest utilization was observed in 5-7-6-2 (88.7%), suggesting intense robot activity that may affect long-term reliability. Overall, Table 3 illustrates key trade-offs in system design, with 5-3-4-1 emerging as the most efficient and sustainable configuration.

Table 3. Key Performance Highlights and Recommended Scenario

| Category | Scenario | Value |
|---|---|---|
| Lowest Waiting Time | 5-3-4-1 | **71.67 min** |
| Highest Waiting Time | 5-7-2-1 | **111.87 min** |
| Highest Distance | 5-3-2-2 | 46,632(meters) |
| Highest Utilization | 5-7-6-2 | 88.7% |
| Lowest Utilization | 5-7-2-1 | 37.5% |
| Recommended Scenario | 5-3-4-1 | - |

Table 4 contrasts single and double transport configurations. The single transport system achieved overall average waiting times (<100 minutes) and moderate travel distances (25,000–28,000 units), with robot utilization ranging from 45–52%. This setup offers operational balance and long-term maintainability, making it ideal for systems that prioritize reliability. Conversely, the double transport system, while intended for greater throughput, resulted in longer waiting times (>100 minutes) due to poor queuing and overworked robots. It led to travel distances surpassing 45,000 units and utilization rates reaching up to 88%, which increased energy consumption and risks of system fatigue.

Table 4. Comparison of Single vs Double Transport Systems

| Feature | Single Transport | Double Transport |
|---|---|---|
| Average Waiting | Lower | Higher (100+ min) |
| Average Distance | ~25,000–28,000 meters | ~45,000–46,600 meters |
| Utilization | Around 45–52% | Peaks at 86–88% |
| Advantage | Balanced, sustainable | Fast but highly intensive |
| Disadvantage | Lower capacity | Risk of robot overuse and wear |

Table 5 illustrates how system parameters can impact performance. While adding more AGVs can aid in material handling, their success relies on additional strategies like queue organization and transport methods. By increasing queue capacity, the system can perform better by minimizing delays and ensuring tasks are allocated more evenly. In summary, while double transport configurations can boost capacity, they might also lead to inefficiencies. On the other hand, single transport setups tend to provide a more stable, efficient, and sustainable option, especially in settings where consistent operations are essential.

Table 5. Observations on System Variables and Their Effects

| Variable | Effect |
|---|---|
| Number of Robots | Not sufficient alone; does not guarantee efficiency |
| Number of Queues | **Positive effect: reduces waiting time** |
| Double Transport | Higher capacity, but also higher waiting time |
| Single Transport | Lower waiting time, more balanced system |

## 4.2 Evaluation of Individual AGV Performances of 5-3-4-1

A thoughtful comparative analysis was undertaken to examine the average stay times of three distinct AGVs within the system: AGV, AGV1, and AGV2. As depicted in Figure 6, the average stay time for each AGV is presented on an hourly basis, along with the overall averages for all AGVs. The findings indicate that the average stay times are as follows: AGV - 70.13 mins, AGV1 - 69.26 mins, and AGV2 - 73.73 mins. This insight allows for a better understanding of the performance of each AGV, facilitating informed decision-making for potential improvements.

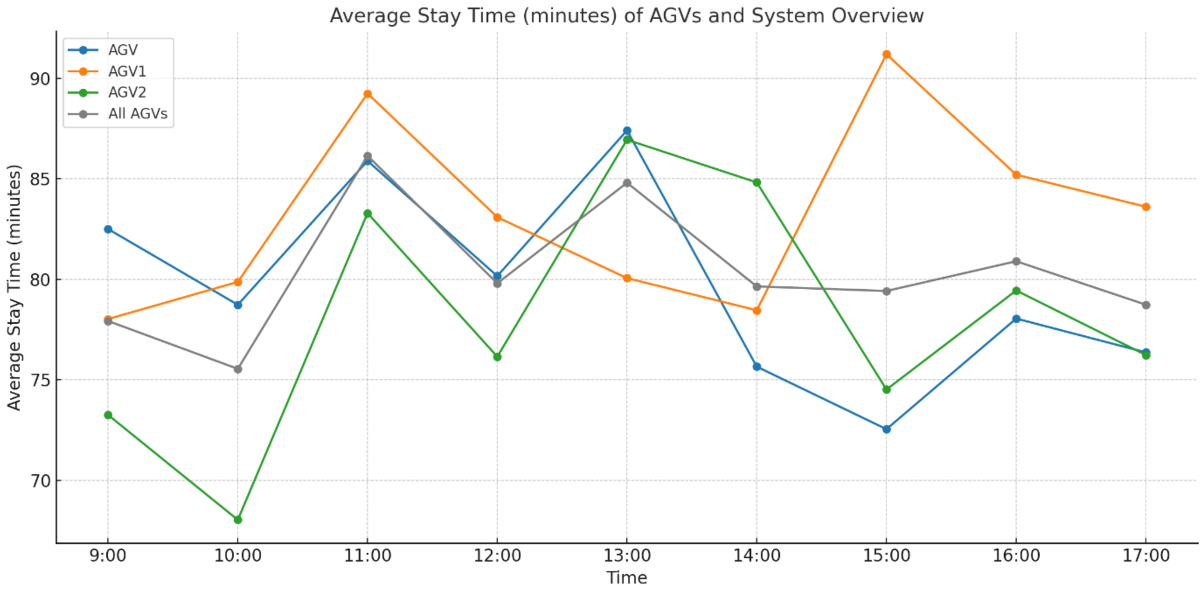


Figure 6. Average Stay Time of Individual AGVs and Overall System of 5-3-4-1 Scenario

### 4.3 Evaluation of Individual AGV Performances of 5-7-2-1

The graphical trends presented in Figure 7 depict the average stay times of seven AGVs (AGV, AGV1 through AGV7) for the scenario 5-7-2-1 over hourly intervals, along with a consolidated line representing the average across all AGVs. A significant increase in stay time is observed during the 10:00 to 11:00 period, particularly for AGV2, AGV3, and AGV1, reflecting a congestion peak likely caused by task accumulation or routing delays. In contrast, post-14:00 periods show a general decline or stabilization in stay times, suggesting improved task flow or reduced system load. AGV7 displays noticeable variability, especially toward the end of the shift, which may point to uneven workload distribution. The average line serves to summarize the overall system behavior, highlighting periods of imbalance and potential bottlenecks in warehouse operations.

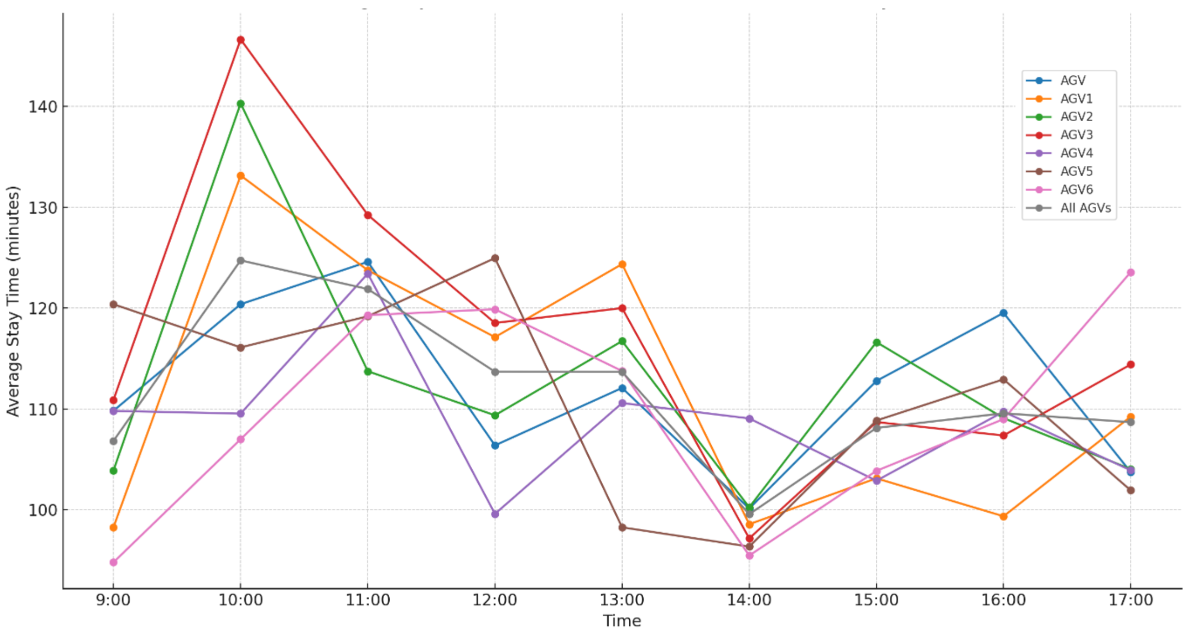


Figure 7. Average Stay Time of Individual AGVs and Overall System of 5-7-2-1 Scenario

The bar chart in Figure 8 illustrates how single and double transport systems perform across three important metrics: Average Waiting Time, Total Distance Travelled, and AGV Utilization. The Single Transport system shows lower waiting times, averaging around 80 minutes, a balanced total distance of about 26,500 units, and a robot utilization rate of approximately 48.5%. This suggests a more efficient use of resources. On the other hand, the Double Transport system provides quicker services but comes with drawbacks, including longer waiting times exceeding 100 minutes, greater distances of around 46,000 units, and a higher AGV utilization rate of about 87%. This indicates that the system may be experiencing overuse and strain.

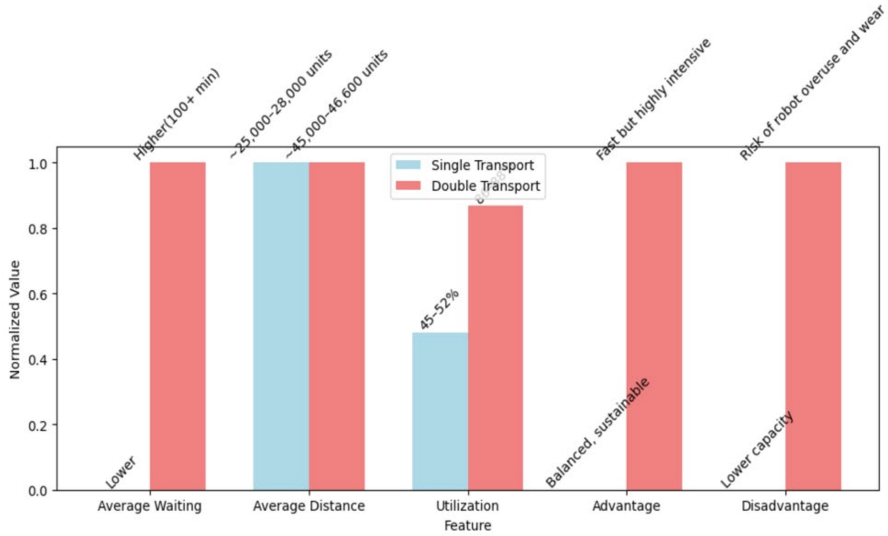


Figure 8. Comparison of Single vs Double Transport Systems

## 5. Conclusions and Future Direction

This study looked into how well AGVs perform and scale in a classical warehouse environment for the GTS system by using FlexSim 25.0.2 simulations. The findings show that AGVs significantly improve operational efficiency by cutting down picker travel time and boosting order fulfillment rates. Single-load systems demonstrate a balanced performance, with the best scenario (5-3-4-1) achieving a low waiting time of 71.67 minutes and a sustainable utilization rate of 45–52%. On the other hand, double-load systems can handle more capacity but lead to waiting times over 100 minutes and utilization rates of 86–88%, which increases the risk of wear on the robots. These results underscore the essential role of AGVs in the shift towards smart warehousing.
Future studies should concentrate on managing dynamic obstacles and optimizing routes in real-time to improve system scalability. Furthermore, investigating energy use and coordinating multiple robots in larger warehouse setups will provide practical solutions for long-term efficiency, pushing forward warehouse automation. In addition, future research could explore the impact of alternative warehouse layout designs—such as fishbone, inverted-V, and traditional parallel aisle configurations—on AGV navigation efficiency and overall system performance, offering deeper insights into layout-driven optimization strategies.

## Acknowledgment

The authors would like to express their sincere gratitude to FlexSim Software Products, Inc. for providing access to a licensed version of FlexSim 25.0.2, which was instrumental in conducting the simulations and analyses presented in this study. Special thanks are also extended to Ölçsan Teknoloji AŞ, Türkiye's authorized representative, and particularly to Mr. Burak Sondal for facilitating the licensing process and providing continuous support throughout the research period.

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## Biographies

**Büşra Şahinal** is an Industrial Engineer who holds a bachelor's degree from the Department of Industrial Engineering at Çankaya University and is set to complete her master's degree at the same institution in 2025. She possesses extensive expertise in production planning, project management, supply chain optimization, and process analysis. With proficiency in simulation tools (FlexSim, Arena), ERP systems, and Excel VBA programming, she has developed innovative solutions to enhance operational efficiency. Furthermore, her skills in data engineering, leveraging Python for data analysis, visualization, and process optimization, have strengthened her technical capabilities. Her areas of interest include autonomous systems, smart manufacturing technologies, composite materials, and machining processes, where she aims to make both academic and practical contributions.

**Syed Shah Sultan Mohiuddin Qadri** is an Assistant Professor in the Department of Industrial Engineering at Çankaya University, Ankara, Türkiye. He holds a Ph.D. in Industrial Engineering from Yasar University, Izmir, Türkiye. Dr. Qadri earned his BS and MS degrees in Applied Mathematics from the University of Karachi and NED University of Engineering & Technology, Karachi, Pakistan, in 2010 and 2013, respectively. He has worked as a researcher on a TÜBİTAK-funded project, and his research interests include simulation optimization, intelligent transportation systems, heuristic optimization, and traffic modeling. Dr. Qadri is dedicated to advancing optimization techniques for solving complex real-world problems.