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Master’s Degree in Mechanical Engineering

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Automated warehouse system performance analysis and simulation

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Abstract

With the accelerated development of e-commerce, the logistics service industry has expanded rapidly. As one of the most critical elements in the supply chain, the performance of warehouses has received more and more attention. This paper firstly identifies the key performance indicators (KPIs) that affect warehouse performance from economic, environmental, social, and other perspective through the literature review and ranks the indicators. Then, using FLEXSIM software, different Stacker crane-based and Shuttle-based AS/RS systems were built to complete the implementation of relevant performance indicators. Performance of alternative warehouse systems is contrasted using the fuzzy hierarchy method to select the optimal automation solution. At the same time, providing a reliable method for decision-makers in the process of designing an automated warehouse.

Keywords: Warehouse performance, Simulation model, FlexSim, KPIs, FAHP

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1. INTRODUCTION

An indispensable element combining supplies with production and the market is the warehouse system. Nowadays, warehouses are becoming more and more important to the overall success or failure of enterprises. Warehouses play an intermediary role among various supply chain stakeholders and can affect the supply chain's costs and services [1]. A warehouse is defined as a functional and organizational unit created to store materials in a specific area of a warehouse building [2]. The warehouse has two basic functions, independent of its position in the organization of the enterprise, that is, the function of inventory with static protection characteristics, including storage of materials that do not need to be used temporarily, raw materials, semi-finished products, and goods, and the function of material handling related to receiving and dispatching goods. The functionality of a warehouse today is no more than traditional storage functions. Furthermore, by promoting high inventory availability, shorter response time, value-added services, returns, customization, and consolidation, the warehouse system can increase customer service value [3]. As Figure 1 shown, there are several warehouse operational processes: receiving, transfer and put away, order picking/selection, accumulation/sorting, and shipment, which constitute the warehouse flow. Receiving activities include unloading the product from the transport vehicle, updating inventory records, and inspecting to detect any quantity or quality discrepancies. Transfer and storage involve the transfer of incoming products to a storage location. It may include repackaging (for example, placing complete pallets into boxes or standardized bins) and physical movement (from the receiving terminal to different functional areas, between those areas, and from those areas to the shipping terminal) [4]. Order picking/selection is the primary operation of retrieving goods from specified storage locations based on customer orders. It is necessary to accumulate/sort picking orders into individual (customer) orders if picking orders have been batched. Shipping involves scheduling and assignment of trucks to docks the orders after the product is collected. Warehouse systems are mainly applied in logistics, manufacturing, automotive, food, retail, healthcare, construction, and other industries. The global warehousing market is currently growing at a Compound Annual Growth Rate (CAGR) of 6 – 8%, according to Beroe Inc (2020), a procurement intelligence firm.

Automated warehouse refers to a system that can automatically storage and retrieve materials without direct manual intervention, which has significantly promoted warehousing technology development. A typical automated warehouse consists of four units: cargo handlers, storage mechanism (shelf system), conveying equipment, and control devices. The cargo handlers can move horizontally on the track or move in the vertical direction on its column to complete the storage and retrieval operation. The cargo throughput per unit time of the warehouse depends on the speed of the handle device. Conveying equipment usually refers to the conveying equipment that connects the cargo storage machine with other long-distance transportation devices, such as forklifts, guided vehicles, shuttle cars, and roller chain conveyors. The control device organically links all the automated warehouse equipment to make it act according to the predetermined procedures and requirements to form an automatic control system. Through activities automation, compared with traditional warehouses, automated warehouses have apparent advantages in saving workforce, space, shortening operation time, improving warehouse management and productivity. According to Logistics IQ's latest post-pandemic market report, the warehouse automation market is valued at approximately US$15 billion in 2019. It is expected to reach US$30 billion by 2026, with a compound annual growth rate of approximately 14% during the forecast period. Meanwhile, the global sales of e-commerce in 2019 was 3.53 trillion US dollars, and it is expected to reach a staggering 6.54 trillion US dollars by 2022. As the main driver of the warehouse market, it will also promote the growth of automated warehouses.

The ever-increasing complexity of warehouse operations and easily accessible information has led to the need for companies to conduct effective and efficient warehouse performance evaluations. In a dynamic supply chain, continuous improvement of warehouse performance has become vital for most suppliers, manufacturers, and related retailers to gain and sustain competitiveness in the global market. Over the last two decades, many researchers have put insight into the sustainability and accountability of warehouse performance. The existing literature on warehouse design and performance evaluation/optimization can be classified into three categories: warehouse design decisions, simulation models, and performance evaluations [5]. Gu et al. (2009) emphasized that warehouse design decisions are tightly coupled and difficult to define clear boundaries. Furthermore, since design decisions can significantly impact operational efficiency, operational performance metrics should not be ignored during the design phase. Once the warehouse is operational, changing design decisions can be expensive or even impossible [6]. However, warehouse performance is a multi-dimensional concept. There is not a consensus of a group of measures used to assess warehouse performance [7]. Researchers usually use the key performance indicators (KPIs) determined by performance research methods to optimize warehouse systems. The key performance indicator pools may vary from different warehouse systems. The ISO 22400 standard defines the KPIs used in the production sector. This standard specifies and classifies a set of KPIs in current practice. Moreover, as sustainable and green supply chains receive more and more attention and warehouse intelligence development, enriching the performance index system has become an important task [6]. This paper is based on previous research and aims to analyze the indicator system through literature review, The simulation model of the automated warehouse is established to complete the realization of key performance indicators, and the overall performance of the warehouse is compared through the comparative analysis of the key performance indicators of different systems.

Figure 1. Typical warehouse operations and flows

2. STATE OF THE ART

2.1 Automated warehouse

The development of the warehouse system has mainly gone through the following stages as shown in Figure 2:

- **Manual warehouse:** The handle of materials is mainly realized manually, and its real-time and intuitive nature are apparent advantages.
- **Mechanized warehouse:** Materials can be moved and handled by various conveyors, industrial conveyors, manipulators, cranes, stackers, and elevators. Use shelf pallets and movable shelves to store materials and manually operate mechanical access equipment. Use limit switches, screw mechanical brakes, and mechanical monitors to control the operation of the equipment. Mechanization meets people's requirements for speed, accuracy, height, weight, repeated storage, and retrieval.
- **Automated warehouse:** With the development of automation technology, AS/RS, AVS/RS, automated guided vehicle (AGV), automatic shelves, automatic storage and

retrieval robots, automatic identification and sorters have been successfully applied warehouse system [8].

- **Integrated automated warehouse**: In the industry 4.0 era, information technology is fully and deeply penetrated the manufacturing industry, which promotes the expansion and upgrade of existing hardware equipment, improves the warehousing logistics operation process, and improves the level of flexible application of warehousing technology and equipment, so that the overall the efficiency and the adaptability of production far exceed the sum of the independent benefits of each part. Warehouse Management System (WMS), which has been widely adopted at present, is the embodiment of integrating information technology into the automated warehouse. Besides, enterprise resource planning (ERP) system, customer relationship management system (CRM), and order management system (OMS) have also been applied to some supply chain management (SCM).
- **Intelligent automated warehouse:** Continue to research based on automated warehousing, realize integration with other information decision-making systems, and develop in the direction of intelligence and fuzzy control. Artificial intelligence promotes the development of warehousing technology, that is, intelligent warehousing. At present, intelligent warehouse technology is still in the initial stage of development. The application of artificial intelligence can make the warehouse fully intelligent, such as JD's unmanned warehouse, which maximizes the performance of the warehouse. Nowadays, in the context of 5G, intelligent automated warehouse has a broad prospect.

Automated warehouses were not invented recently. In fact, warehouse automation (the first batch of AGVs) originated in the 1950s, but it is still the hottest trend in warehouse systems today. Figure 3 below shows the three drivers behind the growing automation trend [9]. In short, this trend is driven mainly by rising costs due to operational challenges caused by higher consumer expectations. Today, the COVID-19 pandemic has exacerbated many persistent and hidden problems in global logistics, and many companies are trying to invest in supply chain technology to improve efficiency. The development of supply chain technology has the following trends:

- Machine learning**:** Machine learning algorithms integrate a large amount of historical and real-time data to filter and extract valuable data, which helps the warehouse system provide higher decision-making capabilities. Market leaders like Amazon have reaped many rewards for workforce planning systems that rely on machine learning. Many companies are following suit.
- Automated robots: Intelligent systems and robot automation can significantly reduce manual operations, reduce the risk of human error, reduce labor costs, enhance warehouse functions, and improve product processing and delivery processes. Collaborative robots and similar devices have also gained much recognition in warehouse automation. According to the Deloitte 2019 Annual Industry Report, more than 32% of supply chain executives actively use robotic technology for warehouse automation.
- Internet of Things (IoT): The application of the Internet of Things helps warehouse systems to respond quickly and accurately to real-time data. Gartner's "Supply Chain Survey 2019" report shows that 59% of participants have partially or fully used the Internet of Things in their company's supply chain.

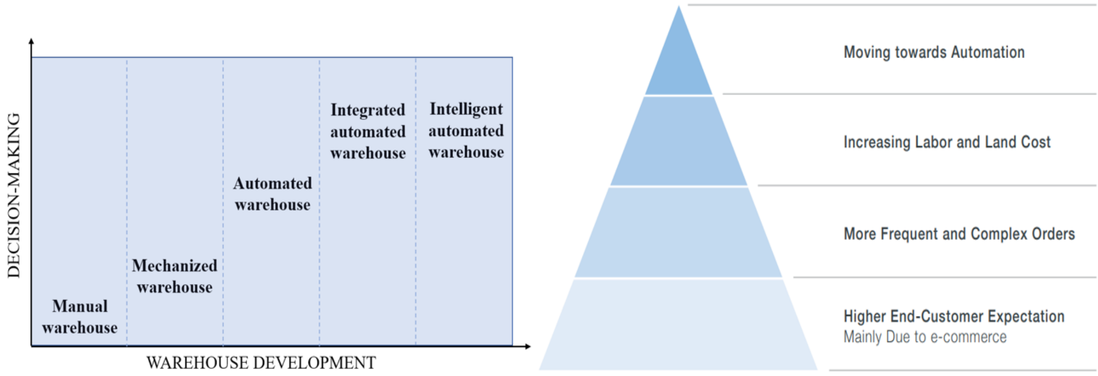


Figure 2. Warehouse development stages and trend [9]

2.2 Sustainable warehouse

The impact of warehouse operations on the environment has also received attention, and some studies have tried to incorporate factors other than economic indicators into the research on warehouse performance. He et al. (2017) developed low-carbon logistics, and a Performance Measurement System (PMS) has been proposed to evaluate low-carbon logistics considering economic, social, and environmental performance [10]. Simultaneously, due to the high energy consumption of warehouses, many organizations are exploring renewable energy, especially solar energy. However, some activities (such as modification of material handling devices) to reduce the environmental impact of warehouse operations will also lead to an increase in operating costs. Therefore, a balance between economic, social, and environmental factors must be maintained because one factor and another can influence the other [11].

2.3 Lean warehouse

The term "lean storage" was first proposed by Sharma and Shah (2016) [12]. It is an extension of lean production in the logistics field. Seeking perfection by reducing or eliminating waste is the core of lean concepts and the realization of lean principles and techniques. Lean warehouse focuses on organizing warehouse orders most effectively and minimizing non-value-added activities. Therefore, identifying the waste in the warehouse system is the key to understanding the lean warehouse. Various studies have investigated the impact of lean production on warehouse performance and defined relevant key performance indicators [5]. Tracking warehouse KPIs can monitor the efficiency of warehouse processes and take corrective measures to reduce waste in warehouse operations, thereby improving productivity, accuracy, customer satisfaction, and flexibility.

The performance research method used in studies can be grouped into three types: mathematical, analytical, and simulation models. The analytical model predicts the performance of the warehouse system by linking performance indicators with the main system parameters. The mathematical programming model refers to using equation sets and related mathematics to describe the problem and then use programming algorithms to analyze the results. Simulation experiments can be used to determine which combination of KPIs can produce the best system performance and how these factors interact with each other. Simulation software (such as FlexSim, Arena, Etc.) is usually used to simulate the warehouse system. By setting single or combined KPIs variables, the impact on the entire system can be analyzed.

3. METHODOLOGY

3.1 Research framework

Improving the performance of the supply chain is a continuous process that requires analyzing the performance measurement system and initiating a mechanism to achieve the KPIs target steps [13]. The key performance index is a numerical value obtained in actual operation, and valuable tools representing system performance can be obtained through monitoring systems such as sensors. "KPIs accomplishment" links planning and execution and constructs steps to achieve performance goals as daily tasks. Therefore, to analyze the warehouse system performance:

- The comprehensive indicators system is identified by the literature review.
- The simulation model of the automated warehouse is established to accomplish relevant key performance indicators.
- Evaluation of the simulation results are compared through Fuzzy Analytic Hierarchy Process.

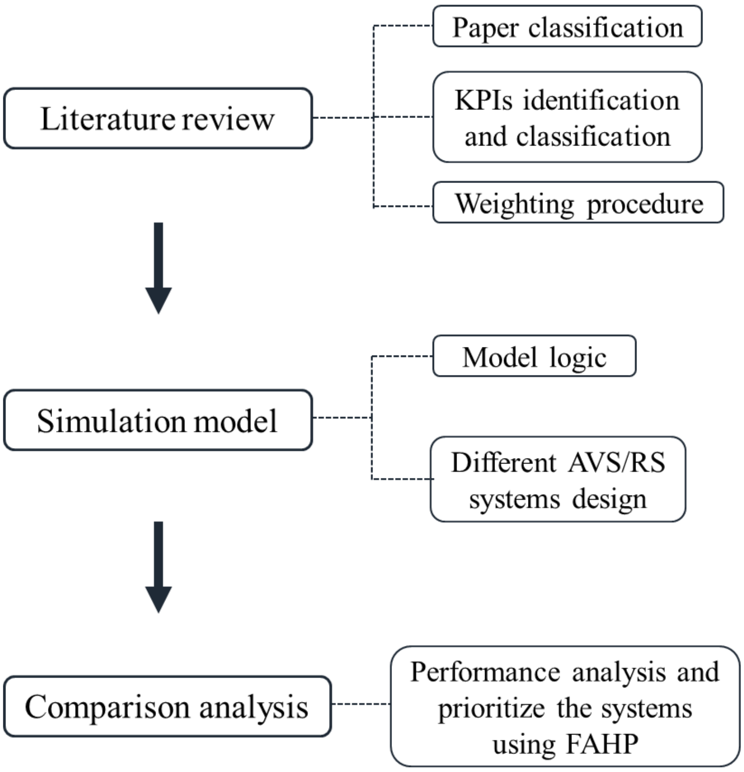


Figure 3. Research Framework

3.2 Paper selection procedure

The first step is to select the most comprehensive papers, we defined the following queries based on the Scopus database: TITLE (warehouse) and NOT TITLE-ABS-KEY ("data warehouse"). Searching for the exact keywords throughout the abstract will result in too many unfocused papers being extracted. Therefore, we limit the query to titles. The query extracted 4402 documents on November 27, 2020. After that, we finally selected 890 best papers by the sampling method according to two criteria: (a) high-quality paper selection and (b) random paper selection. To be considered high-quality paper, it must meet the following three At least one of the conditions:

- The article is published in the Q1 journal.
- The article was published in a journal with SJR (Scimago Journal & Country Rank) 0.5 or higher.
- The article has at least 50 citations.

We finally collected 890 papers through quality filtering and randomly selected 100 of them for content analysis and KPI extraction, Figure 5 shows the paper selection scheme.

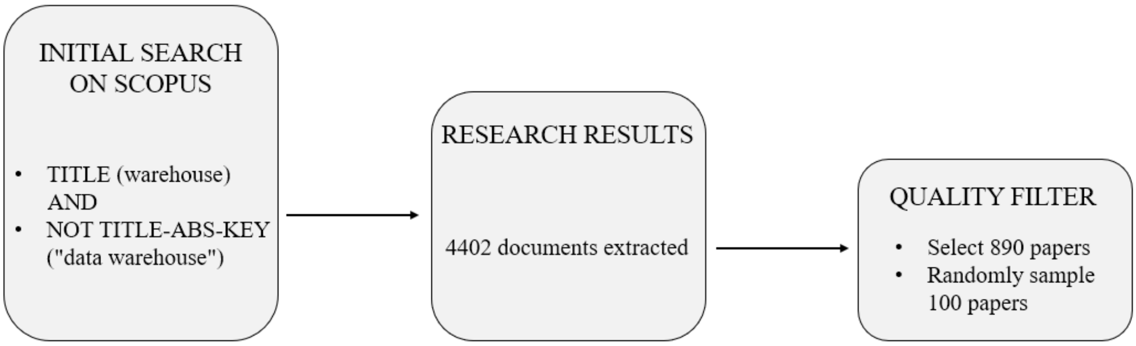


Figure 4. Paper selection scheme

3.3 Classification scheme and weight method

This section introduces a classification scheme to categorize the selected articles and KPIs. The purpose of categorizing articles is to analyze the relationship between planning issues, determine relevant performance indicators, evaluate the effect of combining planning issues, and identify how planning problems are related and which KPIs should be considered simultaneously to optimize warehouse performance. Simultaneously, to identify and explore the relationship between KPIs and clarify the boundaries of indicators in decision-making, we need a classification scheme.

3.31 Papers classification

After the total selection, we excluded 13 papers out of topic and 12 whose full text was not available, the number of papers to be analyzed are K (K=75).

The performance evaluation should be layered to different levels related to the hierarchical organization level to adjust the goals of different business functions, stimulate concurrent activities, and ensure the connection between the strategic vision and operations. Moreover, depending on the direction of the study, the key performance indicators covered in the article will also be different. To this end, we use the technology-organization-environment (TOE) framework as the theoretical basis to classify the factors determined through literature review and divide them into five categories: organization, operation, structure, resources, and technology [15]. The main factors in analyzed papers can be classified according to processes, resources, and structure. Products arriving at the warehouse go through multiple steps called processes or operations. Resources include all the means, equipment, and staff needed to operate the warehouse. Finally, the warehouse structure includes a set of physical and internal environmental factors considered when starting a new warehouse or updating to an old warehouse.

3.32 Weight method

A total of 59 unique indicators were extracted from the 75 papers examined. In the examined sample, the average number of indicators used to evaluate a warehouse is 5.2, while there are papers that consider only one indicator.

Since different articles consider different factors, the indicators involved will also be different, so we need a suitable weighting method to rank KPIs. To evaluate the impact of any indicator, we define three metrics: the weighted frequency, the relative frequency, and the global frequency.

In the paper classification step, the papers are classified into 3 clusters, which can respectively be represented by notation K1 (structure factor), K2 (operation factor) and K3 (resource factor). We extract the papers of each cluster individually and then calculate the relative frequency of each indicator. Consequently, each indicator gets a relative frequency in a category.

The relative frequency $f_{\theta i}^{r}$ of a generic indicator θ can be calculated as follows: $f_{\theta i}^{r} = \frac{N_\theta}{N_{Ki}}$. Where N_θ is the number of θ_th indicator, and N_{Ki} is the total number of all mentioned indicators in the i_th cluster. In order to take account of the paper clusters in which the indicator is present, we define a weighted frequency, which is the percentage of each cluster. The weighted frequency of a papers cluster is calculated as follow: $f_i^w = \frac{N_i}{K}$. K represents the total number of examined papers (75). Finally, a global frequency index G_θ is calculated as a combination between the previous frequencies. G_θ is obtained as follows: $G_\theta = \sum_i^3 f_i^w \times f_{\theta i}^{r}$.

3.33 KPIs classification and identification

Anthony's pyramid defines three different levels of granularity information: strategic, tactical, and operational (Gorry and Scott Morton, 1971) [14]. A structured decision-making method can be defined to satisfy many clearly defined performance standards. The strategy level is the highest, which refers to the aggregate information used in the long-term (for example, five years) decision-making process. The tactical level is the mid-level management level, which controls whether to achieve the higher-level goals effectively and efficiently. It usually has a decision-making process of about two years. The operational level is at the bottom of the pyramid and refers to very detailed information, usually used for frequent but not very sensitive decisions.

Traditional warehouse performance measurement standards include hard and soft indicators. Hard indicators can also be called direct indicators (such as time, cost, etc.). Some simple mathematical expressions can be adopted to calculate these indicators. Meanwhile, soft indicators are indirect indicators, such as managers' perceptions of customer satisfaction and loyalty. These indicators require more complex measurement tools (e.g., Regression analysis, fuzzy logic, Data Envelopment Analysis, etc.) [16]. Many studies classify all direct indicators according to four performance evaluation dimensions: time, quality, cost and flexibility. TBL is the most comprehensive method to integrate sustainability. Ignoring any aspect of TBL will cause managers to fail to integrate sustainability [10]. Torabizadeh (2020) proposed that the performance of a sustainable warehouse management system is based on the multi-dimensional concept of the triple bottom line (TBL) method， and constructed a framework (Figure.7) for identifying indicators of sustainable warehouse management system from three different perspectives of sustainability: economic, environmental, and social [17].

Variable	Definition
SW	Sustainable warehousing
EC	Economic
EN	Environmental
SO	Social
WOP	Warehouse operation performance
EPM	Economic performance measurement
RE	Resources
ECM	Emission waste & environmental commitment
LPDW	Labor practice & decent work
PRS	Product responsibility & society

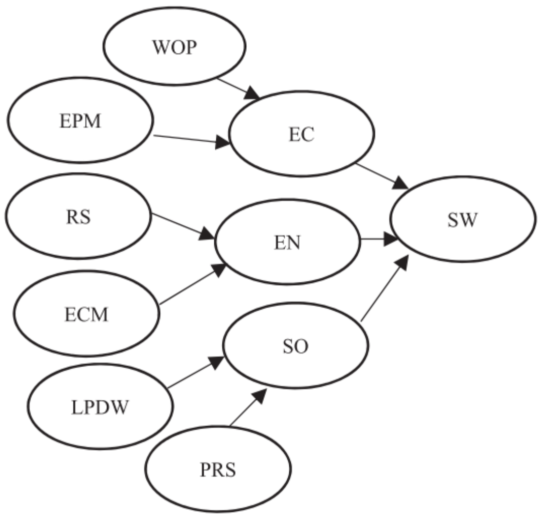


Figure 5. Concept model based on TBL of Sustainable warehouse system [17]

Based on the above theory, identifying the indicators from three perspectives: economic indicators, social indicators, and environmental indicators, which can help us better identify the key performance indicators of the warehouse system. We subdivide them into five separated subclusters:

- Generic performances.

- Time Related Performances.
- Cost Performances.
- ICT Performances.
- Warehouse Measure.

The definition of some KPIs can be found in the following tables, and others can be queried through the ISO 22400 standard. Table 2 lists the generic performance KPIs. Table 3 reports the time-related indicators of the sub-processes related to warehouse activities. In Table 4, the KPIs that express the cost of different warehouse operations are reported. Information Communication Technology (ICT) has become an essential tool for warehouse systems, especially automated warehouse systems, to realize the entire warehouse function. The relevant indicators for measuring ICT are reported in Table 5.

Environmental indicators which are reported in Table 6 can be divided into internal and external KPIs. Internal indicators measure the environment inside the warehouse, including temperature, humidity, atmospheric pressure, roof temperature, and pollutant concentration. These KPIs have a direct impact on the staff and products in the warehouse. In addition, the operation of the warehouse will have a positive or negative impact on the external environment, such as energy consumption, Energy Recovery, Pollutant Emission, Passive Consumption, Vehicle Autonomy.

Based on activities related to social sustainability, companies are responsible for considering their impact on their human resources and the human society in which they live. Moreover, the safety of operators is closely related to activity automation. Social KPIs are presented in Table 7.

In the process of literature review, we find the KPIs in each literature, mark them, and finally summarize the number of papers in which the specific KPIs are mentioned.

Generic Performance	Definition	Unit	NP	G_θ	
Capacity Flexibility	Capacity flexibility refers to the ability to adjust the total production capacity in any period with the option of utilizing contingent resources in addition to permanent resources.	$-$	30	9.22%	S
Receptivity	The acceptance index consists of the total number of load cells that can be stored in the warehouse, that is, its storage capacity	LU	18	5.24%	T
Travel Distance		m	16	5.17%	O
Throughput	Throughput refers to the number of units that are processed and moved through your building, either during stocking and inventory processes or when fulfilling orders.	LU/min	15	4.53%	T
Resource Utilization		%	11	3.28%	O
Vehicle Capacity		LU	7	2.21%	O
Area occupation	The area occupied by inventory items, or the area used to manage storage and retrieval activities: In the case of a fully manual warehouse system, this indicator represents the inventory area, while for an automated system, it measures the entire infrastructure.	%	4	1.33%	O
Machine Collision		$1/hour$	4	1.23%	O
Inventory Turnover		$days$	2	0.67%	S
Stock Balance	The stock balance is an index that represents the overall balance of stock volume inside the warehouse. It is calculated as a weighted sum of difference; the index grows with an increase of system ill-balance.	$-$	2	0.68%	T
Bottleneck Rate		LU/min	2	0.65%	T
Positioning Accuracy		%	2	0.61%	O
Critical WIP		LU	1	0.33%	T
Shelf Occupation	The shelf occupation is like selectivity, but it refers exclusively to the percentage of space occupied on the shelves and not in the free storage areas.	%	1	0.33%	O
Peak Utilization	The peak utilization is the system utilization when the number of items managed by the system is more than the critical value, i.e., they are enough to make the system work at its own bottleneck rate.	%	1	0.29%	T
Unprocessed Order		%	1	0.33%	T
Picking Accuracy		%	1	0.33%	O

Table 1. Generic performance

Time Related Performance	Definition	Unit	NP	G_θ	
Travel Time		min	23	7.48%	O
Lead Time	The service time is considered on a par with the lead time, i.e., the time that elapses from the customer's commercial request to the requested order's supply.	$days$	17	5.30%	T
Cycle Time		min	12	3.60%	T
Picking Time		min	12	3.59%	O
Storage Time		min	3	0.98%	O
task time	The task time is the time the system takes to execute an activity of storage or retrieval.	min	3	0.90%	O
inventory time	the inventory time, usually expressed in days, measures how much time the average inventory will last.	$days$	3	0.99%	T
Warehouse Av.		%	2	0.61%	T
Retrieval Time		min	2	0.65%	O
Make span	The time difference between the start and finish of a sequence of jobs or tasks.	$hours$	2	0.65%	T
Order Elaborate Time		min	2	0.65%	O
Packing Time		min	1	0.33%	T
Charging Platform Av.		%	1	0.29%	O

Table 2. Time Related Performance

Cost Performance	Definition	Unit	NP	G_θ	
Holding Cost	Refers to all costs to maintain the system activities.	$€/day$	19	5.91%	T
Storage Cost		$€/task$	12	3.61%	T
Inventory Cost		€	11	3.30%	S
Direct Labor Cost	Direct labor cost is the cost of activities directly involved in the production of the finished products.	€	8	2.27%	S
Maintenance Cost		$€/year$	4	1.33%	S
Space Cost	space's cost includes all the costs sustained for being able to maintain the area in which the infrastructure of the warehouse system is present.	$€/m^2$	4	1.36%	S
Indirect Labor Cost	Indirect labor cost is not direct labor cost but is the cost of operation that makes it possible.	€	3	0.63%	S

Table 3. Cost performance

ICT Performance	Unit	NP	G_θ	
Solver Iterations	-	3	0.94%	O
Algorithm Reliability	%	3	0.94%	T

Table 4. ICT performance

Environment	Definition	Unit	NP	G_θ	
Temperature		$°C$	10	3.00%	O
Energy Consumption		kWh	9	2.59%	T
Humidity		g/m^3	8	2.32%	O
Barometric Pressure		$mmHg$	4	1.30%	O
Energy Recovery	The percentage of energy that is generated by the system itself on the total energy consumed.	%	3	0.68%	T
Pollutant/Dirty Conc.		$\mu g/m^3$	2	0.34%	T
Pollutant Emission		$g/hour$	2	0.34%	S
Vehicle Autonomy		$hours$	1	0.29%	T
Roof Temperature		$°C$	1	0.34%	T

Table 5. Environmental KPIs

3.4 Simulation model design

3.41 Model logic

To simulate the automated warehouse systems, we chose to use Flexsim software, which has a very efficient simulation engine that runs both the simulation and the visual model view and can be accelerated the running speed by discrete event simulation (DES) methods. At the same time, Flexsim simulation has been widely used in production, manufacturing, especially logistics and other fields.

To simulate all these different elements in the warehouse, Different types of objects, which we add to the 3D model, have different purposes and functions within the simulation model. Some of the most common objects are:

- Flow items - Objects that move (or "flow") through the simulation model, usually from one station (typically a fixed resource) to another downstream station.
- Fixed resources - Objects that remain stationary in the 3D model and interact with flow items. Each fixed resource performs a specific function.

- Task executers - Objects that can move around in the 3D model and perform tasks such as transporting flow items, operating machines, etc.
- The List - a shared asset that can represent a list of tokens, flow items, task executers, task sequences, numbers, strings, etc. Using the Push To List and Pull From List activities, the contents of a list can be dynamically updated during a simulation run.
- Event - simulates the logic of these real-life events using simulation events on 3D objects. Each simulation event as a chunk of pre-programmed logic that tells the 3D object how to interact with flow items. The logic and behavior can be modified of when these events occur to make them more like the real business system.

The task logic of 3D simulation models of FLEXSIM is that: In the first step, flow items get introduced to the model using a source object, which creates flow items and sends them to the next downstream fixed resource(s). Secondly, flow items begin to interact with the 3D objects in the model and subsequently move from one fixed resource to the next downstream fixed resource by interacting with task executers.

Process flow is an inserted powerful tool, which is also used to build the model logic. retrieval requests can be simulated by using list in process flow (figure 6). By listening to the event, the items would be push to storage list when entering the racks, and the list records the item relevant properties. When the retrieval orders generated, the items are located and pulled from the storage list, and then pull to list. The order list is used to define the task sequence and query.

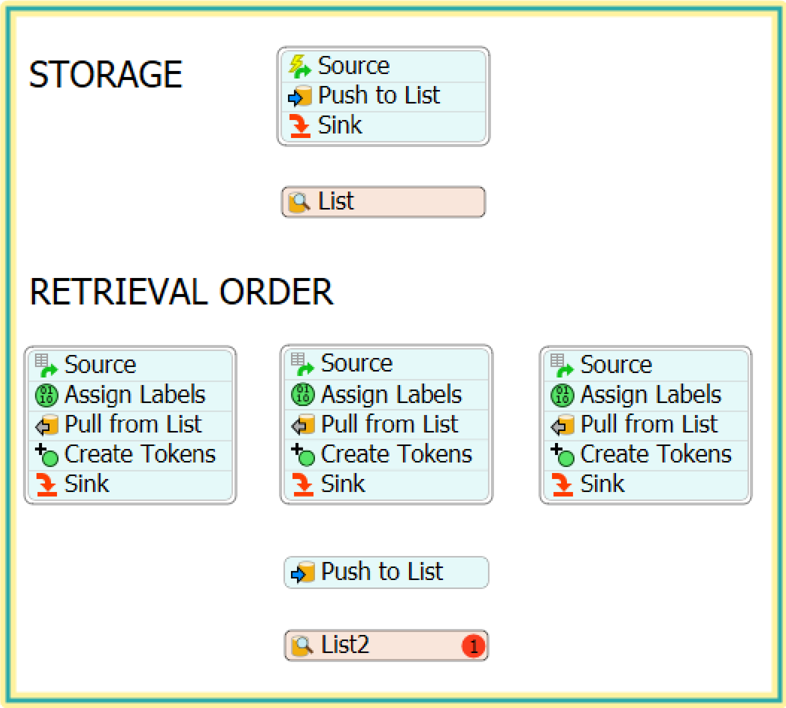


Figure 6. Process flow of retrieval requests

Automated warehouses can be divided into five main sections according to their function, i.e., the handling area, the inbound area, the storage area, and the outbound area. The function of the handling area is to carry out the acceptance, sorting, packaging, labeling, verification and other work of the inbound goods, and to record the variety, specification, quantity, packaging status, and restocking time of the inbound goods. The function of the inbound area is to transport the goods from the handling area to the racks, waiting for warehousing. The main function of the storage area is to store goods. The outbound area mainly transports the corresponding goods from the goods storage area according to the outbound instructions. Therefore, according to its functional division, the layout of the automated warehouse is shown in the following figure.

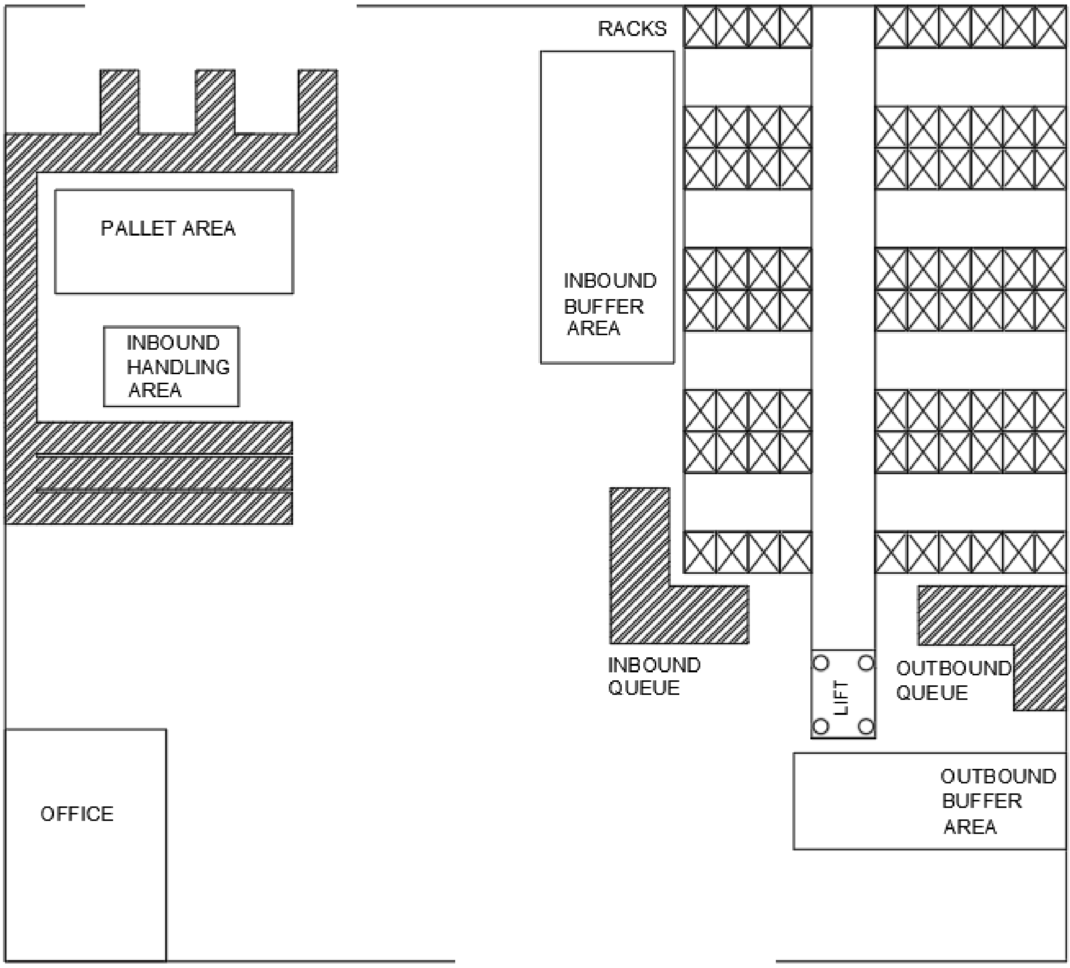


Figure 7. Layout of automated warehouse according to functional division

In the simulation of two warehouse systems, the storage requests follow the real behavior of the warehouse and are set as follows:

• storage of RM-Type1, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 120 seconds. By packaging two RM-Type1s, FP-Type1 is generated.

• storage of RM-Type2, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 30 seconds. By packaging eight RM-Type1s, FP-Type2 is generated.

- storage of RM-Type3, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 60 seconds. By packaging four RM-Type1s, FP-Type3 is generated.

When three different types of goods arrive, they are packed in the handling area, then placed on the pallet and then sent to the storage processing area. Store operations are performed using a randomly stored policy.

The retrieval requests follow the real behavior of the warehouse and are set as follows:

- retrieval of FP-Type1, 10 ULs, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 50 minutes.
- retrieval of FP-Type2, 2 ULs, inter-arrival time between two consecutive request follows a normal distribution with average time equal to 15 minutes.
- retrieval of FP-Type3, 5 ULs, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 30 minutes.

3.42 Stacker crane based AVS/RS system

In stacker crane-based storage and retrieval system we modeled, the stacker can travel horizontally along the aisles, and the crane move vertically along the beam simultaneously. When moving to a storage or retrieval location, the stackers load or unload the pallets by using extender. We design two stacker crane system models, represented by notation S1 and S2 respectively. And two models adopt the same size of storage location, each has 1.0m length and 1.3m width.

The rack configuration of S1 consists of 8 racks and 4 aisles (figure 8). Each aisle has an AS/RS vehicle, and service two adjacent racks. Each rack is made up of 10 bays and 7 levels, only one load unit can be stored in a cell. Each storage location has 1.0m length and 1.3m width. In total the capacity of the system is 560 storage positions.

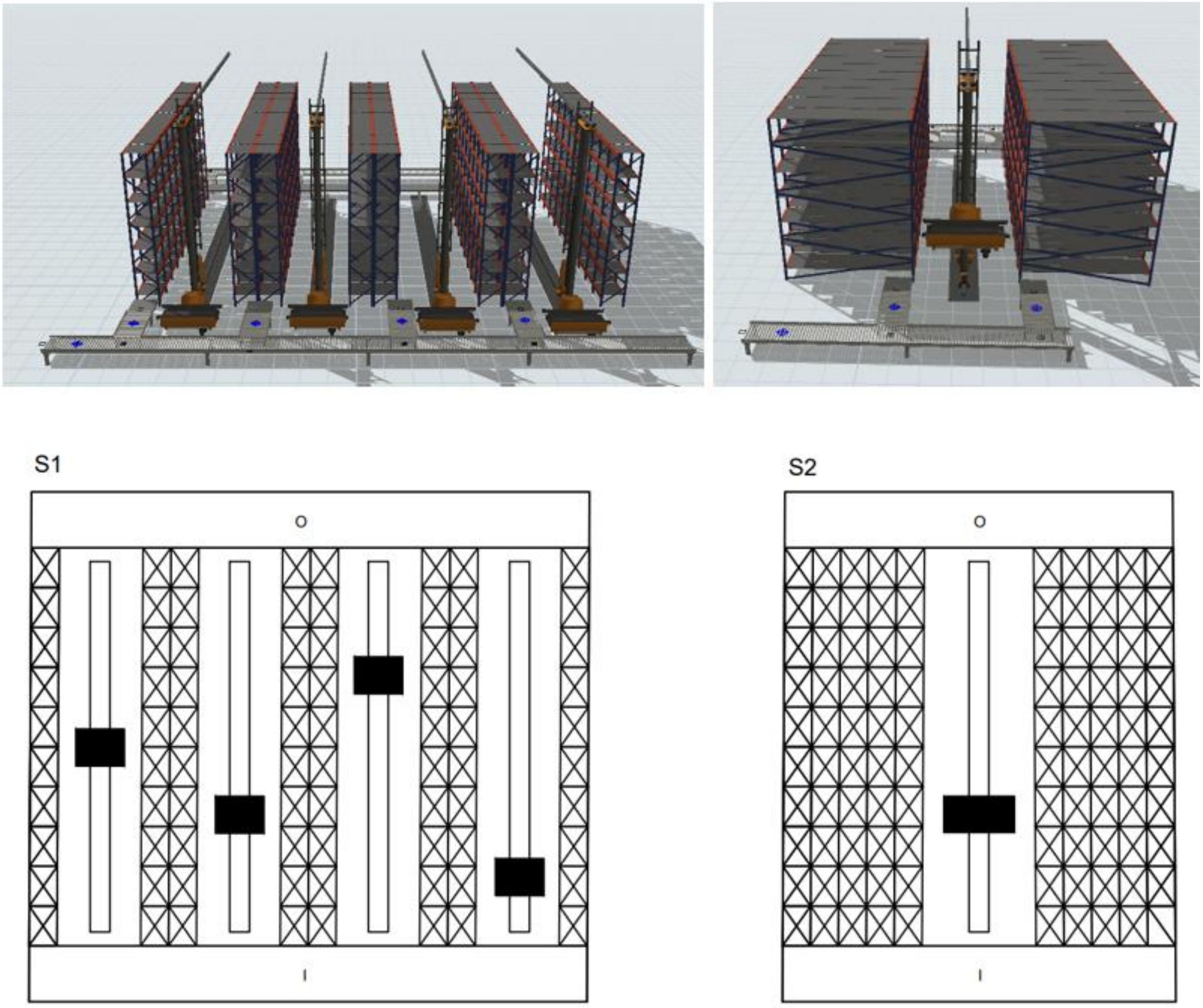


Figure 8. The rack configuration of Stacker vane based AS/RS systems

The rack configuration of S2 consists of 2 racks and 1 aisle (figure 8). The system has one AS/RS vehicle, and service two adjacent racks. Each rack is made up of 10 bays and 7 levels, 5 load units can be stored in one channel. The capacity of S2 is 700 storage positions in total.

The storage and retrieval requests policy of S1 adopt random policy, and FILO policy is adopted in S2. The two models adopt same vehicles, and the following properties of vehicle in two simulation models are considered (Table 6).

	Vehicles (S1)	Vehicles (S2)
Vehicle Capacity	1 LU	1 LU
Vehicle Max. Speed	2 m/s	2 m/s
Acceleration	1 m/s	1 m/s
Deceleration	1 m/s	1 m/s
Lift speed	1 m/s	1 m/s
Extension speed	1 m/s	0.5 m/s
Load time	10 s	10 s
Unload time	10 s	10 s

Table 6. Vehicle properties in Stacker crane system

3.43 Shuttle based AVS/RS system

In this section, we adopt a novel shuttle-based storage and retrieval system (MODEL2). In this system, autonomous vehicles with four wheels (i.e., AGVs) can drive in and out of storage racks for storage (i.e., transporting pallets with items from the inbound area to racks) and retrieval operations (i.e., loading items pallets are transported from the shelf to the order picking location). During the whole process, the AGV can travel horizontally on the aisle floor and move vertically into the horizontal aisle with the help of elevators. The configuration of this system is shown as figure 9.

The rack system consists of 7 tiers, each tier is made of 1 main channel and 4 sub channels. The heigh of each tier is 1m, the width of each channel is 1.3m, and its length is 1m. And 10 storage locations are available respectively on the left and right of each sub channel, so 80 storage locations in total in each tier, and the capacity of the system is 560 storage positions. Each storage location has 1.0m length and 1.3m width.

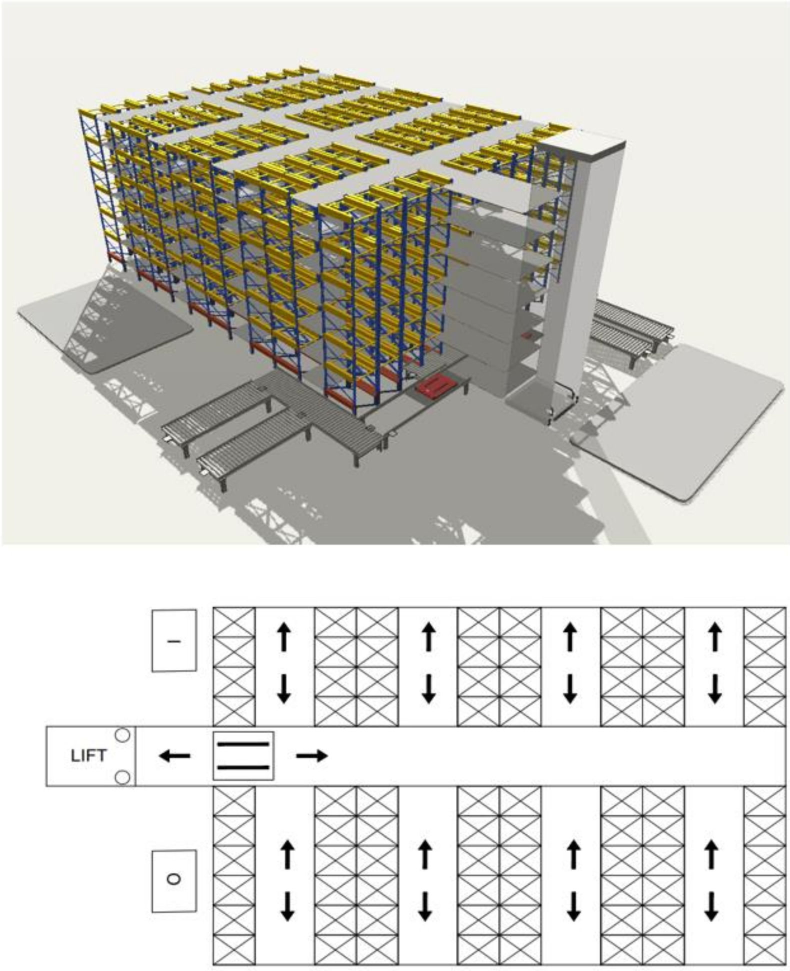


Figure 9. The rack configuration of Shuttle based AVS/RS systems

In the proposed system, we employ two AGVs and one elevator. To avoid collision between AGVs, we adopt a collision algorithm, that is, when the AGV travels to the main aisle or elevator, the area will be locked, only one AGV is allowed to be in the allocated area.

The process of the entire warehouse is shown in the following flowchart. When a storage request is received, the system calls the idle AGV and assigns the task. The AGV moves from the parking spot to the pallet loaded with items in the inbound queue, and then judges whether it needs to take the elevator and the current state of the elevator. If the elevator is idle, travel to the elevator entrance and reach the target floor, then leave the elevator to enter the aisle, travel to the corresponding storage rack for unloading tasks, and finally return to the parking spot. At the same time, after the system receives the retrieval request, it calls the idle AGV and assigns tasks to it, identifies the rack location of the task, and the status of the elevator. If the elevator is idle, take the elevator to the target location for the loading task, otherwise the AGV will wait at the elevator entrance. After loading, go to the outbound queue to unload pallets.

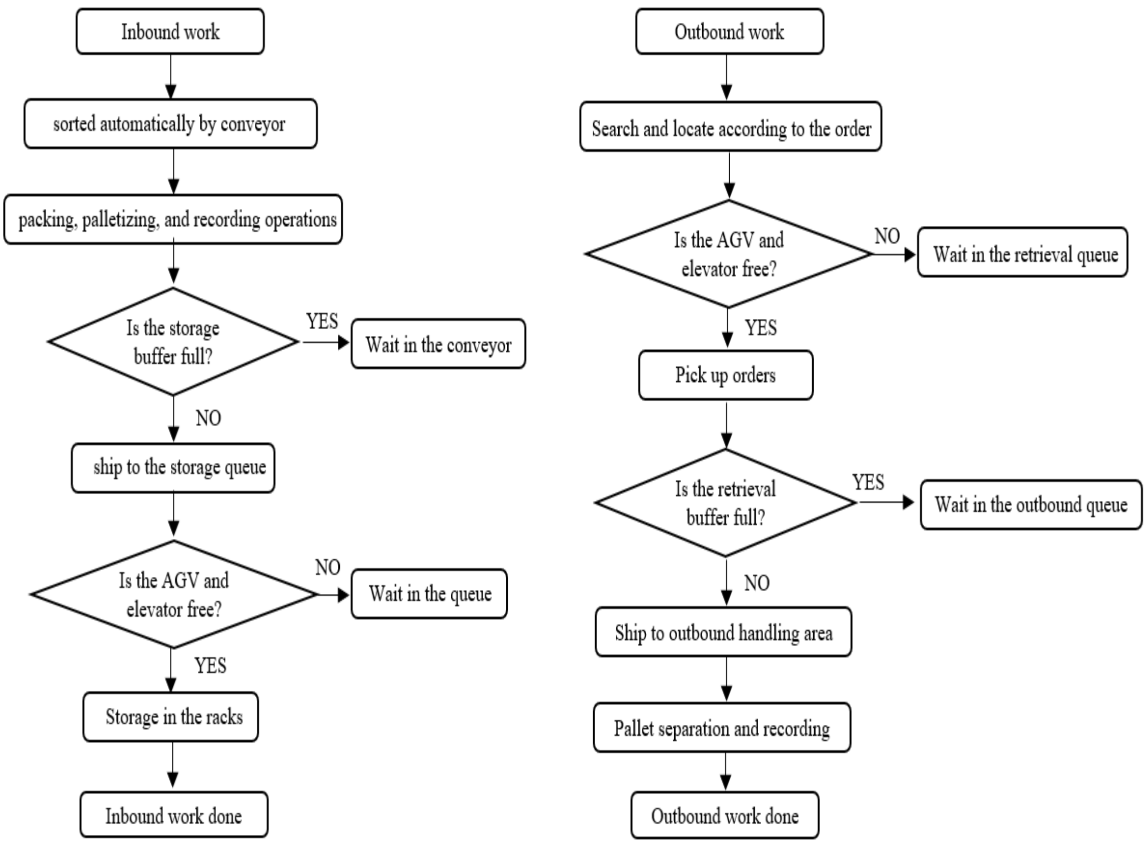


Figure 10. Inbound and Outbound workflows

The AGV and elevator properties are considered as following table.

	AGVs
Vehicle Capacity	1 LU
Vehicle Max. Speed	4 m/s
Acceleration	2 m/s
Deceleration	2 m/s
Lift speed	2 m/s
Load time	10 s
Unload time	10 s

Table 7. Vehicle properties in Shuttle based system

3.5 Fuzzy AHP

The evaluation and selection of best warehouse performance can be analyzed as a multiple-criteria decision making problem (MCDM), considering qualitative and quantitative multiple factors. The analytic hierarchy process refers to a decision-making method that decomposes the elements that are always related to decision-making into goals, criteria, plans, etc., and performs qualitative and quantitative analysis on this basis. Developed at Wharton in 1980, the AHP is one of the most potent and flexible weighted scoring decision-making processes, designed to help people set priorities and make the best decisions. The basic principle of the analytic hierarchy process is to decompose the problem into different constituent factors according to the nature of the problem and the general goal to be achieved. Then, the factors are aggregated and combined at different levels according to the correlation and influence of the factors and the affiliation relationship between the factors to form a multi-level analysis structure model. Thus, the problem ultimately comes down to determining the relative importance weight of the lowest level (the scheme and measures for decision-making) relative to the highest level (the general goal) or the arrangement of the relative advantages and disadvantages. AHP has been widely used to solve multi-standard decision-making problems in the logistics chain [19].

The biggest problem with the analytic hierarchy process is that when there are many evaluation indicators at a certain level (such as more than four), it is challenging to guarantee thinking consistency. In this case, the Fuzzy Analytic Hierarchy Process (FAHP), which combines the advantages of the fuzzy method and the analytic hierarchy process, will solve this problem well.

Fuzzy Logic was developed on the mathematical basis of the Fuzzy Collection theory founded by Professor L.A. Zadeh in 1965 [18], argues that all-natural languages are vague, such as "red" and "old" concepts, which have no clear connotation and extension and are therefore ambiguous and ambiguous.

The basic ideas and steps of the fuzzy analytic hierarchy process are basically the same as those of AHP, but there are still two differences:

- The established judgment matrix is different: in AHP, the judgment consensus matrix is established by comparing the elements pairwise; in FAHP, the fuzzy consensus judgment matrix is established by comparing the elements pairwise.
- The method of calculating the relative importance of each element in the matrix is different.

The Fuzzy Analytic Hierarchy Process (FAHP) improves the existing problems of the traditional Analytic Hierarchy Process and improves the reliability of decision-making. The approach of fuzzy AHP to calculate the weight of the performance index is described as follows [20]:

a) Develop a hierarchical structure for prioritizing the performance measures.

   The highest level of the hierarchical structure we have built is warehouse performance, which is the purpose of decision-making. At the same time, we take the key performance indicators implemented in the simulation system as the standard layer to evaluate the performance of the system. The warehouse systems built in the simulation model serve as planning layers, so that we can compare and analyze the performance of warehouses by comparing the performance of each performance indicator, and finally select the optimal warehouse automation solution.

b) The establishment of fuzzy complementary judgment matrix.

In the fuzzy analytic hierarchy process, when making pairwise comparison judgments between factors, a quantitative expression of the importance of one factor than another factor is used, and the resulting fuzzy judgment matrix A has the following properties:

$$A = \left(a_{ij}\right) n \times n$$

$$a_{ii} = 0.5, i = 1, 2, \quad \cdots, \quad n;$$

$$a_{ij} + a_{ji} = 1, i, j = 1, 2, \quad \cdots, \quad n;$$

To quantitatively describe the relative importance of any two factors concerning a criterion, the scale method of 0.1～0.9, as shown in Table 7, is usually used to give a quantitative scale.

Intensity of Importance	Definition	Explanation
0.5	Equal importance	Two elements contribute equally to the objective
0.6	Moderate importance	Experience and judgment slightly favor one element over another
0.7	Strong importance	Experience and judgment strongly favor one element over another
0.8	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
0.9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
0.1, 0.2, 0.3, 0.4	Inverse comparison	If the element a_i is compared with the element a_j to obtain the judgment a_{ij}, then

	the element a_j is compared with the element a_i and the judgment obtained is a_{ji}.

Table 8. Quantitative scale of fuzzy complementary judgment matrix

c) Calculation of the Weight of Fuzzy Complementary Judgment Matrix.

A fuzzy consistent matrix (r_{ij}) is constructed from a fuzzy complementary matrix. The formula for solving the weights (W_i) of the fuzzy complementary judgment matrix is presented as follows:

$$a_i = \sum_{j=1}^{n} a_{ij} \quad (i = 1,2,3,\dots,n)$$

$$r_{ij} = \frac{a_i - a_j}{2(n-1)} + 0.5$$

$$W_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{an}\sum_{k=1}^{n} r_{ik}\,, WHERE\ a = \frac{n-1}{2}$$

d) Check the consistency of fuzzy complementary judgment matrix.

In this step, we need to perform a consistency test to determine whether the weight calculated in the previous step is reasonable. When the offset consistency is too large, it is unreliable to use the calculation result of the weight vector as the basis for decision-making. We use the compatibility principle of the fuzzy judgment matrix to test the consistency, and the method is presented as follows:

1） For fuzzy judgment matrices $A = \left(a_{ij}\right)n \times n$ and $B = \left(b_{ij}\right)n \times n$, we can define a compatibility index $I(A,B)$.

$$I(A,B) = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left|a_{ij} + b_{ij} - 1\right|$$

2） The weight vector of the fuzzy judgment matrix A is $W = (W_1, W_2, \cdots, W_n)$, and satisfy $\sum_{i=1}^{n} W_i = 1$ and $W_i \geq 0 (i = 1,2, \cdots, n)$. The characteristic matrix of judgment matrix A can be constructed:

$$\begin{cases} W^* = (W_{ij}) n \times n \\ W_{ij} = \dfrac{W_i + W_j}{W_i}, (\forall i, j = 1,2,3, \cdots, n) \end{cases}$$

3） We introduce an index 'a', which indicates the consistency requirements of the decision-maker for the fuzzy adjudgment matrix. The smaller the value of a the higher the requirement for the consistency of the fuzzy judgment matrix. Generally, $a = 0.5$ [20]. When the compatibility index meets the following requirements, the judgment matrix meets the consistency requirements.

$$I(A, B) \leq a$$

e) Calculate the global priority weight of each element and rank the systems.

4. Result of the research

4.1 Papers classification results analysis

According to the method proposed above, we summarize the classification results of articles. Table 1 lists the classification standards and results we got, which can be divided into the following three categories:

- Warehouse structure factors: including warehouse location, safety, and environmental factors, typical of the strategic level. Warehouse size, configuration(layout), typical of the tactical levels.
- Warehouse operational factors: including storage, inventory, picking, sorting, and assignment issues between them, typical of the operational level.

- Resource factors: including labor, energy, typical of operational level. About the level of automation, specifically related to storage robots, AI, autonomous navigation, online monitoring and control, and integrated systems, typical of the tactical and operational levels.

Area of focus	**Sub-factors**	**Number of papers**	**NP in total**	f_i^w
Warehouse structure factor	warehouse location	9	23	31%
	warehouse size	1		
	warehouse configuration (layout, SKU)	9		
	safety	2		
	environment (temperature, humidity, pressure)	2		
Warehouse operation factor	storage	3	44	59%
	picking	17		
	picking and sorting	1		
	packing and storage assignment	1		
	picking and packing assignment	2		
	Inventory model	20		
Resource factor	warehouse robots, autonomous navigation, AGV, AI, online supervisory control, integrated warehouse	6	8	10%
	labor	2		

Table 9. Papers classification result

In summary, operation factor is the most concerned aspect of the literature evaluating the performance of warehouse systems, followed by the structural aspect, and the resource aspect last.

Warehouse structure factors are mainly concerned with warehouse location and configuration. The warehouse location problem is a decision that needs to be considered before building a new warehouse, so we classify it as a structural factor. Warehouse location is a crucial issue that determines how many warehouses to operate and how to provide services to customers [21]. The papers which focus on the warehouse configuration factor mainly study the influence of layout and storage units (such as shelves, SKU, etc.) on the overall performance. Picking and inventory models are two of the most concerned aspects of the warehouse process. The most concerned KPIs are reported respectively in table.

Factors	Most concerned KPIs
Picking	Travel.Time (13) Travel.Distance (8) Picking.Time (8) Throughput (7) Capacity.Flexibility (6) Vehicle.Capacity (4) Cycle.Time (4) Lead.Time(4)
Inventory model	Holding.Cost (14) Capacity.Flexibility (9) Receptivity (7) Storage.Cost(6) Lead.Time (5) Cycle.Time (5) Inventory.Cost (4)

Table 10. Most concerned KPIs in picking and inventory factors

4.2 Simulation results analysis

Each system was simulated for a total of 48h, and related KPIs was monitoring and recording by FLEXSIM statistics collectors, which collect the data from objects and track variables automatically in each time clock. By analyzing the collected data, the inbuilt dashboards can more intuitively represent the collected data in a graphical manner.

4.21 Related KPIs of Generic performances

Receptivity refers to the storage capacity, which is the invariant number determined during model building. Area occupation is compared by the area used to manage storage and retrieval activities, which refers to the footprint of the rack system. Travel distance of stacker crane systems consists of horizontal travel distances along aisles, vertical travel distances along beams and the displacement of the extender. Travel distance of shuttle system is the total travel of two automated guided vehicles and vertical displacement of the elevator. The following table lists the travel distance for various systems. Considering the total number of storage and retrieval tasks, we calculate average travel distance for each task ($T_{average}$) by the following equation:

$$T_{average} = \frac{Total\ travel\ distance}{Total\ number\ of\ tasks}$$

	Object	Distance	Total Travel Distance (m)	Storage task	Retrieval task	Average travel distance (m)
S1	ASRSvehicle1	16846.35	71253.97	1880	1446	21.42
	ASRSvehicle2	17822.85				
	ASRSvehicle3	17577.75				
	ASRSvehicle4	19007.02				
S2	ASRSvehicle1	56320.72	56320.72	1674	1010	20.98
S3	StorageAGV	79240.6	171023.25	1893	1535	49.89
	RetrievalAGV	64201.32				
	Elevator	27581.33				

Table 11. Travel distance of systems

Throughput performance can be identified by storage throughput and retrieval throughput. It is noticed that the storage throughput variant with time (Figure 12) in three systems is nearly steady, and S2 and S3 feature higher throughput than S1. However, the retrieval throughput is totally dissimilar. Comparison throughput is represented by load units per hour (Figure 11).

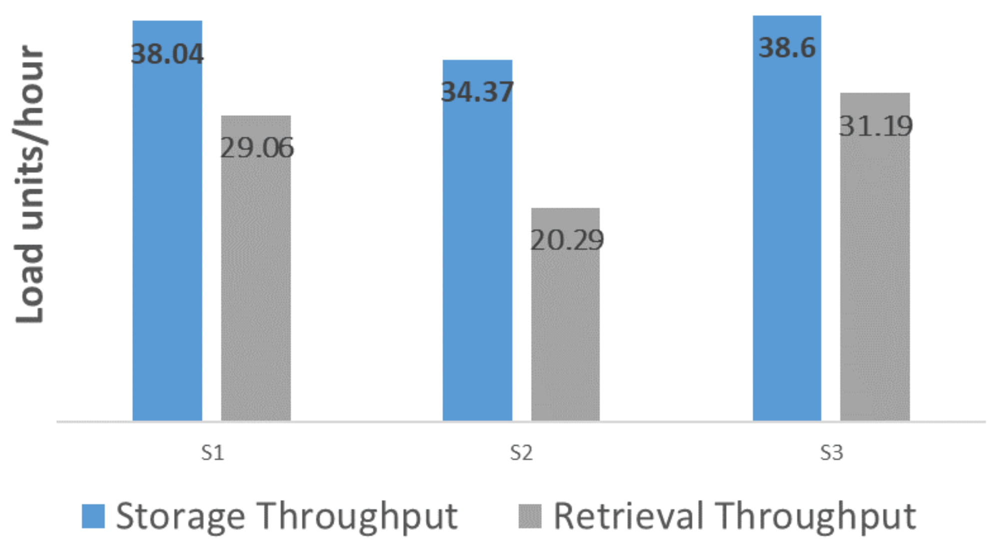


Figure 11. Throughput performance of systems

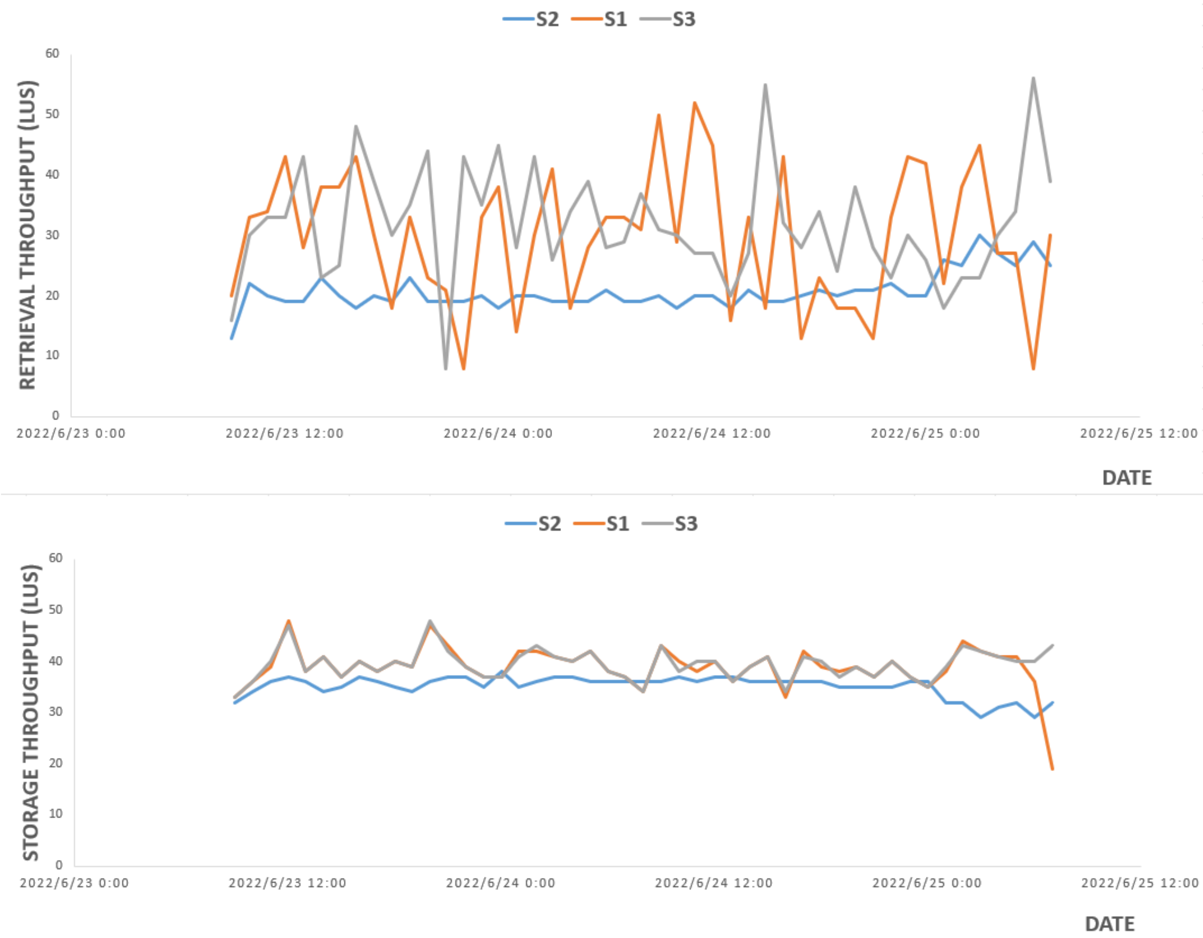


Figure 12. Throughput performance time plot

Shelf occupation is obtained by the percentage of space occupied in the storage area. It is related to the frequency of storage and retrieval requests, when the frequency of the requests is fixed, the smaller the curvature of the change in occupancy, the more performance is indicated. Obviously, the shelf occupation reaches the lowest level at the end of simulation time.

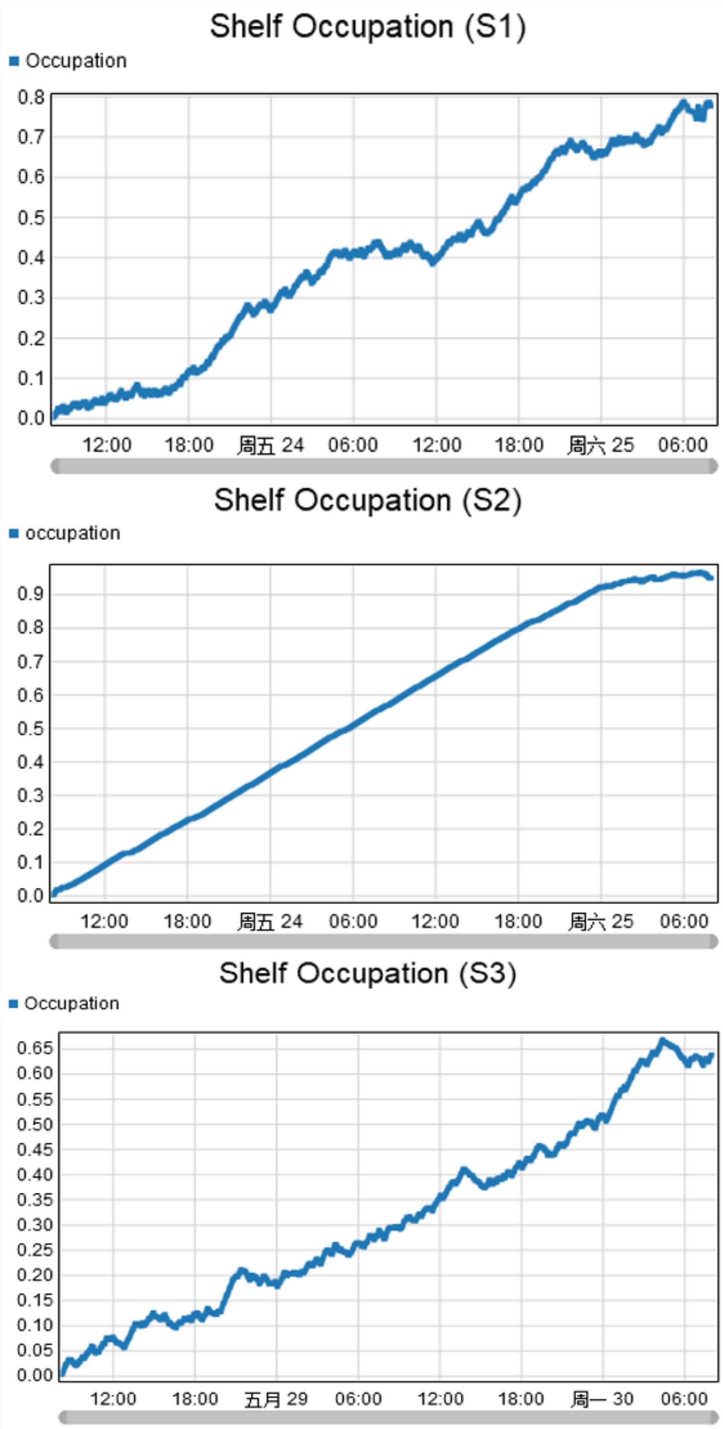


Figure 13. Shelf Occupation time plot

The vehicle distinct states which include busy and idle are monitored when models running, and busy states contain travel empty, travel loaded, loading and unloading. The state of vehicles in three models are reported in the following figure. Resource utilization(B6) is represented by the vehicle utilization in the models. The Model S2 has the highest utilization rate, while S1 is the opposite. Elevators are usually bottlenecks in the shuttle-based systems, however in such a shuttle-based system we modeled, AGVs feature bottlenecks more easily.

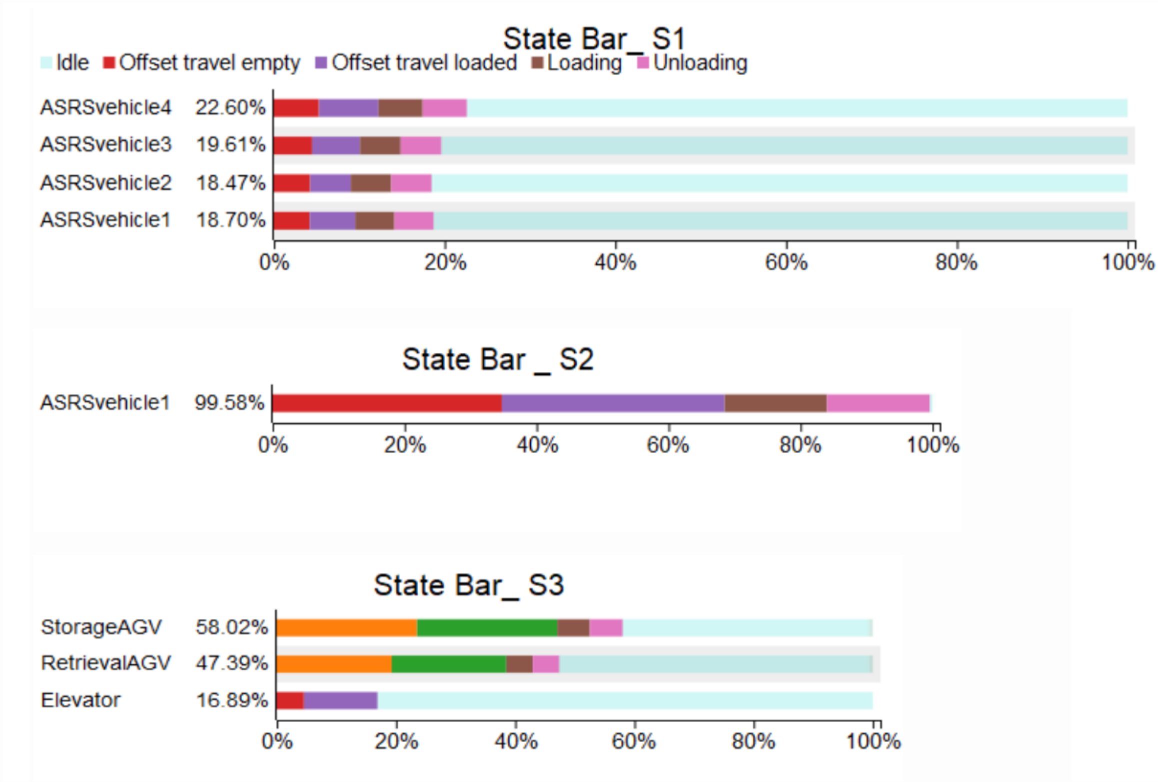


Figure 14. Vehicle state bar

4.22 Related KPIs of Time performance

A graphical definition of the main time indicators is represented in Figure.

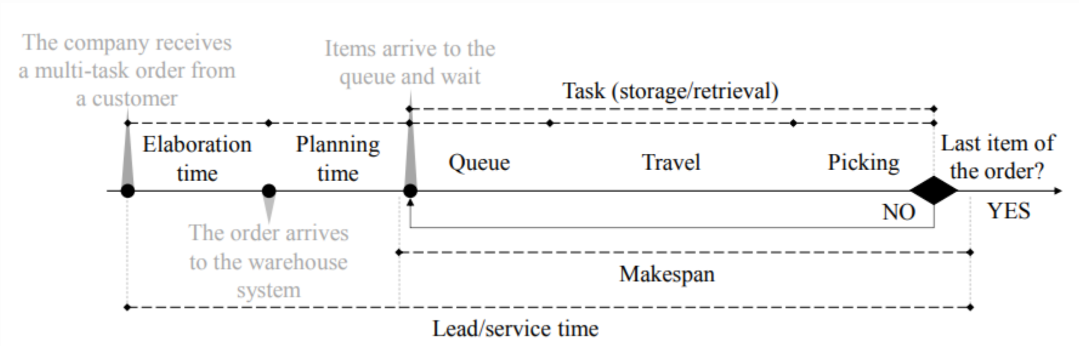


Figure 15. Graphical definition of Time related indicators

Picking time refers to the time difference between vehicle on load and vehicle on unload. It is noticed that the average picking time of Model S3 varied in a wide range when dealing with various tasks, that is due to the larger difference of the travel distance (Figure 16).

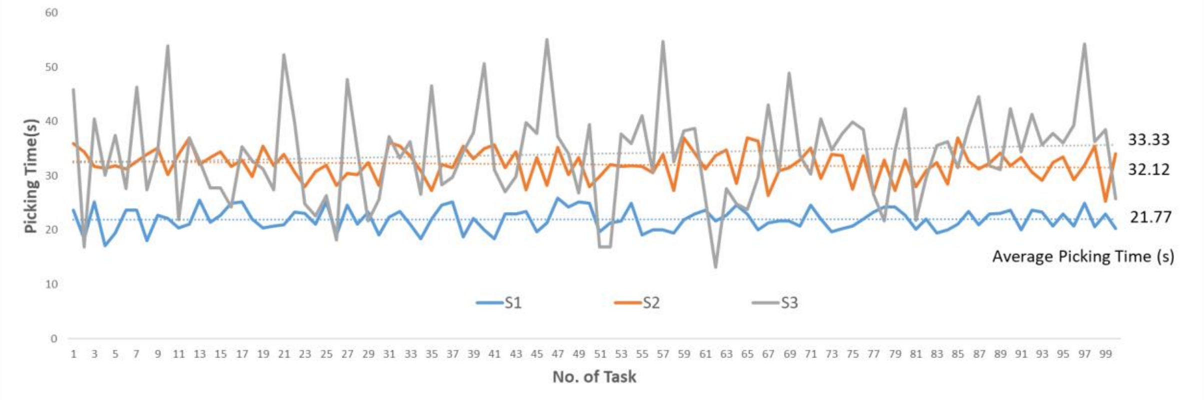


Figure 16. Picking time vs No. of task

Storage time is the time interval between items arrival to the queue and storage in the rack, which sums up the queue stay time (Figure 17), travel time, load and unload time. When orders received, waiting for being picked up and then transfer to the outbound queue, therefore the retrieval time is obtained by the sum of waiting time in order queue, picking time, load and unload time.

Inbound Queue Waiting Time _ S1

AvgStaytime	MinStaytime	MaxStaytime
27.00	13.00	5132.00

Inbound Queue Waiting Time _ S2

AvgStaytime	MinStaytime	MaxStaytime
185.00	17.00	1064.00

Inbound Queue Waiting Time _ S3

AvgStaytime	MinStaytime	MaxStaytime
24.68	5.00	115.46

Outbound Queue Waiting Time _ S1

Min	Max	Avg
0.00	1063.31	204.03

Outbound Queue Waiting Time _ S2

Min	Max	Avg
0.00	53638.64	32801.60

Outbound Queue Waiting Time _ S3

Min	Max	Avg
0.00	1235.50	161.29

Figure 17. Queue waiting time statistics

	S1	S2	S3
Storage time (s)	68.77	237.12	68.01
Retrieval time (s)	245.8	32853.76	204.62

Table 12. Storage and Retrieval time of systems

Inventory time highly depends on the inventory model and throughput of the system.

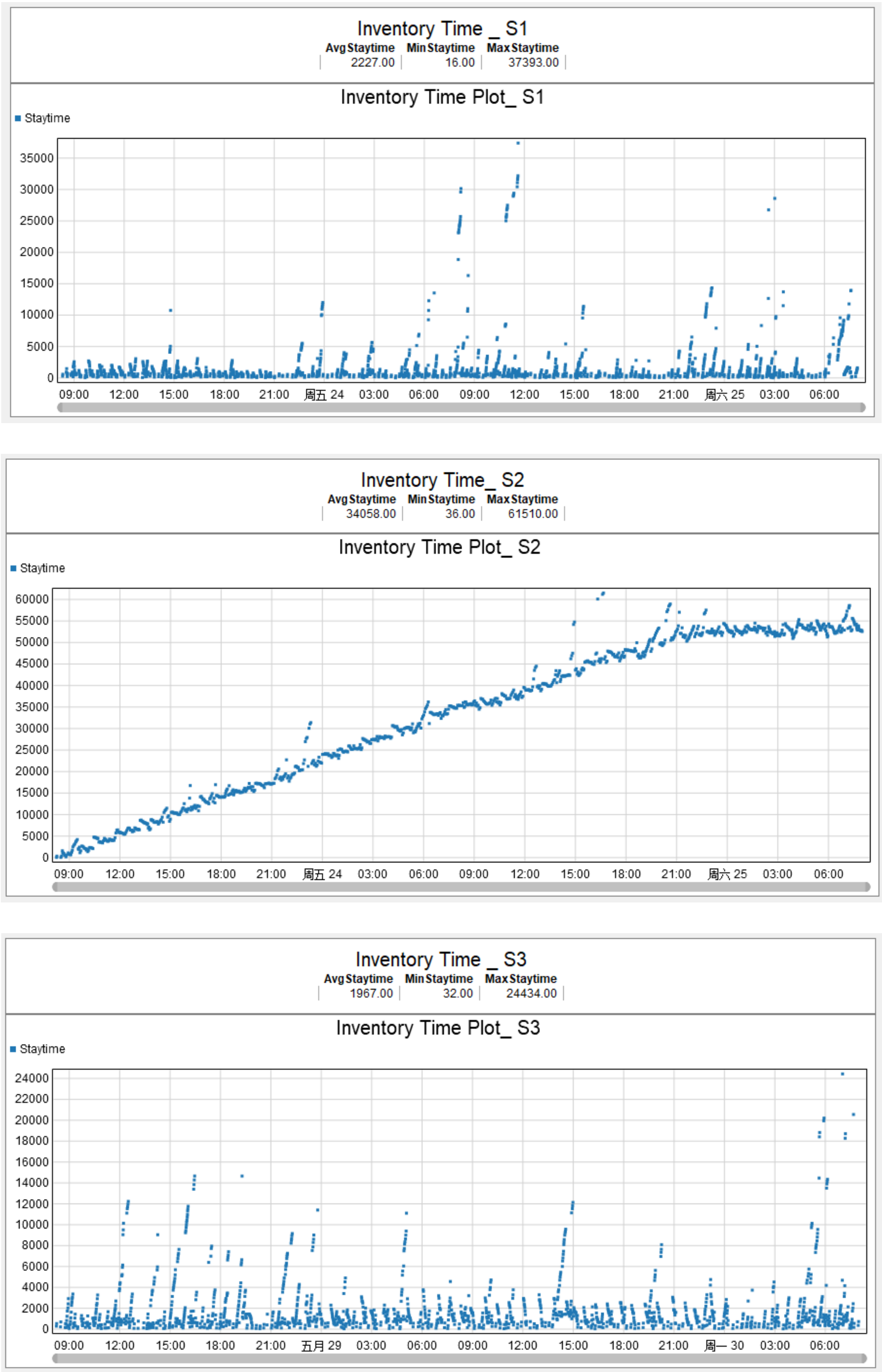


Figure 18. Inventory Time Plots

Cycle time represents the frequency of order shipment. The lower the cycle time, the faster the fulfillment operation is. Cycle time is calculated as the duration between two orders being shipped.

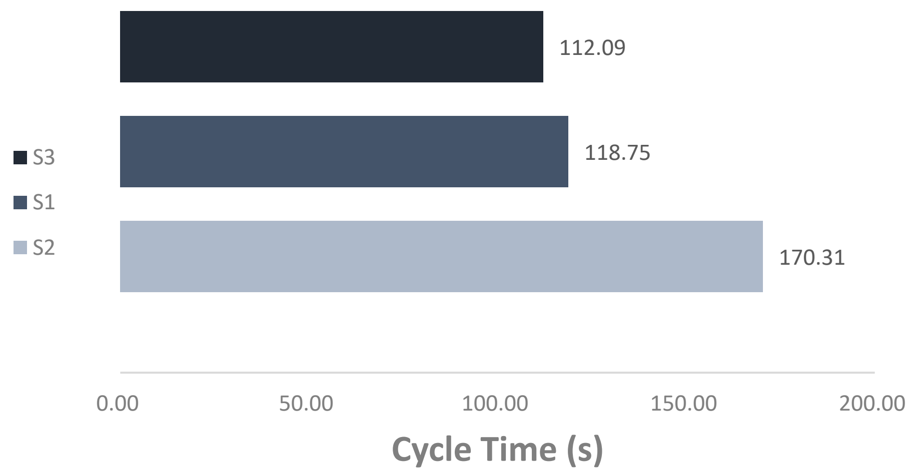
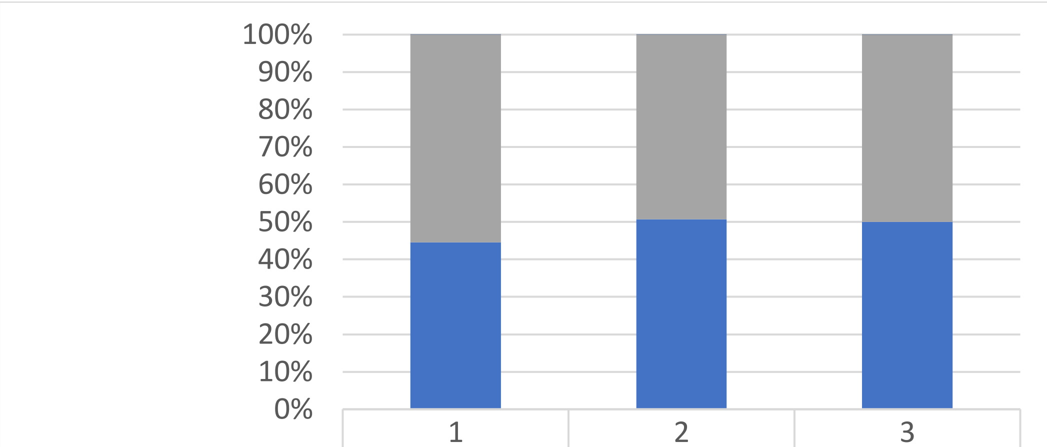


Figure 19. Cycle Time performance

The Figure demonstrates the percentage of travel empty and loaded, and then average travel time for each task is obtained.



	1	2	3
Average	21.24	44.10	43.14
Travel loaded Time	39155.21	58364.18	73864.75
Travel Empty Time	31494.94	60013.16	74010.95

Figure 20. Travel Time Performance

4.3 Compare and Evaluation

In the simulation model, we mainly implement KPIs in generic performances and time related performances. A hierarchy structure is built on the basic of these KPIs to compare three different automation systems.

Goal level	Criteria level A			Plan level B	
Automated Warehouse Systems Performance	Generic Performances	*A1*	Receptivity	Stacker Crane Systems	*S1*
		A2	Area Occupation		*S2*
		A3	Travel Distance		
		A4	Throughput		
		A5	Shelf Occupation		
		A6	Resource Utilization		
	Time Related Performances	*A7*	Picking Time	Shuttle Based AVS/RS Systems	*S3*
		A8	Storage Time		
		A9	Retrieval Time		
		A10	Inventory Time		
		A11	Cycle Time		
		A12	Travel Time		

Figure 21. Hierarchy structure of weighting system

Fuzzy complementary judgment matrix of criteria level is constructed by using the weighted frequency. Basically, the higher frequency value, the more important of relevant KPI. A triangular fuzzy number (TFN) is defined as (a, b, c) which represents lower bound, middle value and upper bound. The differences between weighted frequency of indicators are used to determine the elements of fuzzy matrix (Table 13). The result is listed in the Table 14.

ELEMENTS	Definition	Corresponding TFN
0.5	Equal importance	(0,0,0)
0.6	Moderate importance	(0,0.1,0.2)
0.7	Strong importance	(0.2,0.3,0.4)
0.8	Very strong importance	(0.4,0.5,0.6)
0.9	Extreme importance	(0.6,0.7,0.8)

Table 13. Elements and corresponding TFN of Criteria level

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	a
A1	0.5	0.4	0.6	0.3	0.8	0.6	0.4	0.8	0.8	0.8	0.4	0.6	7
A2		0.5	0.7	0.4	0.9	0.7	0.6	0.8	0.8	0.9	0.4	0.6	7.9
A3			0.5	0.3	0.7	0.6	0.4	0.7	0.7	0.7	0.3	0.4	6
A4				0.5	0.9	0.8	0.6	0.9	0.9	0.9	0.6	0.7	8.8
A5					0.5	0.3	0.2	0.4	0.4	0.4	0.1	0.2	3.2
A6						0.5	0.3	0.7	0.7	0.7	0.3	0.4	5.6
A7							0.5	0.8	0.8	0.8	0.4	0.6	7.4
A8								0.5	0.6	0.6	0.1	0.3	4
A9									0.5	0.6	0.1	0.2	3.7
A10										0.5	0.1	0.2	3.4
A11											0.5	0.7	8.4
A12												0.5	6.6
R	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10	r11	r12	Wi
r1	0.5000	0.4591	0.5455	0.4182	0.6727	0.5636	0.4818	0.6364	0.6500	0.6636	0.4364	0.5182	0.0916
r2		0.5000	0.5864	0.4591	0.7136	0.6045	0.5227	0.6773	0.6909	0.7045	0.4773	0.5591	0.0990
r3			0.5000	0.3727	0.6273	0.5182	0.4364	0.5909	0.6045	0.6182	0.3909	0.4727	0.0833
r4				0.5000	0.7545	0.6455	0.5636	0.7182	0.7318	0.7455	0.5182	0.6000	0.1065
r5					0.5000	0.3909	0.3091	0.4636	0.4773	0.4909	0.2636	0.3455	0.0602
r6						0.5000	0.4182	0.5727	0.5864	0.6000	0.3727	0.4545	0.0800
r7							0.5000	0.6545	0.6682	0.6818	0.4545	0.5364	0.0949
r8								0.5000	0.5136	0.5273	0.3000	0.3818	0.0668
r9									0.5000	0.5136	0.2864	0.3682	0.0643
r10										0.5000	0.2727	0.3545	0.0618
r11											0.5000	0.5818	0.1032
r12												0.5000	0.0883

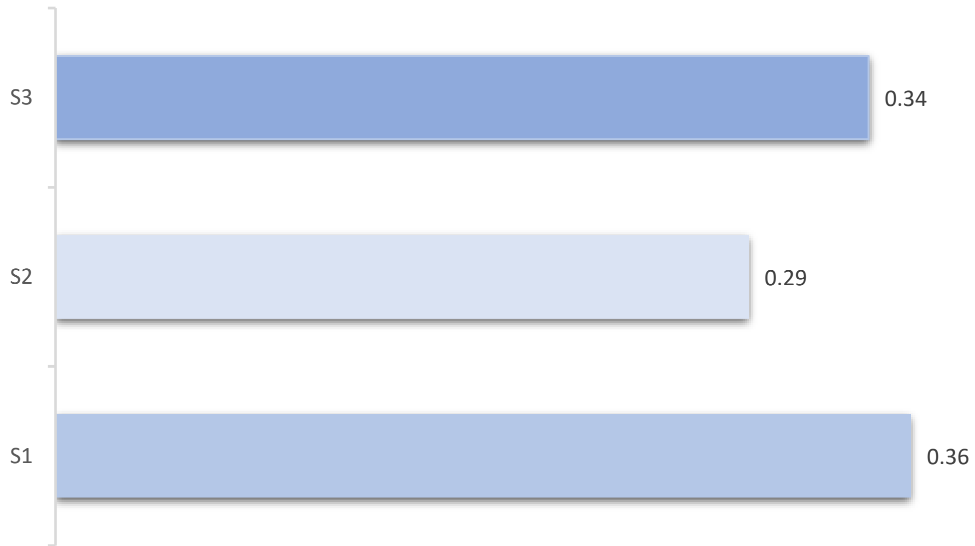
Table 14. Fuzzy complementary judgment matrix of criteria level

In the plan level, utilize the simulation results we got in the previous step, compare the warehouse systems in each single indicator, and construct a fuzzy judgment matrix (Table 15).

W	S1	S2	S3
A1	0.3083	0.3833	0.3083
A2	0.2583	0.4083	0.3333
A3	0.3833	0.4333	0.1833
A4	0.3333	0.2583	0.4083
A5	0.3083	0.2333	0.4583
A6	0.3083	0.4333	0.2583
A7	0.4583	0.3083	0.2333
A8	0.3833	0.1833	0.4333
A9	0.4083	0.1333	0.4583
A10	0.4083	0.1333	0.4583
A11	0.3333	0.2583	0.4083
A12	0.4833	0.2333	0.2833

Table 15. Weight results of plan level

Finally, the global priority weight of each system is calculate as shown in the following figure. The overall system performance of S1 is prior than S2 and S3. Therefore, the best automation solution for the warehouse system is chosen.



5. Conclusion

The monitoring and implementation of key performance indicators (KPIs) is closely related to the performance of automated warehouses, and the application of simulation models can provide indispensable help to decision makers in the process of warehouse design or optimization. Through a literature review, this paper identified a series of key performance indicators for automated warehouse management systems but failed to identify new KPIs due to the limited number of papers studied and the continuous development of warehousing technology. In the simulation model, we implement a subset of KPIs in terms of general performance and time-dependent performance, which are used to compare and analyze different automation systems. Due to practical limitations, the cost and environment-related performance could not be analyzed.

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