Politecnico di Torino

Master of Science Program in Engineering and Management
Path Innovation

Master's Degree Thesis

"Design of an innovative picking system for AVS/RS warehouses through discrete event simulation"

Supervisors:
Prof. Franco Lombardi
Prof. Giulia Bruno
Prof. Alberto Faveto

Candidate:
Nodirjon Yusufov
Student ID:
s277214

Academic Year 2021/2022

Abstract

Increasing need for a solution of complex activities performed in warehouses are playing the core role for their transformation. In recent years, due to high volume of available technologies and advancement in information management systems, businesses are switching to automated warehouses with higher efficiencies in order fulfillment time and quality, with extra consciousness on energy consumption. One of such technologies was developed by an Italian company Eurofork that was built by merging a shuttle, a satellite and a robotic picking arm into an Automated Guided Vehicle (AGV). The technology is considered to be a main tool to design an automated warehouse of AVS/RS type. This study further extends the previously conducted research and the simulation model, in the Discrete Event Simulation environment using a special software, with its novelty in integrating real life transaction history from an Italian manufacturer, to discuss performance indicators in single command activities in a conceptual warehouse. For the simulation to be performed in a desired level, external variable parameters and important output KPIs have been defined, with an aim of testing them in various storage policies. In the next step, performance indicators then were derived from the simulation software to data analysis tools, to analyze under which circumstances, which of the storage policies had higher throughput, shorter cycle time and most importantly, provided better energy efficient results.

Keywords

Automated warehouse, AVS/RS, Robotic picking arm, Order picking, Discrete event simulation, Storage policies, Order list.

Table of Contents

1. INTRODUCTION

1.1. Automated Storage and Retrieval Systems

In the era of digitalization and the boost of e-commerce, warehouses are becoming an important asset of the competitive advantage of companies. Fulfilling orders from time-sensitive customers is requiring sellers and distributors to conduct high-speed operations inside warehouses. Technologies widely used in Industry 4.0, low-cost sensors, Internet of Things (IoT), data management systems and high performance computing are the crucial tools of this process (Lototsky, Sabitov, Smirnova, Sirazetdinov, Eizarova, 2019). While travel time in order picking process of picker-to-part systems takes 60% of total time spent (Battini, Calzavara, Persona & Sgarbossa, 2016), Automated Storage and Retrieval Systems (AS/RS) are a modern solution to decrease time spent for such operations.

According to the aim of use (picking/packing of an order, managing buffer storage, storing goods, etc.) there are several types of AS/RS applications in use (Romaine, 2020):

- Unit-Load AS/RS cranes are used with narrow-aisle, high-level racks to handle heavy load, typically a pallet.
- Mini-Load AS/RS cranes utilize totes or trays as a handling unit and can be used in multiple levels for less heavy loads.
- Shuttle (or vehicle) based AS/RS, also, Automated Vehicle Storage and Retrieval Systems (AVS/RS) that can pick single or multiple units. Such systems can also use totes which enables the technology operate with multiple Stock Keeping Units (SKU) in multiple levels.
- Autonomous Robot based AS/RS, also, Robotized Mobile Fulfillments Systems (RMFS) that handle moveable racks on ground level.

1.2. Objective of the thesis

This paper is a follow-up research to an existing project in which a robotic arm mounted on the shuttle is proposed by the Italian company Eurofork, as an autonomous picking system that can potentially be a more productive alternative to the already existing AVS/RS system. The proposed solution is expected to be more productive and have less energy consumption, by providing an opportunity to create mixed unit pallets, thanks to the picker robotic arm. Consequently multiple unit orders are fulfilled fully autonomously, eliminating the need to organize a manually picking area during the order fulfillment process. Efficient performance of the system bases on several external factors, including the positioning of stock in an inventory. Therefore this research focuses on determining efficient item-allocation methods to support the activities of the proposed technology. The research uses a real order list from an Italian electronics manufacturer in order to simulate the order fulfillment process in Discrete-Event Simulation environment, extracting performance analysis data. The research is then further studied using data analysis tools in order to provide solid, data-driven decision support.

1.3. Thesis structure

The thesis starts with reviewing the existing literature in the context of automated warehouses. Firstly it analyses the existing studies that focused only on summarizing the researches conducted on the automated storage and handlings systems. Papers that focused on the performance of such systems are then followed up. As a finish-line for the literature review, the list of the most important research papers focusing on the performance of only AVS/RS are presented in the chronological order, highlighting the modelling modes and objectives.

As a next chapter the whole work framework of the study is explained. First, explanation of the design of the conceptual warehouse takes place, including the flow of activities for 3 generally important functions of the warehouse. After that extensive initial assumptions were described that is composed of storage policies considered in the simulation, the order list – the core of this study, received by a local manufacturer, input parameters and output indicators of paramount importance are listed further. Structure of the work is concluded by the tools used to run simulations and perform data analysis.

Following section of the paper discusses important steps taken in order to successfully run the simulation. The pre-existing model is explained which is followed up by the list of simulations prepared to run for the case we are considering. The whole process from initializing the run to obtaining the final results are illustrated as the conclusion of this chapter.

As the final step, the results obtained from the simulation are then analyzed using different statistical and data analysis tools. First, in order to see the fundamental values of indicators, general data analysis is carried out for all the storage policies. To attract and make use of latest data analysis tools, averages of several simulation data is calculated in the specific data analysis platform – Minitab. In the final stage of the data investigation, effects of the output parameters towards different storage policies are declared.

The research is finalized by the conclusions, final thoughts on the results and suggestions to future studies of the technology in interest.

2. LITERATURE REVIEW

According to the literature findings it is convenient to divide all the available research into two groups: the focus area that describes available versions of automated storage and retrieval systems and the other set of academic papers that discuss (with or without simulation models) efficiency of such systems and how to optimize the system in terms of several attributes: storage policy, technology, warehouse structure and so on. This paper belongs to the second category, as it aims to extract useful data from the simulation in order to define the best location policy for warehouses while using the newly introduced technology.

2.1. Automated storage handling systematic literature review

Generally, storage and retrieval systems with shuttle vehicles, lifts and picker robotic arms have been the subject since the last decade of the XX century (Malmborg, 2003). As automated and semi-automated handling systems are being deployed more and more distribution and fulfillment centers, there has been and increasing trend in the number of submitted research literature, which Azadeh, De Koster, Roy (2019) summarized in their research. The paper reviews new categories of automated and robotic handling systems, such as shuttle-based storage and retrieval systems, shuttle-based compact storage systems, and robotic mobile fulfillment systems. Figure 1. represents the classification of automated systems reviewed in the research.

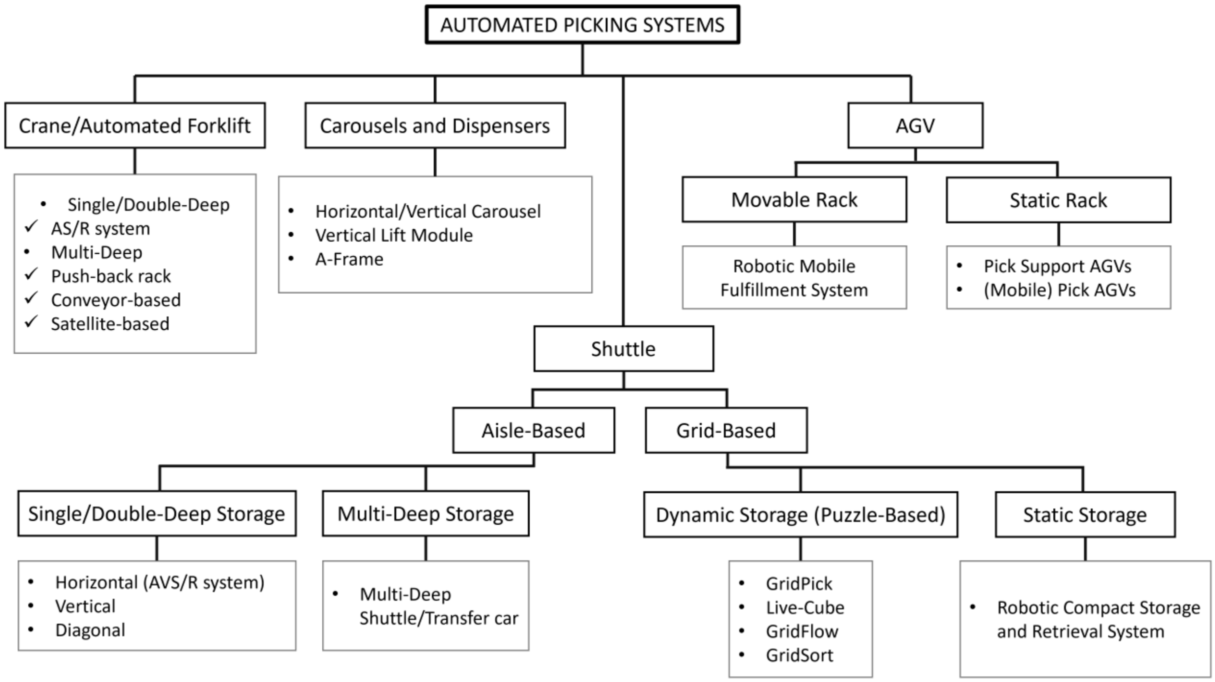


Figure 1. classification of automated warehouse systems studied

Another systematic literature review is summarized by Jaghbeer, Hanson and Johansson (2020) where they reviewed 74 papers about design of the system with its performance. The study outlined that regardless the high diversity in the design, the performance categories of throughput, lead time, and operational efficiency have received the most attention in the literature. Another earlier literature review carried out using the content analysis method by Staudt, Alpan, Di Mascolo and Rodriguez (2015) classified performance indicators acquiring from selected papers as time, cost, quality and productivity dimensions.

2.2. AVS/RS performance analysis research literature

Various studies have been carried out starting from the first years of XXI century, in order to evaluate the performance of AVS / RS as in the most efficient ways possible. Most of the methodologies used are based on analytical models, that follow up performance of hundreds of simulations in order to subsequently validate the results, using specific simulation software.

One of the first analysis was carried out by Malmborg in 2002 in which the author suggests some tools that can be used as supporting factors for the choice of the most suitable technology and decisions concerning the viability of the AVS / RS systems performance. Starting from this focus, it proposes to use, for example, the cycle time of storage and retrieval operations, use of vehicles and the production volume, in the most efficient way possible considering the size of the warehouse and everything that composes it: storage aisles, storage rack height and depth, vehicles and number of lifts.

In 2007 Kuo et al. highlighted that the most important decisions regarding the implementation of a new automated warehousing technology faces mainly two challenges questions:

- the costs that the new system could bring to the company
- the difficulties inherent in introduction of such a new system.

Given their growing popularity, the introduction of ULS/RS systems (Unit Load Storage and Retrieval System - storage and retrieval systems for units), its introduction in the supply chain would have led to economic savings across the company expenditures. To demonstrate this, apart from considering the usual performance measures, the author used in these analyses transaction waiting time and the vehicle utilization as two more additional measures for two systems:

- Random storage system
- Point-of-service-completion dwell point rules

The results are illustrated in the context of a conceptualization study adapted from an actual system installation.

Some in-depth performance analysis of AVS/RS can be found in the work done by Marchet, Melacini, Perotti and Tappia (2011) using open queuing network approach, where they estimated the performance in terms of order cycle time and waiting times. The analytical model then is compared to the simulation model to validate the estimates and the results demonstrated good estimates for the performance measure of the AVS/RS. Further in their research, Marchet et al

(2012) proposed the application of suggested framework and noted the key design improvement differences between the two types of AVS/RS configuration: tier-captive and tier-to-tier.

The optimum rack configuration studies using simulation based performance evaluation of AVS/RS has been deeply analyzed by Ekren, Heragu, Krishnamurthy and Malmborg (2010). Pre-defined scenarios of number of vehicles and lifts in the system is implemented in the research, which included simulation-based regression model, and resulted in sorting out the important factors affecting AVS/RS performance.

While majority of studies considered sequential commissioning of the lift and vehicles, Zou, Xu,Gong and De Koster (2016) proposed parallel policy for autonomous tier-captive storage/retrieval systems. To investigate the performance of the aforementioned policy, fork-join queuing network has been formulated in which an arrival transaction will be split into a horizontal movement task for the vehicle and the vertical movement task for the lift. Simulation models have been developed to validate the effectiveness of the system performance and the results show that in systems less than 10 tiers, the parallel processing policy outperforms the sequential processing policy by at least 5.51 percent.

2.3. Important AVS/RS literature review summary

Once the most important literature is analyzed, one can clearly confirm that the studies that prioritize performance analysis factors of the automated storage handling systems to decide on storage policies are of rare occurrence. The current conducted research is being reported in order to prevent the scarcity of such discussion. Since the system studied in this paper is a representation of the AVS/RS, the most cited and noted literatures on the topic is listed below in the table.

MODELS STUDIED IN AVS/RS		
LITERATURE	**MODELLING**	**OBJECTIVES**
MALMBORG, 2002	Analytical	Performance evaluation
MALMBORG, 2003	Analytical	Cycle time and throughput analysis
KUO ET AL., 2007	QNM	Performance analysis
FUKUNARI ET AL., 2008	Simulation	Cycle time analysis
KUO ET AL., 2008	QNM	Performance analysis
FUKUNARI ET AL., 2009	QNM	Performance measures
ZHANG ET AL., 2009	Simulation	Transaction waiting times analysis
EKREN ET AL., 2010	Simulation	Design of experiments
EKREN AND HERAGU 2010	Simulation	Regression analysis
EKREN ET AL., 2010	Simulation	Performance analysis
MARCHET ET AL., 2012	Analytical	Performance evaluation
ROY ET AL., 2012	SOQNM	Performance analysis
EKREN ET AL., 2013	SOQNM	Performance evaluation
MARCHET ET AL., 2013	Simulation	Design trade-offs analysis
EKREN ET AL., 2014	SOQNM	Matrix-geometric solution
ZOU ET AL., 2016	FJQNM	Performance analysis
EKREN, 2017	Simulation	Performance evaluation
EPP ET AL., 2017	QNM	Performance evaluation
KUMAWAT AND ROY, 2021	SOQNM	Performance evaluation

Table 1. Literatures relating to AVS/RS studied earlier

3. WORK FRAMEWORK

As mentioned in the introduction, by conducting this research work it is aimed to test the existing AVS/RS alternative system that includes a technology developed by the company Eurofork with real industrial demand – the order list. The list is taken from another Italian company that produces technological hardware, the name of which is kept anonymous for data security purposes. The order list is further amended to optimize the simulation model processes and includes order frequency of 15 stock keeping units (SKUs). In the following sections the concept of the warehouse and its working mechanism is explained in details, including the different types of technologies used. In order to assess the performance of the automated system we are defining important input and output variables that we use for the analysis. Such indicators are then explained further. The simulation environment is managed through the special software called FlexSim and its features together with the data analysis tools are explained as the finishing part of the work framework.

3.1. Automated warehouse system studied in the research

Since there are many types of automated picking, storage and retrieval systems, performance indicators of which vary accordingly, it is essential to define which type of system is used in the work framework. The design of the warehouse and operation flow in the system is explained below. Although the study focuses on only two main operations:

- Picking
- Order fulfillment (retrieval function)

in order to fully describe the operation flow, the complete 3 main activity diagrams are explained further:

1. Picking
2. Retrieval
3. Storage

3.1.1. Warehouse design

The conceptual automated system, that is developed for this research, can be considered as an alternative for an AVS/RS and consists of automatic guided vehicles (AGVs) that are composed of 3 typical warehouse picking technologies: a Shuttle, a Satellite and a Robotic Arm. SKUs are stored in pallets, that are stored in racks designed with a convenience of a satellite traveling in between. Each AGV operates in a horizontal level, therefore vertical lifts are mounted in each corridor (aisle) of the warehouse giving an AGV ability to reach to higher vertical levels and enabling the satellite to travel in corridors. If we consider the rack system as a reference, in order to complete any operation, an AGV moves in X direction, a satellite movement is in X and Y directions, a Robotic Arm is used to pick up parts, or pallets and a lift system is used to manage movements in Z direction.

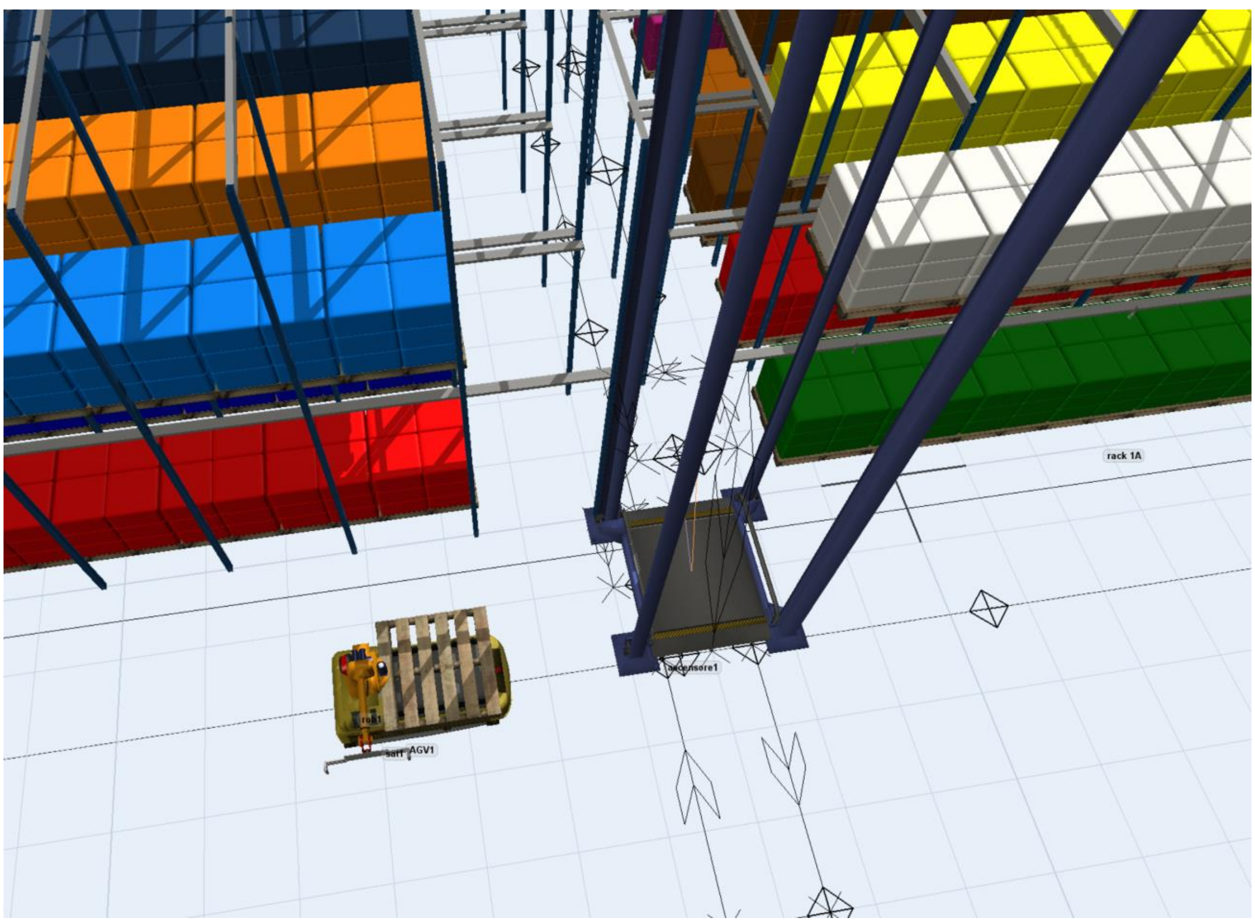


Image 1. The conceptual automated warehouse system: an AGV, a lift and racks.

3.1.2. Process flow: picking

The operational flow of picking activities in the automated warehouse is initiated by the arrival of customer orders which may require a creation of single SKU or multiple SKU pallets, according to the desire and expectations of clients. After the order is received by the operation management system, it sends a signal to the vehicle (as explained above, an AGV that is composed of a shuttle, a satellite and a robotic arm grouped together) in order to start the fulfillment process. The warehouse can be equipped with several such AGVs or a single AGV, depending on its needs and fulfillment rate. If an AGV is not busy with another picking activity, i.e., if it is available to perform the activity for the current order, that order is assigned to the AGV, otherwise the order needs to wait for the AGV become available. Once the system loads the order information on the AGV that is ready for the action, it defines the first product to include in the pallet. The location of the product's pallet depends on the storage policy logic (if it is randomly stored, or stored according to a class, product weight, etc.). Therefore the vehicle should first identify the coordinates and start travelling horizontally in order to reach the slot where the pallet of the product is stored. The target slot can be in the ground floor, or in higher levels in case the warehouse has more than one level. In the former case, the vehicle just travels to the target directly, otherwise for the vertical movement it needs an elevator to be lifted. If the elevator is occupied by another shuttle, the operation flow needs to wait. Once the elevator is ready to use, the AGV is lifted on the required level and the satellite can travel to the pallet of the target SKU. It brings the pallet closer to AGV so that the robotic arm installed can reach and pick the SKU. After picking the first product, the satellite needs to bring back the current pallet and AGV analyses if there are any more SKUs to be picked for making the customer order complete. In case of the mixed-SKU order, the AGV needs to travel to the target slot as explained in the previous step. After finishing the picking process for the specific order, the shuttle travels towards the are to complete the discharge of the pallet with a single or a mixed SKU and goes back to the buffer area and waits for the next assignment. The logic of the Picking process flow is explained graphically in the activity diagram below (Ariano, 2021).

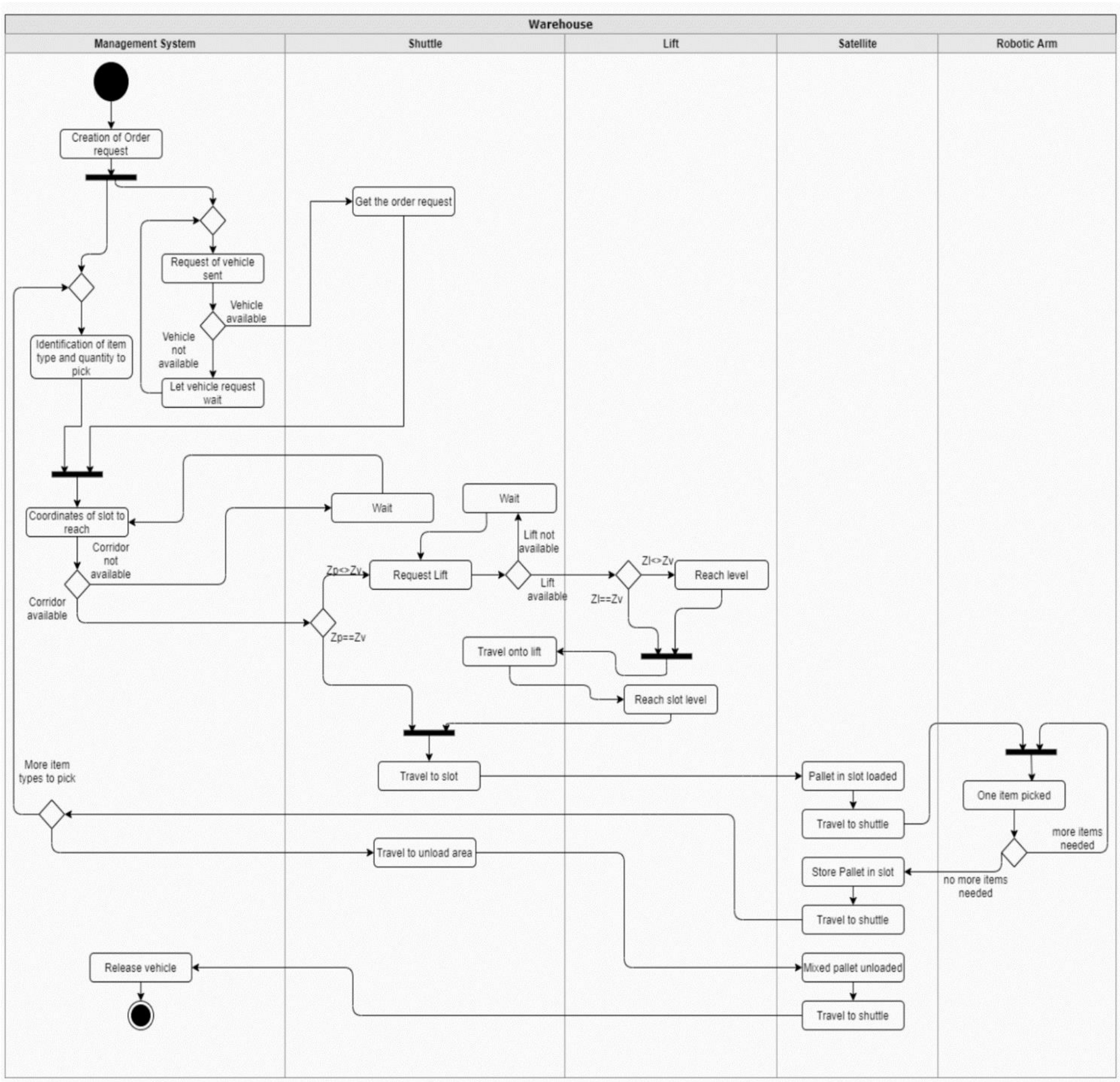


Figure 2. Picking Process Flow

3.1.3. Process flow: retrieval

The retrieval operation resembles the previous mission explained in its logic and is explained graphically in the Activity Chart below textual explanation. The core difference of this activity lies in the object to move to the discharge area: in the picking process, the AGV is used to create a single or a mixed SKU pallet according to the customer order, whereas in the retrieval mission the technology is used to bring the whole pallet of the desired SKU in the discharge area. To initialize the process, the AGV should first accept the signal from the management, and in case its free to conduct the assigned mission, it starts the movement. As in the previous operation, the elevator is needed in case the target pallet is not located on the ground floor. The availability of the elevator depends on the parallelly ongoing processes. Once the AGV reached the slot where required SKU's pallet is located (again, according to the storage policy) the satellite travels towards the pallet, brings and loads the pallet into the AGV. The shuttle then reaches the ground floor in order to finish the process. The vehicle leaves the pallet in the discharge area and goes back to the buffer area to wait for the next order details. As can detected following the operation logic, the robotic arm is not used in the process so it is omitted in the Activity Diagram (Ariano, 2021)

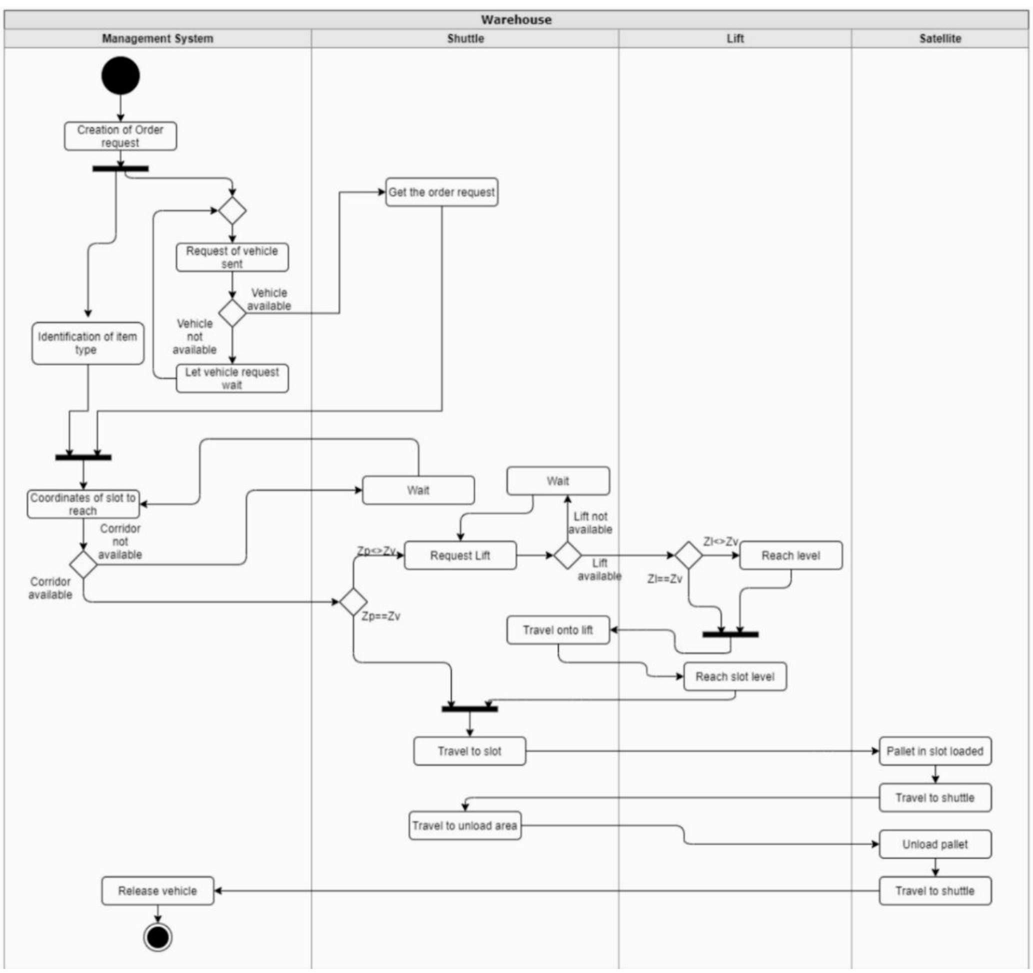


Figure 3. Retrieval Process Flow

3.1.4. Process flow: storage

The complexity of the storage activity is that the system first needs to identify in the whole storage area a free slot to locate the incoming pallet. While to do so, the system is required to get familiarized with the content of the pallet, since according to the current storage policy, and the availability of the slots, it should calculate the coordinates. Once the coordinates of the buffer space is identified, the system sends the signal to a free AGV and that initiates the movement of the vehicle. Once the pallet is loaded on the shuttle, it travels to the elevator or directly to the buffer slot area in case the coordinates are on the ground floor. At the correct location where the AGV stopped, the satellite gets detached from the system, while carrying the pallet that needs to be stored. It then moves in the proper direction in order to find the free slot, unloads the pallet to the point sent by the management system and gets on the AGV. The entire vehicle then reaches the ground floor and travels back to its initial state. The Activity Diagram that explains the whole logic can be found in the following figure. (Ariano, 2021)

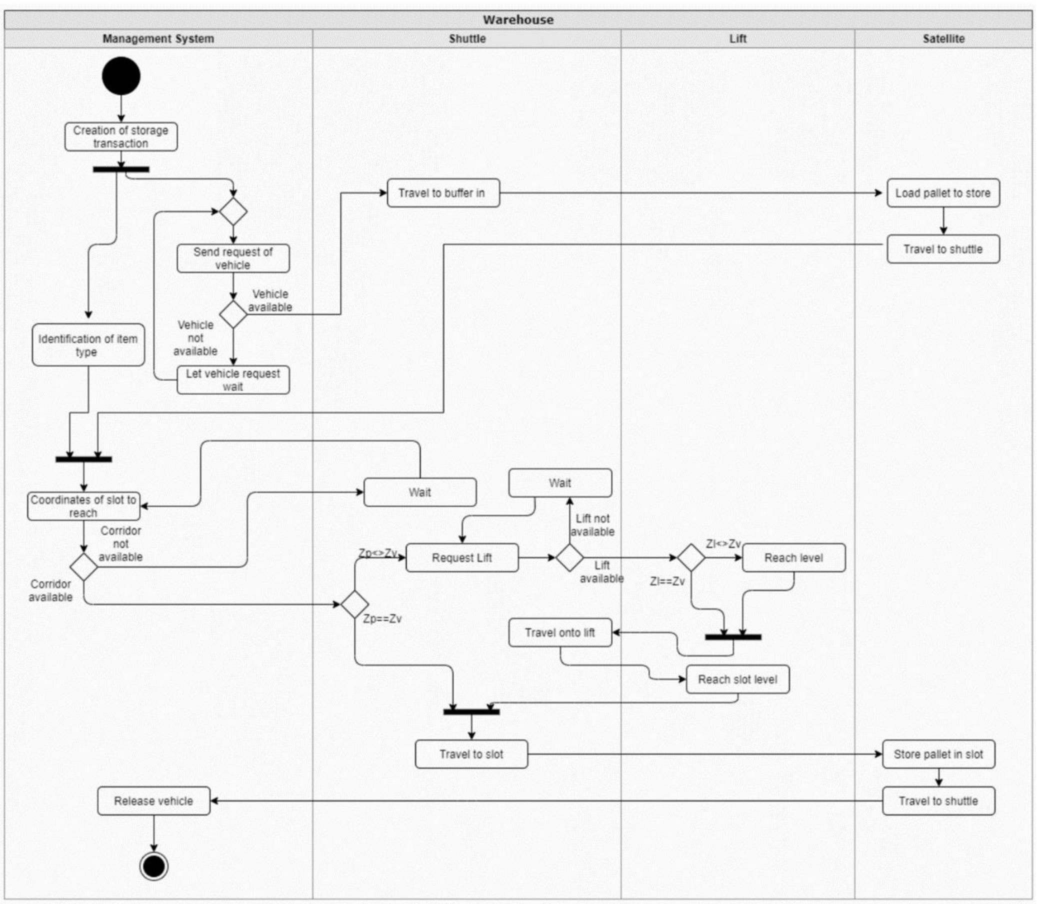


Figure 4. Storage Process Flow

3.2. Initial Assumptions

Since this is a simulation inclusive research that focuses on performance indicators of an automated warehouse, it is built on some generally accepted assumptions. In order for the study to be valid and credible, it is important to propose such assumptions before starting the simulation and the analysis. The sum of these assumptions make up the environment that the performance analysis is carried out. Therefore in the following paragraphs we have a deep look around which kind of conditions the simulation is run. First the most vital part of the warehousing logic – storage policies considered in this case is explained. Further definition is carried out on the order list and its creation, modifications made and justification for these amendments. This chapter of the thesis then concludes with input variables and output KPIs.

3.2.1. Storage Policies

The vital purpose of the storage policies is to assign items to various warehouse storage locations based on some logic or without any specific classification - randomly. Stored units may be assigned randomly as explained above, or items with some similar characteristics may be grouped in the same space of the warehouse, or items may also be located together based on order or picking volume. There are five main types of storage policies studied in different research papers, however, for the study we are conducting we limited our focus only on 4 of them. Each of the policies are explained in detail below.

Random Storage

When a warehouse uses a Random Storage policy, the unit load is stored in any, most typically, in the closes available location. This means that every SKUs have equal odds of occupying available slots (Zaerpour N. et al., 2013). In reality the storage of the unit load is not truly random, however a picker or a warehouse personnel decides where to locate units. Which also means that the random storage policy shortens travel time and is energy-efficient. The advantages versus downsides of this method is listed below.

Advantages	Disadvantages
• efficient space utilization	• detailed record implementation
• flexibility	• easy to get lost in records
• quick storage, less time consumed	
• fast learning curve	

So as pointed out, none of the product characteristic is taken into consideration while deciding the item location. The graphical representation of random storage is exampled below.

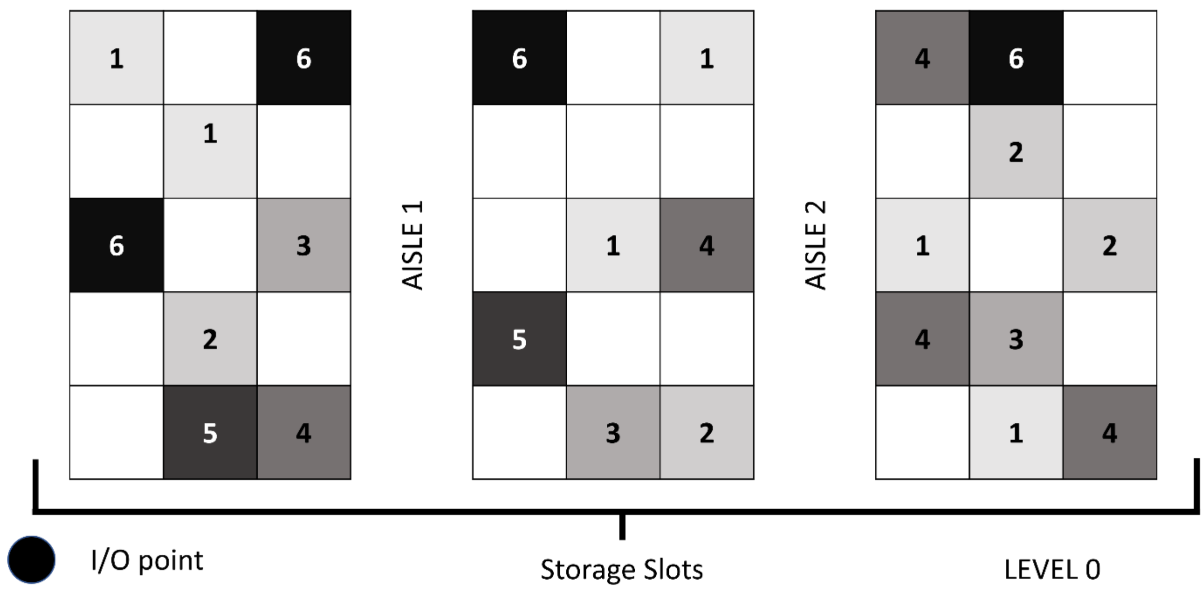


Figure 5. Random Storage Layout

It should also be noted that because there is no rational reasoning behind this policy, we are leaving it outside of the scope of our study.

Class-Based Storage

Also known as “ABC strategy”, a Class-Based Storage policy is built on the idea of subdividing all the available inventory into three categories – A, B and C. The grouping logic of the products is consistent to the frequency of storage and retrieval operations on unit loads. The classification is based on Pareto principle – the law of the vital few: in the warehouse generally 80% of the process operations are directed at 20% of the items, 15% of operations are directed at 30% of the items and the remaining 5% of activities are carried out on the 50% of the items. Fast moving products (category A products) are preferably stored in the easiest-to-pick and least-effort areas. In most of the cases, these areas are located in front end of the warehouse, so that the distance travelled from the target slot and the discharge area is shortened to its minimum. Products with less frequent demand (category B and C) are usually stored behind the A-type products. To increase the efficiency of this strategy, the constant change in the classification of products into categories is necessary in the scenario of frequent changes in customer demand. So, if after a while, some items from the B-type are ordered with high frequency, there should happen an immediate switch of the group of products from category B to category A. Extended characteristics of the 3 categories are represented below.

- CATEGORY A – accounts for products that make a high turnover in the warehouse, however have smaller number of locations.
- CATEGORY C – includes products which require longer period of time to be stored in the warehouse if compared to so-called “A-type” of products. These products are very high in volume, in fact, account for the biggest volume among these 3 categories and therefore need to be stored in much space.
- CATEGORY B – is composed of products with demand rate between of the products in the category A and C. Therefore with time these products could be assigned to the higher or lower level of importance.

Several authors of previous warehouse management research papers have identified and emphasized that significant savings in the travel time can be obtained by using the ABC storage strategy examples of which include work done by Jarvis and McDowell (1991), Caron, Marchet and Perego (1998). The research studied by Hausman, Schwarz and Graves (1976) concluded that if 3 categories are stored in one aisle, savings up to 60% can be realized. Rosenblatt and Eynan (1989), took this policy into next level while investigating the effects of the ABC storage strategy for warehouses with not only three, but with N categories.

Once products are correctly categorized, the discussion then jumps into the layout of the division of the products in the warehouse. The plan the layout design, the crucial factor needs to be taken into account is the location of the discharge area – referred as depot in many research studies. While the aim of the design is to decrease the travel time and efforts made to reach to the dedicated storage area, the category A products are located as near as possible to the depot. The structure then is filled up with B-type products with immediate access after the category A. The rest of the inventory – type C is located the furthest from the depot, since the probability of the current order including an SKU from type-C product is very low. According to commonly used practices the layout of the ABC storage policy can be of 3 types and are graphically described below:

1) Diagonal
2) Within-Aisle
3) Across-Aisle

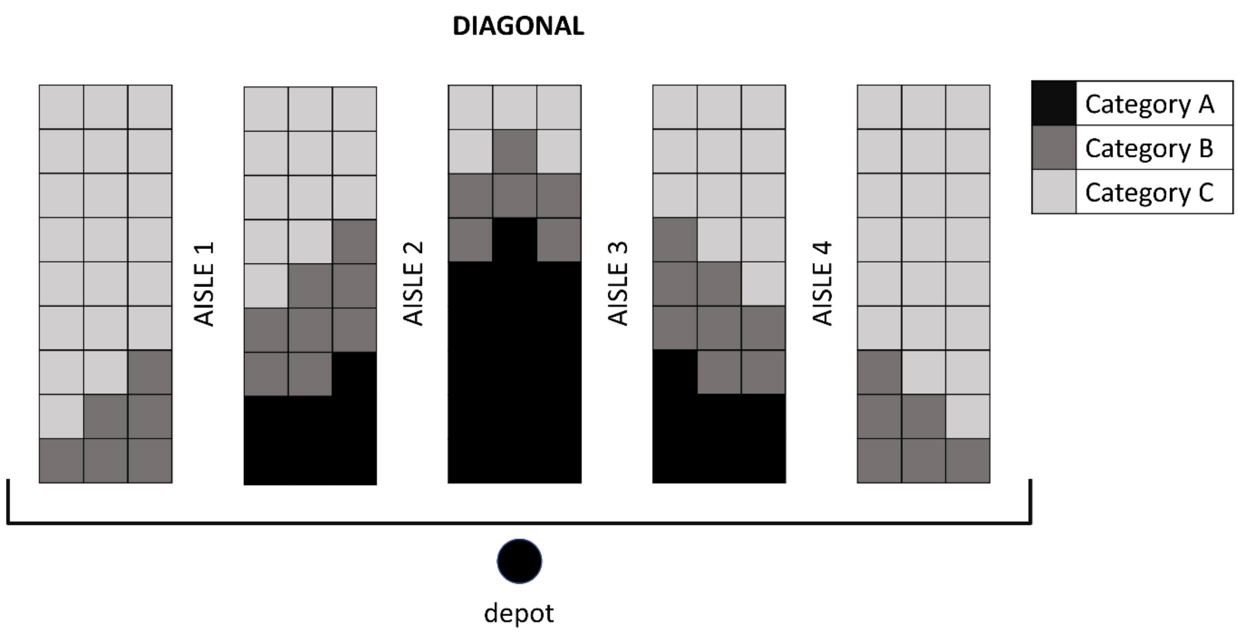


Figure 6. ABC Storage Layout: Diagonal

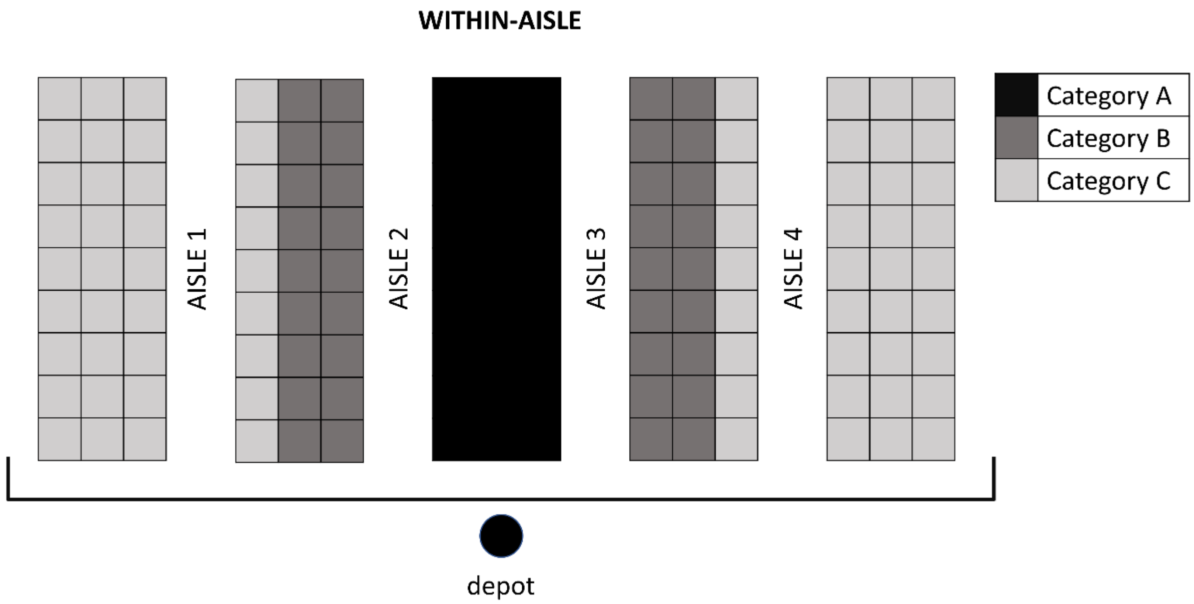


Figure 7. ABC Storage Layout: Within-Aisles

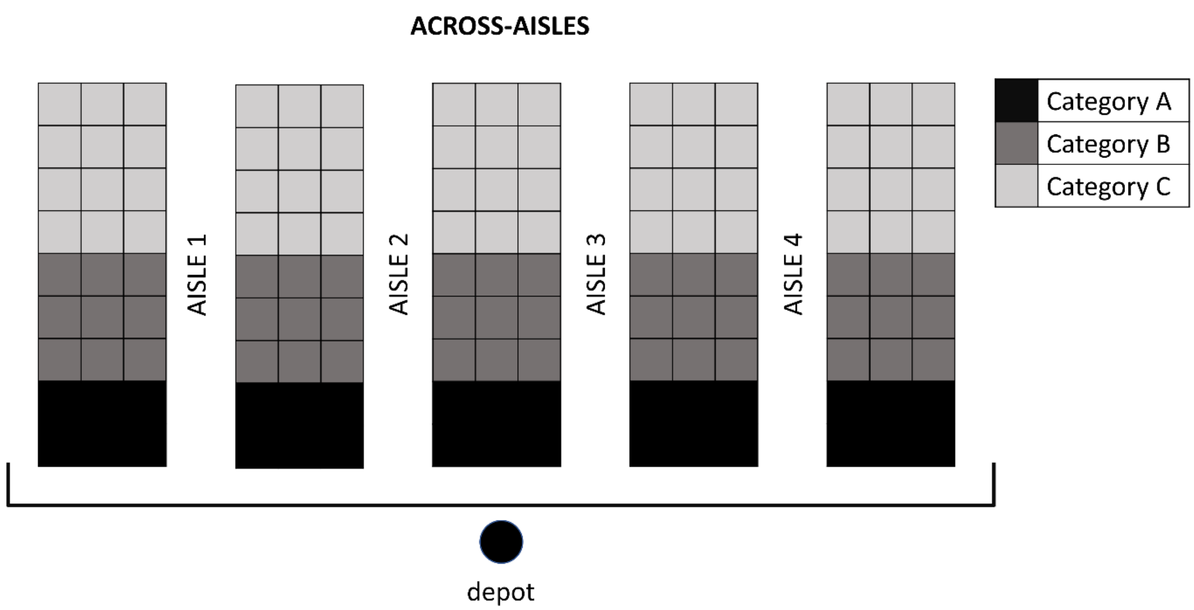


Figure 8. ABC Storage Layout: Across-Aisles

This study is taking the Class-Based Storage policy into account and classifying the SKUs used in the simulations as per the rule, with 60% of frequency for the products of Category A, 30% of frequency for the products in the Category B and 10% of frequency for the products of Category C. Full information about the SKUs and the order list is available in the dedicated section.

Dedicated Slots Storage

This policy is based on the solid rule: “Every part has its location and every location has its part” (Milijus, 2006). Every SKU making up the whole inventory is assigned a dedicated storage location in the warehouse and only stored in that location. The flexibility of the location makes it harder for organizations that operate with higher number of SKUs, since it requires higher storage volume as well as a comprehensive management and S/R system. These challenges make the Dedicated Slots storage policy more convenient for smaller operations and a warehouse. However with a powerful information system, which is becoming more and more available, it can be possible to adopt this warehousing technique also in large-scale operations. According to Kay, 2015, this system minimizes handling costs and maximizes building costs. An example of a layout with Dedicated Slots storage policy is illustrated further.

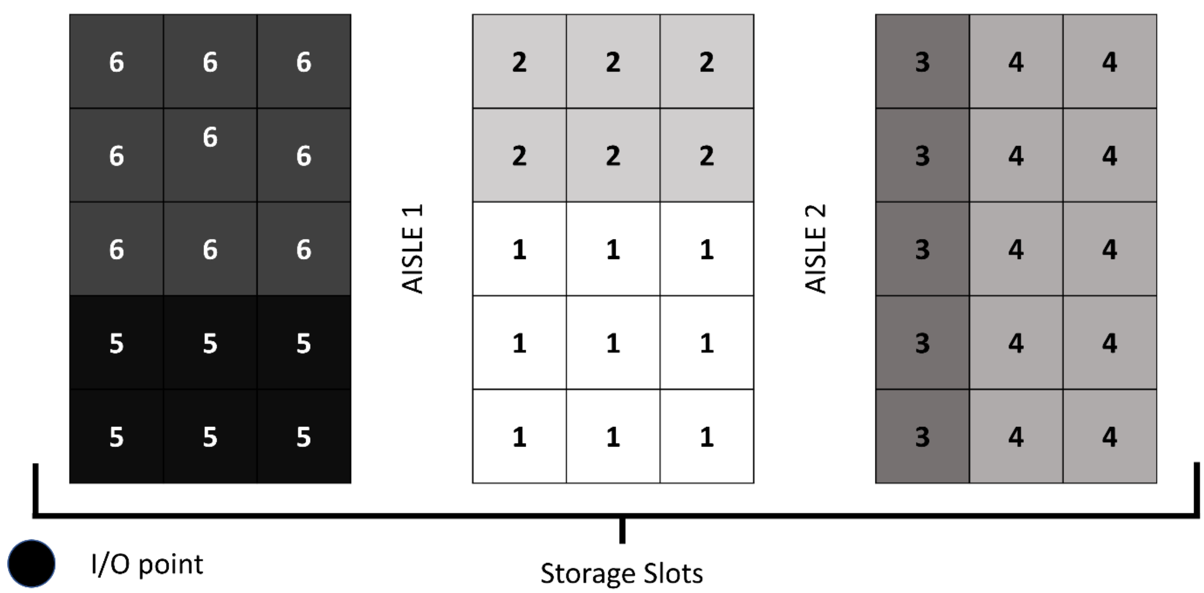


Figure 9. Dedicated Slot Storage Layout

For our case and simulation we will analyze the performances also using this storage practice. As introduced earlier, 15 SKUs will be used for our simulation, which makes our storage logic to split up 15 different areas dedicated for each unit load.

Storage by weight

Another stock keeping technique that we will include in our performance analysis is the Storage policy by weight of each unit load. It can be regarded as a variation of the Class Based Storage policy where the characteristic of interest is the weight (Lorenc and Lehrer, 2019). The idea behind implementing a model like this is to see if locating the heaviest SKUs near the discharge area and keeping lighter products further from it could bring energy efficiency. For the simulation we carry out in the next sections, we identified the weights of each SKUs so while creating the inventory stock in the simulation environment under the context of Storage policy by weight, that information will be necessary.

Storage by Association Rules

In order to understand the simple gist of this methodology it is important to get familiarized with the use of association rules in today's rapidly changing industry spheres. Association rule-mining is generally a data mining approach that is used to explore and interpret large transactional datasets to identify unique patterns and relations. (Sarkar et al., 2018). During operation lifetime of a warehouse, rule-mining technology can define significant interactions between different SKUs. The rule can help to forecast transactional behaviors based on past fulfillment information. Using this approach, the main question that can be answered is what items customers tend to buy together, so that it will be possible to correlate products and items.

The most common algorithm used in an efficient manner to extract frequent item sets and useful association rules from large transactional datasets is called Apriori Algorithm and was introduced in 1994 by R.Agrawal and R Srikant (Li and Mendez-Mediavilla, 2021).

Apriori algorithm takes a deep dive into the large number of transactions in order to identify possible rules and relations in the database. Even a small database can have multiple rules and therefore the algorithm has 4 constraints as the pillars of the measure of interest.

- **Support:** The support of an itemset is the proportion of the transaction in the database in which a considered item, in our case, X appears. Support signifies the popularity of an itemset.
- **Confidence:** The confidence of an itemset signifies the likelihood of another item, in our case, Y, being demanded when the item X is purchased.
- **Lift:** The lift measure signifies the likelihood of the itemset Y being purchased together with an item X, while taking into account the popularity of Y.
- **Conviction:** The conviction measure signifies the incorrectness of the statement when the togetherness of item sets were accidental.

The pseudo-code for Apriori is illustrated bellow.

Algorithm 1 Apriori algorithm

C_s: a candidate itemset of size S
L_s: frequent itemset of size S
T: database of transactions/trips

Apriori(T, ε)
$L_1 \leftarrow$ {large 1-itemsets appear in more than ε transactions}
$s \leftarrow 2$
while ($L_s - 1 \neq \emptyset$)
$C_s \leftarrow$ generate itemsets from $L_s - 1$
for (transactions $t \in T$)
$C_t \leftarrow$ subset(C_s,t) generate candidate transactions size s
for (candidates c $\in C_t$) determines
frequency of c-candidates
count[c] $\leftarrow$ count[c] + 1

$L_k \leftarrow$ {c: c $\in$ Cs $\wedge$ count[c] $\geq \varepsilon$} Pruning
$s \leftarrow s + 1$
return $\cup_s L_s$ union of sets of frequent items
$s = 1,2,\ldots S$

(Li and Mendez-Mediavilla, 2021).

Implementing the data mining technology inside the warehouse environment has been a very attractive topic for the early researchers, one of which conducted extensive computation experiments to justify the preference over a randomized storage policy (Chan and Pang, 2011).

To configure a desired warehouse the study adopted several assumptions: each picking activity starts and finishes in the I/O point located at the front end of the leftmost aisle. Moreover, the shelves of the warehouse have two sides and the products can be stored on both sides with single-block only. Each unit load occupies exactly one storage point and all storage locations are of the same size. In addition the structure of the warehouse is built upon 30 shelve columns and each shelve has 30 storage location on each side, giving the warehouse the maximum capacity of 1800 location points. The Apriori algorithm used in the simulation carried out by the authors was based on 1000 synthetic customer orders as order history. Moreover, the logic of locating the unit loads also includes ABC classification with 60-20 rule, that is, 60% of the transactions include only 20% of the SKUs. So populating the warehouse starts with putting the most valuable products close to the I/O point and spreading the whole inventory further based on the item popularity. The order picking operation is based on single-command cycle policy, i.e., either the item picking or the storage function is completed during one trip. The flowchart of operations used in the simulation of the experimental study can be found in the figure below.

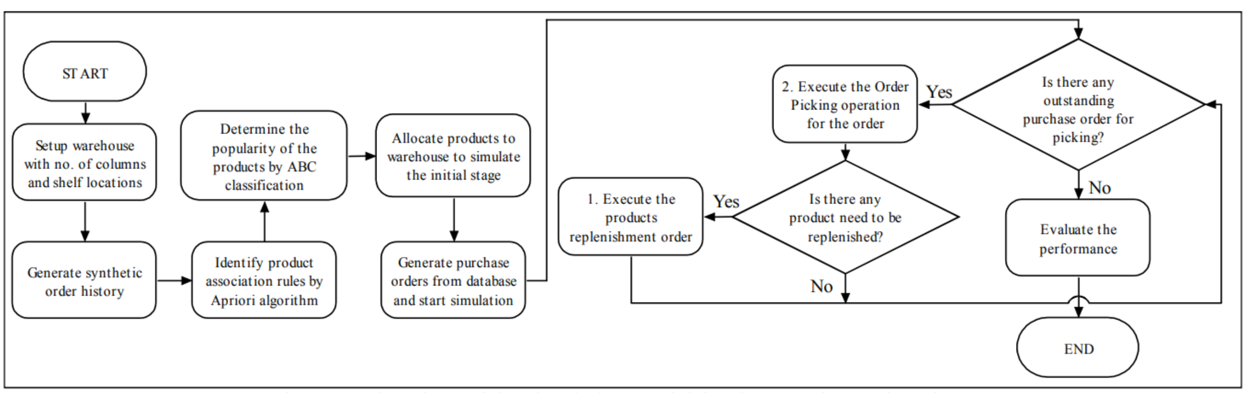


Figure 10. A generic flowchart of operations with Association rule storage policy

The simulation based on the Association Rule storage policy for our case and order list will follow almost the same flow.

3.2.2. Order List

Extensive search of a real-life order list was a challenging task, therefore it took long time to agree with local production companies to use their internal data in our analysis. However, one Italian company in the field of electronics hardware agreed to share order history from one of their e-commerce marketplace channels of the specific geographical region. The agreement between the parties resulted to the highest confidentiality, therefore neither the name of the company, nor the extra information about the transactions will be informed further in this research.

The most important role of the order list lies in three functions of the simulation environment: creating future orders according to the past transactions, identifying any potential association rules to simulate the warehouse design the Association Rule Storage policy and creating relationships of products with their weight in order to design the warehouse with the policy of Storage by weight.

The first draft transaction history prepared to be used in the study consisted of 2921 historical sales orders containing more than 30 SKUs. The following extensive information could be extracted from the file.

- Order ID
- Purchase date and time in the format of yyyy-mm-dd_hh-mm-ss
- Product SKU number (product ID)
- Quantity of each SKU in each order
- Product name
- Product weight

However, for the sake of simplicity, we decided to focus only on the 15 fast moving SKUs, because most of the orders had only 1 unit load and more than 50% of SKUs were included only in 30% of transactions. As a result we had 1892 transactions with the involvement of 15 frequently bought SKUs. To respect the confidentiality agreement, we named product ID as SKU1, SKU2, SKU3 and so on. The total number of SKUs fulfilled in 1892 transactions was 2209. Below is the graph with the number of units sold for each item in the order list we used for the simulation.

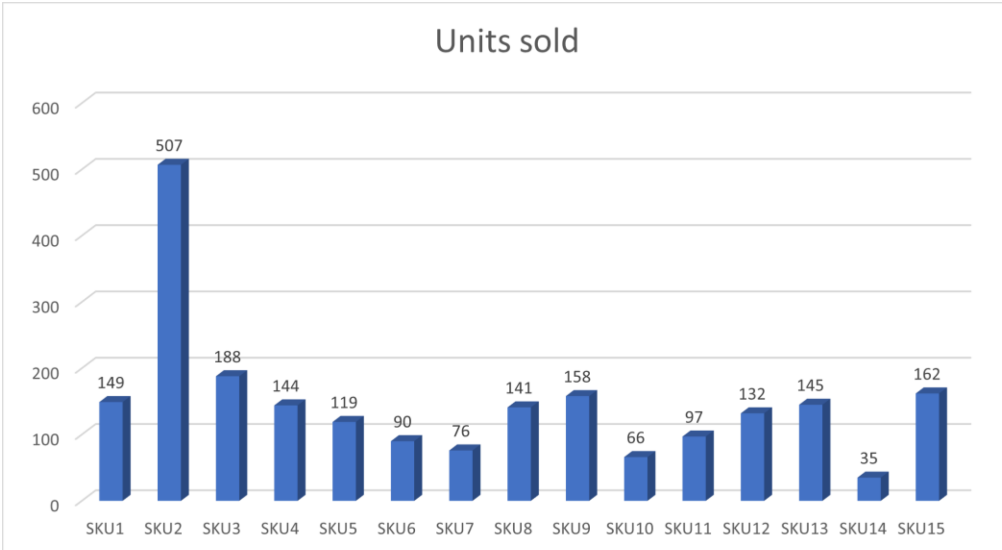


Figure 11. Number of Units Sold for 15 SKUs

Our curiosity also arose in the timing of the transactions – how long does it take from one transaction to the next, in order to calculate the frequency of the order as well as to determine the average cycle time of an AGV or a set of AGVs, if needed. The table below illustrates the most important KPIs belonging to time between orders.

Time between orders (in seconds)	
Minimum time	1
Maximum time	33640
Median time	636
Average time	1329.52
Mode	178
Standard deviation	2653.93

Table 2. Important KPIs of Time between Orders

As seen through the number of simulation models listed above as past examples of the study we are conducting, not only in the storage policy by weight, but also in the association rule based storage policy the weight of products preserved in the warehouse play an important role. The order list that we received also included the weight of the SKUs and it could be easily noted that at least half of the products were rather not too heavy, weighing less than 50 grams, while the other half was around 1 kilogram. The complete list of the products with their respective weight measurements is listed in the table below.

Weight of the each SKU box is indicated in grams								
SKU	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Weight_SKU	10	50	60	16	16	16	18	18
SKU	**9**	**10**	**11**	**12**	**12**	**14**	**15**	
Weight_SKU	18	18	20	830	830	830	830	

Table 3. Weight of Selected SKUs

All of this information is then used as input in the simulation software, which is described in details in the next chapters.

3.2.3. Input variables

As has been claimed earlier, the purpose of the study is to run simulations of the newly proposed technology using a real-life order list and discuss the performance indicators. To successfully launch the process, it is crucial to identify the pre-defined simulation parameters related to the technology and the design of the conceptual warehouse. In order to secure accurate results we also identified the fixed and variable parameters that we would like to include in the simulation.

The objective of the simulation is to give the model different parameters of the objects of the simulation and analyze to which outputs such decisions lead to. By testing the various values of such parameters the optimum design and the storage policy is suggested further. The simulation in consideration is a single-command, meaning that the technology that is being tested in this study only focuses on one operation – picking, and will not consider the retrieval and the storage operations.

As mentioned earlier, this is a follow-up research for already existing simulation model with pre-defined algorithm, structure and input variables. However, to fully support the feasibility of running this simulation with the new order list, number of initiatives and decisions were taken to finalize the parameters of the simulation. As a result, 5 main input variables have been defined and value options are calculated as follows.

Variable input parameter	Acceptable value
Storage Policy	Class Based – code number 2
	Dedicated Slot – code number 3
	Storage by Weigh – code number 4
	Association Rule – code number 5
Levels	2
	6
Bays	5
	15
Number of AGVs	1
	6
Order inter-arrival time	X1
	X3

Table 4. Input Parameters and Acceptable Values

Two parameters listed above as well as two fixed parameters in the previous study – number of corridors (fixed at 3, which also means that there will be fixed 3 lifts in front of each corridors) and number of pallet slots for each bay (fixed at 10) make up 4 different warehouse design. Before sketching the plan it should also be noted that each lift gives an access to the shuttle to travel up to 10 pallet slots, making the middle islands with the length of 20 pallet slots in total. Since the warehouse is going to have 2 and 6 levels accordingly, we can illustrate only 2 top plan of a single layer, that needs to be either duplicated or repeated 6 times to reach the deserved height. In total, the warehouse layout is going to be changed 4 times during the whole period of the simulation.

Layout 1. 5 bays on each sides of 3 lifts, each bay containing 10 pallet slots in 2 levels:

5x3x2x10x2=600 pallets in total

Layout 2. 5 bays on each sides of 3 lifts, each bay containing 10 pallet slots in 6 levels:

5x3x2x10x6=1800 pallets in total

Layout 3. 15 bays on each sides of 3 lifts, each bay containing 10 pallet slots in 2 levels

15x3x2x10x2=1800 pallets in total

Layout 4. 15 bays on each sides of 3 lifts, each bay containing 10 pallet slots in 2 levels

15x3x2x10x6=5400 pallets in total

The design of the Layout 1 of the conceptual warehouse is illustrated below. Not that Layout 2 can also be perceptualized using this scheme, having 6 levels instead of 2 as represented.

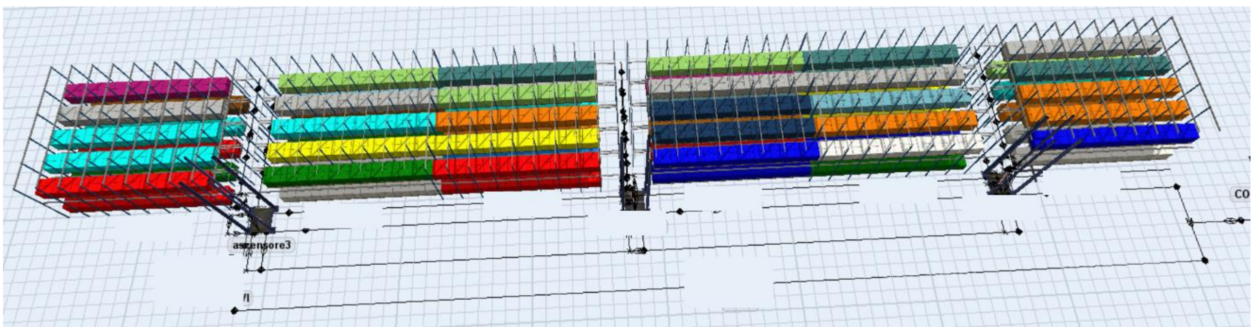


Image 2. Layout 1

The design of the Layout 3 of the conceptual warehouse is illustrated below. Not that Layout 4 can also be perceptualized using this scheme, having 6 levels instead of 2 as represented.

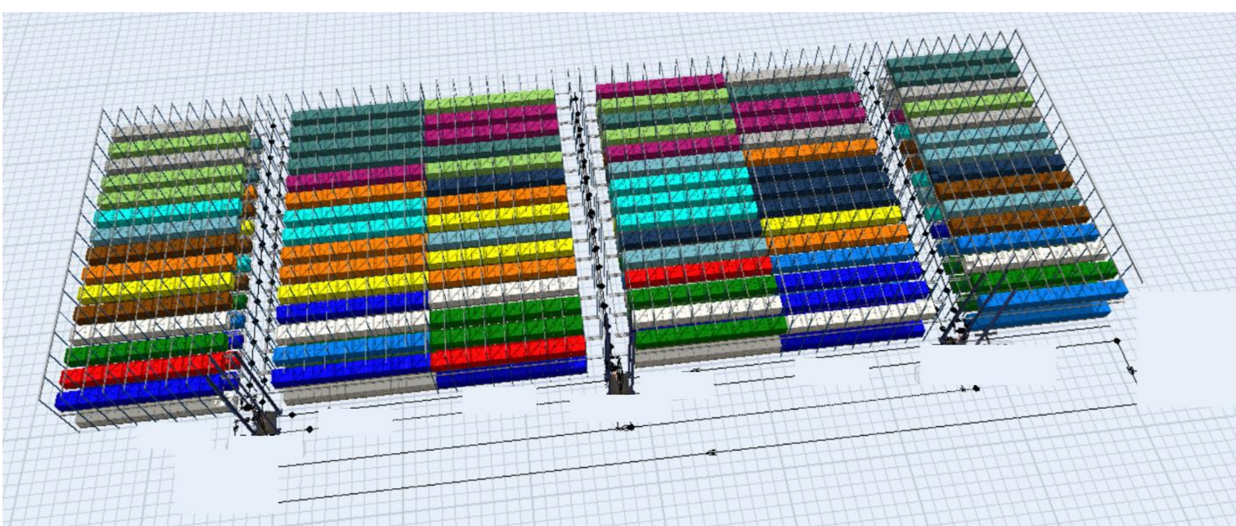


Image 3. Layout 3

3.2.4. Output key performance indicators (KPIs).

The objective of the study is to provide a decision support methodology for companies and representatives in charge who are to set up an automated warehouse using the existing technology – ESMARTSHUTTLE. The novelty of the study is included in the fact that the system is now being tested for a single-command: order fulfillment with an existing order history of a real local company. These conditions should provide candid outcomes to develop a helping hand for decisive actions, however, today any decision a manager makes should always base on a deep-data analysis and facts. So does this simulation and the study itself, therefore the next step to set-up a successful analysis is highlight the output variables.

While a good warehousing technique should improve quality performance, delivery time, customers satisfaction and reduce cost in logistics system (De Marco and Mangano, 2011), different classifications are given to the key performance indicators in order to sort out the 130 indicators in the earlier studies (Krauth, et al, 2005). Frazelle, 2002, for example, classified 25 most important KPIs inside 5 side to 5 side table, naming the left sides of the table as warehouse operations: receiving, put away, storage, order picking and shipping. The top headers of the table are named as follow: financial, productivity, utilization, quality and cycle time. The full table is as follows.

	Financial	Productivity	Utilization	Quality	Cycle Time
Receiving	Receiving cost per line	Receipts per man-hour	% Dock door utilization	%Receipts processed accurately	Receipt processing time per receipts
Putaway	Putaway cost per line	Putaways per man-hour	% Utilization of putaway labor and equipment	% Perfect putaways	Putaways cycle time (per putaway)
Storage	Storage space cost per item	Inventory per square foot	% Locations and cube occupied	% Locations without inventory discrepancies	Inventory days on hand
Order picking	Picking cost per order line	Order lines picked per man-hour	% Utilization of picking labor and equipment	% Perfect picking lines	Order picking cycle time (per order)
Shipping	Shipping cost per customer order	Orders prepared for shipment per man-hour	% Utilization of shipping docks	% Perfect shipments	Warehouse order cycle time

Table 4. 25 KPIs by Frazelle

The simulation we run, however, is a single-command – only for order picking (order fulfillment), therefore the KPIs we consider are slightly different from what is provided in the previous literatures and work done. The full list of important performance indicators that we consider in the simulation is listed further. Further on, some of these indicators will be analyzed descriptively, as well as deeply in order to provide data-driven results.

- **Throughput [orders/h]**

Warehouse throughput refers to the total number of units, or SKUs that are processed and moved through the warehouse system, either during the storage or the retrieval command. In the case of our simulation, we only consider the total number of SKUs that exited from the inventory storage.

- **Receptivity [units]**

Receptivity parameter of the warehouse represents the total number of unit loads that can be stored, given in the specific layout of a warehouse. It can also be referred as the storage capacity.

- **Selectivity [%]**

This percentage parameter is calculated by dividing the total number of directly reachable unit loads to total number of unit loads stored in the structure.

- **Shelf occupation [%]**

Another ratio that describes the total space occupied by all the existing unit loads and is calculated by dividing the total inventory space to the total available space.

- **Unoccupied space [%]**

A logical continuation of the previous indicator, it shows how much of the space is not occupied by unit loads, but yet available. It can easily be calculated by subtracting the shelf occupation from 100%.

- **AGV utilization [%]**

This percentage indicator shows how much of use was exploited by the order picking activities (including travel time and SKU picking time) in total duration in which the vehicle was active. The calculation is done by dividing the total time when the vehicle was active to the total period in which the vehicle was active + waiting for the task to be assigned.

- **Average order cycle time [min/order]**

In most of the recent literature the average order cycle time is defined as the time between two orders placed in a warehouse. However in the model such definition will not fully work, since the order cycle time we utilize starts from the start of the vehicle after it has been assigned an order and finishes when the vehicle unloads the ready pallet in the output area. All the waiting times that could occur during this process should be considered inside of this time. In order to calculate the average of this indicator, we just need to divide the total time by the total number of orders.

- **Average order task time (Picking) [min/order]**

A follow-up indicator and resembles the previous KPI, except this one does not consider the waiting times happened when fulfilling the tasks assigned by the system.

- **Average order waiting time [min/order]**

Another complement of the cycle time, this indicator is calculated by dividing the total wait time that occurred during the fulfillment process by the total number of orders fulfilled during the considered time frame.

- **Directly reachable pallets [units]**

This parameter shows how many pallets a vehicle can reach to without using an elevator and a satellite. We use this factor to calculate the selectivity index.

- **N pallets stored [units]**

Total number of unit pallets that can be stored given the size of a warehouse. This indicator is also used to calculate the occupied and unoccupied space.

- **Area occupation [m3]**

It is the total volume of the warehouse calculated geometrically.

- **Area occupation [m2]**

It is the total space area that the warehouse has taken, calculated geometrically.

- **Average meters run by AGV (or AGVs) [m/AGV]**

As the description suggest, this indicator is calculated by dividing the total number of meters travelled by all the vehicles to the total number of vehicles that were included in the operational activity.

- **Average energy consumption per AGV [KWh/AGV]**

This is yet another built-in performance indicator inside the model. In order to calculate the most precise value earlier studies were useful, namely Akpunar et al., 2017 and Bruno et al. 2016. Moreover, assuming that the maximum load that the pallet can bear is 1500 kg, the formula used in the model is:

$$\frac{p_e - p_f}{1500}$$

Here:

P_e is the power needed when the shuttle is empty;

P_f is the power needed when the shuttle is full.

All of the performance indicators listed above were modelled and inserted inside the simulation environment using the simulation software explained in the following chapter. For user convenience some of the calculations used comprehensive assumptions.

3.3. Tools used in the simulation and analysis

Tools used in the processes support decisionmakers – in this study, the authors, with credible information about how elements of the automated warehouse system operates under a variety of scenarios and conditions. Regardless of the type of the tools chosen, these tools provide objective assessments of performance in the order picking activity.

3.3.1. Discrete Event Simulation

Eder, 2020 concluded in his research that to identify the best design configuration and compute the performance indicators of the Automated Storage and Retrieval Systems, two main approaches have been used by the researchers most of the time in the past: Analytical models and Discrete Event Simulation.

Discrete Event Simulation (DES) is an approach used to model real world systems that can be broken down into a set of logically independent processes that autonomously advance through time. Each event occurs on a particular process, and is assigned a logical time period (a timestamp). The outcome of this event can be a result passed to one or more other processes. The content of the outcome may result in the initiation of new events to be processed at some specified future logical time. The fundamental statistical paradigm that supports DES is based in queuing theory. (Barett, Jayaraman, Patel, Skolnik).

Due to the wide-range of availability of simulation platforms just recently, many of the researchers in the near history have been using them in analyzing the effects of decision parameters in the performance of AVS/RS systems. For example, Lehrer et al, 2015 used the discrete event simulation to evaluate how the task execution of a Shuttle Based Storage and Retrieval system, which is a part of the AVS/RS was affected by the storage rack configuration (number of columns, tiers and isles, as well as the length, height and width). After conducting this research using the simulation model, he extended his study, picking again the DES as the main instrument of simulation in 2016, with more extensive rack configuration of nine different types.

Our research is also based on the DES using an external complementary – the order list in order to evaluate the indicators obtained by the performance of the technology used in an AVS/RS warehouse. More precise information about the DES platform is explained in the next section of the thesis.

3.3.2. FlexSim

FlexSim is a simulation software developed by FlexSim Software Products, Inc. which has prioritized itself the goal to establish a programming environment that is capable of reproducing any production process or environment and examining all management aspects. By this way it is possible to analyze the system in the simplest way and it gives an opportunity to identify any crucial points. The FlexSim simulation environment allows easy modeling, a 3D graphic view and high customization of objects, to set the path and the activities that the various entities must follow and perform, to create an interface that makes it possible the insertion from input of the variables characterizing the objects and displaying all the output statistics requested by the user. Its practicality and efficiency has led it to be used in diverse fields: starting from the production environment with simulations related to production and assembly lines, passing through the study of the handling of materials in which transport systems are considered and for the logistics and distribution area in which particular attention is given to the design of the supply chain and the work flow in a distribution center. Furthermore, it is also used to simulate the flow of data in a network, the maritime coordination of ships, the flow of traffic in the motorway and even pedestrian systems. The software was chosen because, through these peculiarities, it made possible to easily create the simulation model and reach the final purpose of this analysis: to apply the material handling AVS/RS to a warehouse and understand which conditions optimize the whole system and the advantages and disadvantages that a company can derive from its implementation. In addition, it is equipped with a graphical interface that allows the control and evaluation of the simulation during the process time. The program operates on discrete events and therefore the evolution of the state of the objects present in the model is independent of the trend of time but is determined by the occurrence of certain events.

For our experiment and simulation, in order to have the highest accuracy possible, the latest version of the software, that is FlexSim Version 21.0.9 (2021) was used. While various versions of the software might have had different user interface and set of menus, the version utilized for this specific research is explained further.

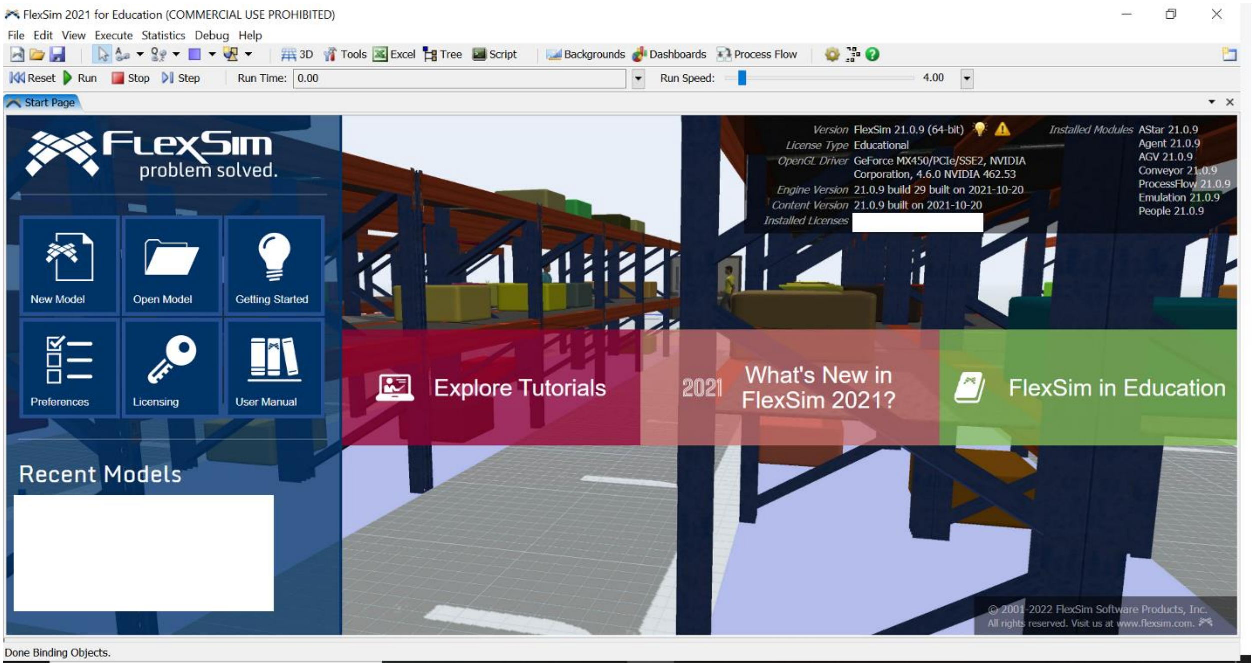


Image 4. FlexSim Initial Interface

Once the program is launched, it will take the user directly in the Start Page where most essential information about the version of the software is displayed on the top right corner of the interface.

The left side of the page contains 6 menus

- New Model – to start sketching the new simulation model;
- Open Model – to open an existing file from the local machine;
- Getting Started – it takes a user to a webpage with basic information on how to use the software;
- Preferences – to customize the working environment by changing options in Fonts and Colors, Environment, Libraries, Dynamic Content, Toolbar and Libraries;
- Licensing – to activate a license in order to use the software in fully-operational mode;
- User Manual – is another button that interacts with the user in order to provide more information about tutorials on the FlexSim web page.

If clicked on the New Model, the software takes the user to the main screen which is divided into several sections, each of which has a specific purpose, starting from to aid in graphics to creating (compiling) the code.

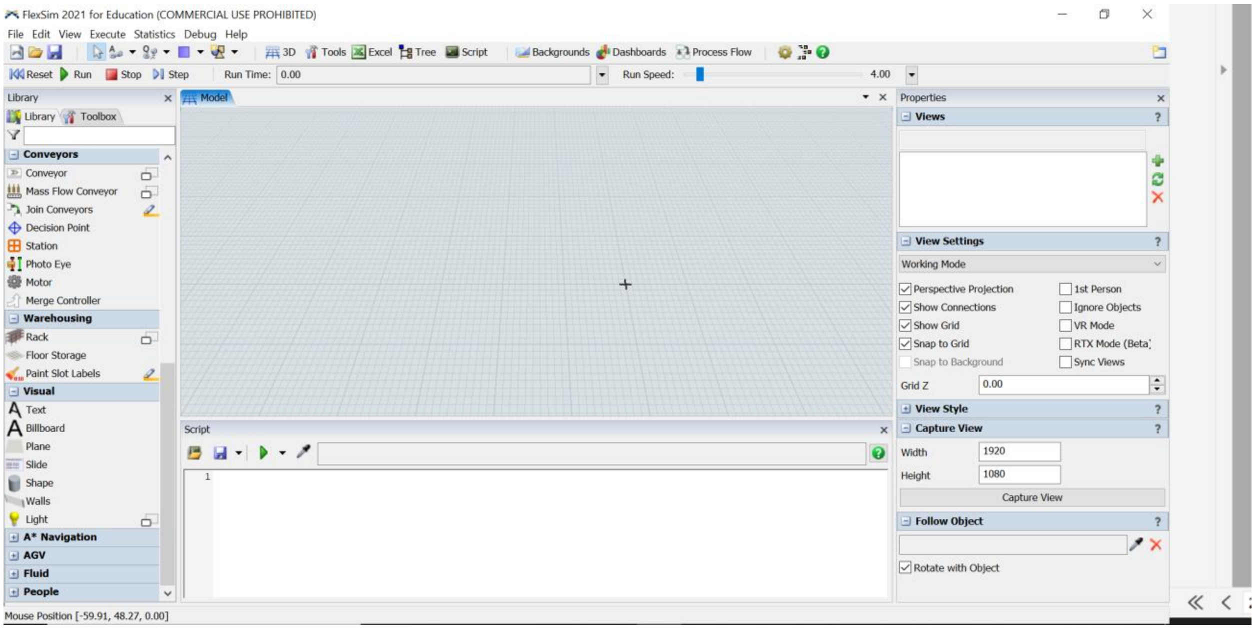


Image 5. FlexSim Model Interface

As can be seen in the screenshot, the left side of the interface presents the various libraries for the objects and the process flow. The middle top showcases the 3D model of the environment specifically built for the simulation in run and while it runs it will be possible to observe the whole process in that section. Alternatively, it is possible to observe the hierarchy of the model (the tree). Lower middle part of the display is the working area for compiling a code and it is possible to see the code lines, custom codes using this view. Finally, the section on the right can be used to observe the characteristics and values of each object.

FlexSim uses the graphics library OpenGL (Open Graphics Library) which is a simple document that stores information about the precise functions and the behavior of the graphically represented items. The choice of this bookcase allows you to have a realistic vision of the space, including dynamic lighting and concrete environmental effects. There is the possibility of creating a virtual driving route (fly paths) which gives the user and any interested parties the opportunity to show all the elements created in a 3D view and to create videos of the same in order if necessary, to show a presentation of the work.

Flexsim enables a developer to have various views of the model: 2D planar, 3D orthographic and perspective views and through its hierarchy (tree). This function makes the software even more complete, with the possibility of controlling the whole model from multiple perspectives and of being able to improve or change it considering every event or action that occurs throughout the simulation. The software is also designed for the statistical analysis of values such as the productivity of an entity, the state of the object or its level of use. Dashboards are graphical interfaces used for a representation of these analyses and can be pre-defined and customized by the user. In addition, other connections can be made with spreadsheet and database for a more complete analysis, if needed.

As far as the study of data is concerned, FlexSim libraries also include a tool that creates multiple sets of input variables and performance indicators, simulates them simultaneously and via the dashboard, allows for an immediate graphic display of the final results. Usually, several simulations of a model are conducted in the software in order to consider various possible and feasible scenarios and through the final results, the most efficient one is chosen.

FlexSim has another powerful tool called OptQuest that was built with an algorithm that manages to independently choose the optimal situation, considering the defined constraints by the user and the required objective functions. The FleXsim objects are widely customizable and present in pre-configured picklists from which, using the Drag and Drop mode, one can take the elements and place them with the mouse. The library already contains all the basic objects that can be used in the construction of the model and each of them is characterized by behaviors that can be parameterized, combined and modified.

3.3.3. Minitab versus MS Excel

Minitab is a software platform, designed essentially for the Six Sigma professionals and is used to perform data analysis of various difficulties. Its main strength comes with its simplicity and effectivity of inputting statistical data, manipulating, identifying trends and graphically representing needed results. Businesses of all sizes use Minitab as a powerful tool to obtain effective solutions for the most Six Sigma projects.

There are number of reasons why Minitab is preferred to MS Excel, which are counted as follow:

1. Using formulas in MS Excel requires from a user certain level of acquaintance with its formulas, however in Minitab only a few clicks get the user to the point wanted.
2. Minitab has an option of "Project Manager" that makes managing many Worksheets easily and effectively.
3. While MS Excel is mainly used as a general tool to manage data, Minitab has extensive functions such as hypothesis testing and statistic visualization.
4. Minitab is more on the analytical side, while MS excel is more on the computation side.

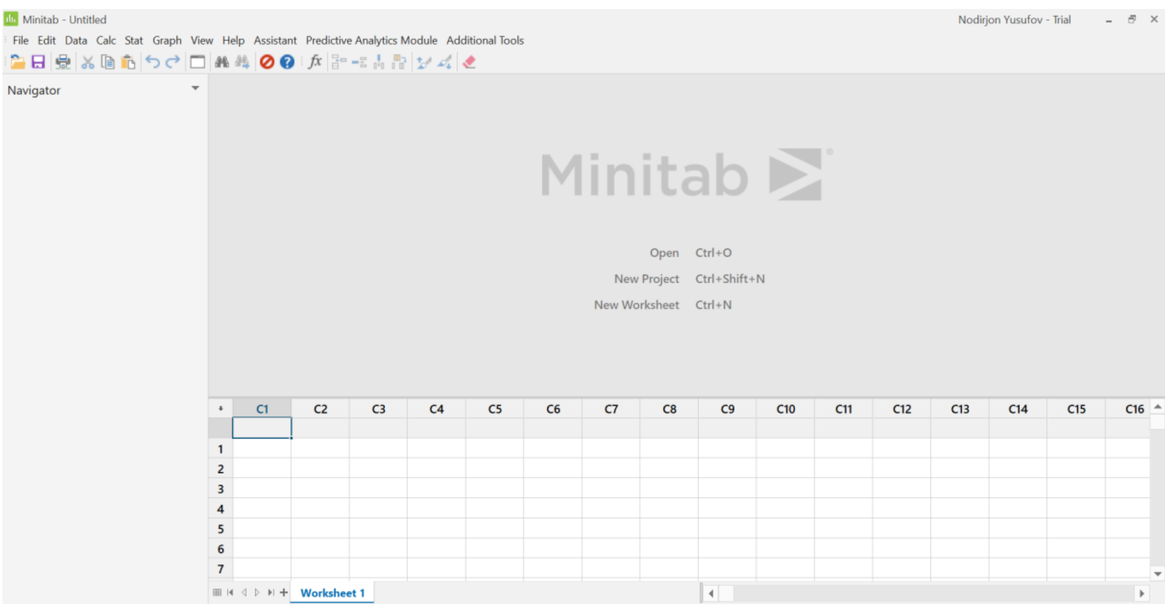


Image 6. Minitab interface

Image above illustrates the user interface window when the Minitab is launched. The main view is divided into two – Session Window and Worksheet. Main data input is carried out in the worksheet are just like MS Excel and the analysis output is shown in the session window. During our analysis we use MS Excel for storing statistical data, performing some basic calculations and drawing different graphs, while Minitab is used in our analysis to perform statistical analysis such as finding mean values, comparing ratios and analyzing trends.

4. SIMULATION EXECUTION

As has been declared in the introduction of this research, this is a consecutive study in the series of studies of the new technology developed. Number of simulations thus were already run that included all the physical characteristics of the technology and the conceptual warehouse was already built inside the FlexSim software. The novelty of this research is that it is the first time that the previously built model is now being tested under the circumstances of the real order list. The discussion of the existing model starts this chapter, which is followed by the original list of simulations that belongs to this specific study. The whole stages of the simulation is further explained, with obtaining the final results making up the finish line of this unit.

4.1. Pre-existing simulation model

In her research, Ariano, 2021 explained the structure of the simulation model in precise details. According to the paper, the process flow of different storage policies vary from each other due to the code that was written in FlexScript – a built-in programming tool of FlexSim and some parts of the code was inserted from the C++ coding platform.

Once the existing model is loaded in the FlexSim simulator, there are several tabs in the working area to be able to modify the model or refer to the simulation results. 4 of the main important tabs are explained below.

Tab 1 displays the 3D model of the conceptual warehouse with predetermined configurations. If the simulation is not running, no SKUs are assigned to slots, therefore the racks are empty. Once the run command is given, it is possible to see the AGV performing the actions as per the information system. FlexSim gives the possibility to observe the process in various run speed, starting from x1 up to x130,000. Thanks to the time control menu (Run Time) it is also possible to automatically stop the process at some pre-set point of time. The view of Tab 1 before the start of the simulation can be seen in the picture below.

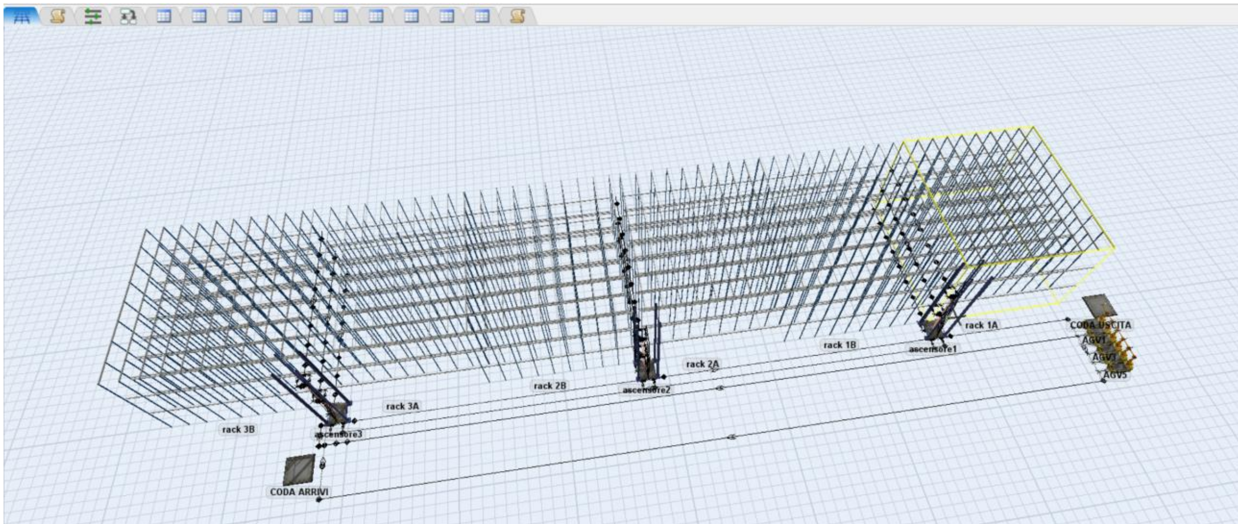


Image 7. 3D Model of the Warehouse.

Tab 2 is the display of programming script, as declared above, written using specific local language, as well as importing from the C++ library. It has the total line of 809.

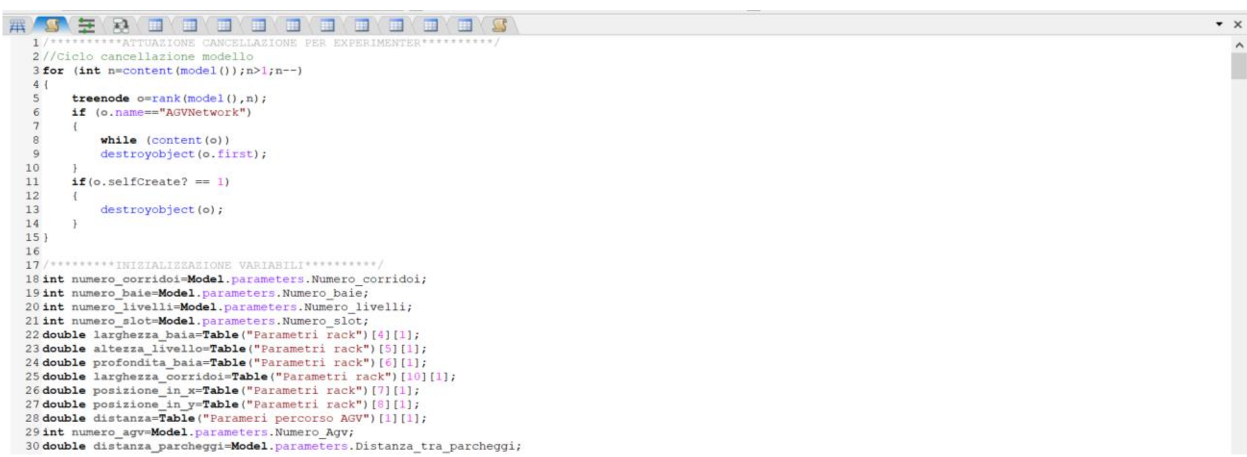


Image 8. Coding Area

Moving on to the next – Tab 3, it is possible to see the input parameters for the current simulation model. These parameters have been discussed and pre-set with the collaborators, as well as other stakeholders of the technology of interest. It is also decided before starting the simulation that some of these input parameters are changed over time, that results in having a diverse simulation list, which is described in the next section. Meanwhile, the changing variables among the inputs in the table, displayed in the picture below are: storage_policy (codified), Numero_baie, Numero_livelli, and Numero_AGV. All the other indexes are kept constant throughout the whole set of rounds.

Parameters 13

Name	Value	Display Units
Storage_policy	2	
Generazione_ordini	1	
Frequenza_ordini_misti	50	
Frequenza_ordini_interi	9999999	
N_sku	15	
Numero_baie	8	
Numero_livelli	3	
Numero_slot	1	
Numero_corridoi	3	
Numero_Agv	6	
Distanza_tra_parcheggi	1	
Numero_pallet_slot	10	
Aggiorno_tabella	5	

Image 9. Input Parameters

The last important tab before the start of the simulation is Tab 4, that is the display of a process flow for five different storage policies. From here it will be possible to see the logic behind any operation and which part of the code is connected t which activities. The screenshot of the tab is provided below.

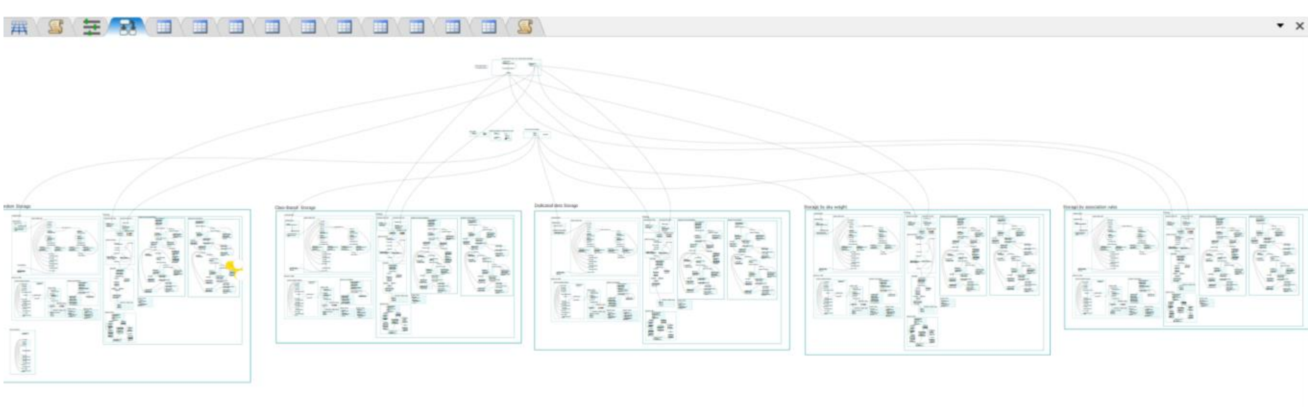


Image 10. Process Flows

4.2. List of simulations

There are several differences of this set of simulations from the previous ones performed to test the ESMARTSHUTTLE. First and the most pointed out one is the fact that it is being conducted with real transaction history and order list. The second difference is that basing on the previous research outcomes, this time we decided not to test the Randomized Storage policy due to its irrelevance with the technology. The next difference is that the SKU database of the model has been updated in alignment with the product list obtained, so that the weight of unit loads are changed. Finally, the simulation list has been developed taking into account the acceptable values of the variables. Below is informed about the list of input variables with their acceptable values, determined by the collaborators.

Levels	Bays	AGV	Storage policy	Interarrival time
2	5	1	Class Based	X1
6	15	6	Dedicated Slot	X3
			By Weight	
			Association Rule	

Table 5. Input Variables

Considering all the possible scenarios, we ended up with 64 different simulations. The full list is in the following table.

# of simulations	Levels	Bays	AGV	SP	IT	# of simulations	Levels	Bays	AGV	SP	IT
1	2	5	1	CB	X3	33	6	5	1	CB	X3
2	2	5	1	CB	X1	34	6	5	1	CB	X1
3	2	5	1	DS	X3	35	6	5	1	DS	X3
4	2	5	1	DS	X1	36	6	5	1	DS	X1
5	2	5	1	bW	X3	37	6	5	1	bW	X3
6	2	5	1	bW	X1	38	6	5	1	bW	X1
7	2	5	1	AR	X3	39	6	5	1	AR	X3
8	2	5	1	AR	X1	40	6	5	1	AR	X1
9	2	5	6	CB	X3	41	6	5	6	CB	X3
10	2	5	6	CB	X1	42	6	5	6	CB	X1
11	2	5	6	DS	X3	43	6	5	6	DS	X3
12	2	5	6	DS	X1	44	6	5	6	DS	X1
13	2	5	6	bW	X3	45	6	5	6	bW	X3
14	2	5	6	bW	X1	46	6	5	6	bW	X1
15	2	5	6	AR	X3	47	6	5	6	AR	X3

16	2	5	6	AR	X1	48	6	5	6	AR	X1
17	2	15	1	CB	X3	49	6	15	1	CB	X3
18	2	15	1	CB	X1	50	6	15	1	CB	X1
19	2	15	1	DS	X3	51	6	15	1	DS	X3
20	2	15	1	DS	X1	52	6	15	1	DS	X1
21	2	15	1	bW	X3	53	6	15	1	bW	X3
22	2	15	1	bW	X1	54	6	15	1	bW	X1
23	2	15	1	AR	X3	55	6	15	1	AR	X3
24	2	15	1	AR	X1	56	6	15	1	AR	X1
25	2	15	6	CB	X3	57	6	15	6	CB	X3
26	2	15	6	CB	X1	58	6	15	6	CB	X1
27	2	15	6	DS	X3	59	6	15	6	DS	X3
28	2	15	6	DS	X1	60	6	15	6	DS	X1
29	2	15	6	bW	X3	61	6	15	6	bW	X3
30	2	15	6	bW	X1	62	6	15	6	bW	X1
31	2	15	6	AR	X3	63	6	15	6	AR	X3
32	2	15	6	AR	X1	64	6	15	6	AR	X1

Table 6. Full List of Simulations – Round 1

Each of 64 unique simulations are then planned to be repeated 5 times with an aim of obtaining diverse set of results for statistical analysis purposes, making the grand total number of rounds 64x5=320.

4.3. Initialization

Prior to start the simulation there are several steps to be completed. As per the discussions with supervisors of this study, we decided that we are going to simulate the operation of the warehouse in 1 full shift of 8 hour working day. Therefore, in the Run Time box of the interface we have set the total duration of the run as 28800 seconds, as illustrated in the picture below.

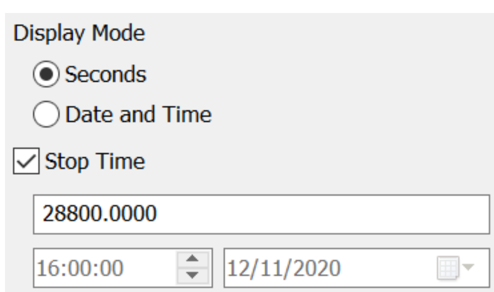


Image 11. FlexSim Model Stop Time

In the next step we insert necessary information about the unit loads and transaction history – order list of these unit loads so that the model is ready to replicate the future orders basing on the past ones. To do that, on the Toolbox dashboard of the interface we fin Excel Import/Export command and upload the excel file. The file was prepared beforehand in the proper format and with proper values for the model to be able to read and understand it.

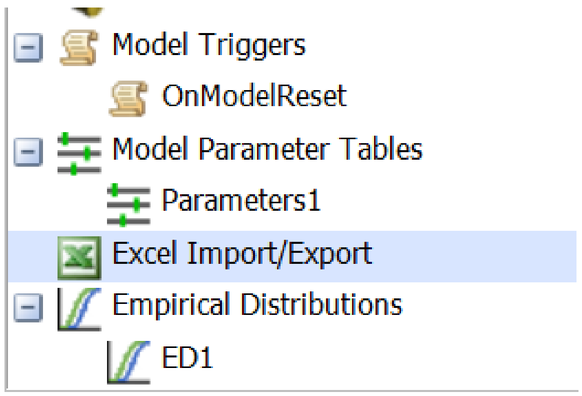


Image 12. FlexSim Excel Import

Once the file is correctly loaded, the table in the working area named as "past_orders" should be updated correctly. The screenshot below from the model represents the table and its configurations. There are 30 columns and 1893 rows, so future orders created by the simulator bases on the historical data of 1892 transactions.

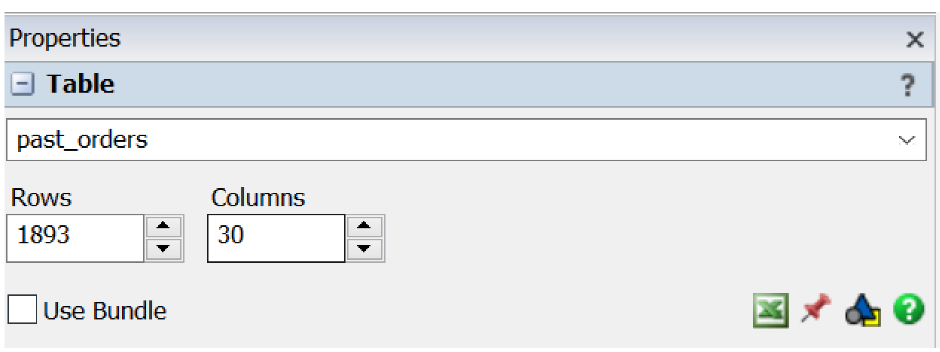


Image 13. Past Orders Table

The next table to be filled in as part of the initialization process is the one with the name "weights_sku". As the name suggests, it contains all the SKUs with their respective weight measurements, as this will be the pillars of the Weight based storage policy.

The initiation of the process flow creates a token which is an indication of the progress of warehouse filling activity, In this section of the process flow, each of the slots in each rack will receive a label that preserves in it the information of the product that it will host because at this stage, the model is working on all the necessary procedures to fill the warehouse in a complete manner. The tables and lists which contain the Shuttles, the Satellites and the Robots are also created in this stage, and some preliminary analyses are performed to initiate tables that will record information needed to calculate the model performance indicators. Once these first actions are complete, the token moves into the other process box. In this section for every location of the rack slot, there is a creation of a pallet that is then automatically loaded with 12 boxes. The label of the slot address, containing the SKU information, is passed first to each pallets and then through to boxes, so that the pallet is dedicated to a slot with the same SKU. This procedure continues until the time that the warehouse is filled completely, which means that all levels, all sides and all bays of the warehouse have been correctly filled with pallets (Ariano, 2021).

4.4. Running the simulation

To improve confidence over running the simulation, one of 5 repeated runs are conducted first, also to assess if the order list is compatible with the pre-built model. This led to running 64 simulations at this stage. Having the model open in the simulator interface, we first "Reset" the processes, to prevent the outcome of each run getting associated wit each other. The reset button takes us to the coding platform, where we press on the "Continue" button by letting the algorithm accept the conditions. As part of the next step, to assign desired input variables, we move to Tab 2 and enter inputs respectively to each run. Since the table does not contain input area for the interarrival time, for the first 32 out of 64 simulations we set this condition using the custom code of the "Empirical_Distribution". Once the first 32 simulations are completed as the frequency of orders at x3 speed, for the next part we again fix the custom code to make the orders to be generated at x1 speed. The difference between the custom codes to define such condition can be seen in the screenshot below.

```
/**Custom Code*/
Object current = param(1);
treenode activity = param(2);
treenode processFlow = ownerobject(activity);
/***popup:EmpiricalDistribution*/
return Empirical("ED1").get();
```

```
/**Custom Code*/
Object current = param(1);
treenode activity = param(2);
treenode processFlow = ownerobject(activity);
/***popup:EmpiricalDistribution*/
return Empirical("ED1").get()/3;
```

Figure 12. Frequency Differentiation Code Scripts

User interface during the process of simulation enables a user to observe it at desired rate of speed, as informed above during explanation of features of FlexSim. While the simulations runs, the output tables are populated with information derived from the process thanks to the process flow, that is controlled by codes. An example of the output table at the end of the first simulation is provided in the next screenshot.

	Model
Throughput [orders/h]	10.1141
Receptivity [units]	600
Selectivity [%]	0.1000
Shelf Occupation [%]	0.9933
Unoccupied space [%]	0.0067
AGV utilization [%]	0.7040
Avg Order Cycle time [min/order]	14.4499
Avg order Task time (Picking) [min/order]	2.3557
Avg order Task time (Retrieval) [min/order]	0
Avg order waiting time [min/order]	10.3412
Directly reachable pallets [units]	60
N pallets stored [unit]	596
Area Occupation [m3]	5220
Area Occupation [m2]	1087.8000
Avg meters run by Agvs [m/Agv]	15826.8769
Avg Energy consumption per Agv [KWh/Agv]	4.3964
Meters Agv1	15826.8769
Energy consumption Agv1	4.3964

Table 7. FlexSim Model Output Table Example

Interesting scenario also arises in the table with the name “Lista_Ordini”, as it is possible to see the list of orders with an array of 15 SKUs, order Entry_time and Exit_time, Waiting_time_at_the_beginning, Waiting_time_during_picking, Cycle_time and Task_time_picking.

To calculate the total number of orders fulfilled during 8-hour shift of the warehouse, we need to take into account the exit time of the order. If an order enters the system, but due to the vehicle unavailability the order needs to wait, and is not completed during that shift, we cannot count it as the fulfilled order, thus, we omit such orders in the list. As can be seen in from the table in the screenshot below, out of 43 orders completed under the circumstances of Simulation_1, (Bays 5, Levels 2, CB, AGV 1, x3 frequency of orders), only 2 orders did not have to wait for the vehicle. Because only 1 AGV is used in this simulation, the table illustrates correctly that the AGV did not have to wait for picking activity, since none of the bays and lifts were occupied by another picking activity.

Orders	Entry_time	Exit_time	Waiting time at the beginning	Waiting time during picking	Cycle time	Task time Picking
Array[15]: {0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	7031.7	7440.6	155.8	0.0	408.8	253.1
Array[15]: {0, 0, 0, 0, 2, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	8341.9	8557.8	0.0	0.0	215.9	215.9
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	8627.3	8839.5	0.0	0.0	212.2	212.2
Array[15]: {0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	8793.4	9070.6	54.1	0.0	277.3	223.2
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	8923.2	9338.0	155.4	0.0	414.8	259.4
Array[15]: {0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	9060.9	10106.0	703.2	0.0	1045.1	341.9
Array[15]: {0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0}	9450.9	10334.6	663.0	0.0	883.7	220.7
Array[15]: {0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0}	9542.1	10565.8	800.5	0.0	1023.7	223.2
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	9551.7	10793.5	1022.1	0.0	1241.8	219.8
Array[15]: {0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0}	9728.7	11013.8	1072.9	0.0	1285.1	212.2
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0}	9921.2	11242.4	1100.5	0.0	1321.2	220.7
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0}	9922.0	11636.2	1328.4	0.0	1714.2	385.7
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0}	9979.6	11881.0	1664.5	0.0	1901.3	236.8
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	10404.5	12109.7	1484.5	0.0	1705.2	220.7
Array[15]: {0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0}	10954.3	12329.9	1163.4	0.0	1375.6	212.2
Array[15]: {0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	11094.3	12561.0	1243.6	0.0	1466.8	223.2
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0}	11096.0	12784.9	1473.1	0.0	1688.9	215.9
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	11432.6	13278.4	1637.6	0.0	1845.8	208.2
Array[15]: {0, 0, 1, 0, 0, 0, 0, 2, 0, 0, 0, 0, 0, 0, 0}	11937.2	13555.7	1349.3	0.0	1618.5	269.2
Array[15]: {0, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 1}	12366.8	13771.9	1196.8	0.0	1405.0	208.2
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1}	12680.4	14246.7	1302.1	0.0	1566.3	264.2
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	13320.6	14524.5	934.1	0.0	1203.9	269.8
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	13967.6	15310.6	1084.6	0.0	1343.0	258.4
Array[15]: {0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	14982.9	15534.5	335.8	0.0	551.6	215.9
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	15186.6	15861.4	355.9	0.0	674.8	318.9
Array[15]: {0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	15234.2	16101.9	635.2	0.0	867.7	232.5
Array[15]: {1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	15237.1	16448.5	872.8	0.0	1211.4	338.6
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1}	21246.3	21444.6	0.0	0.0	198.4	198.4
Array[15]: {0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	21276.9	21679.8	175.8	0.0	402.9	227.2
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	23765.7	24199.5	226.0	0.0	433.8	207.8
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	23969.7	24512.9	237.7	0.0	543.2	305.4
Array[15]: {0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	24462.2	24730.7	58.7	0.0	268.5	209.8
Array[15]: {0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0}	24515.5	25018.0	223.2	0.0	502.6	279.3
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1}	24859.7	25249.8	166.3	0.0	390.0	223.7
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0}	24937.8	25558.7	320.0	0.0	620.9	300.9
Array[15]: {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1}	25383.8	25787.4	182.9	0.0	403.6	220.7
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	25620.5	26011.2	174.8	0.0	390.7	215.9
Array[15]: {0, 0, 0, 0, 1, 2, 0, 0, 0, 0, 0, 0, 0, 0, 0}	25642.9	26446.5	376.4	0.0	803.6	427.2
Array[15]: {0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	26435.7	26906.2	279.8	0.0	470.5	190.7
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1}	27086.8	27358.0	63.0	0.0	271.1	208.2
Array[15]: {0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	27264.4	27597.9	101.6	0.0	333.4	231.9

Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0}	27948.0	28251.2	46.1	0.0	303.2	257.2
Array[15]: {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}	28000.6	28475.1	258.6	0.0	474.5	215.9

Table 8. Order Entry and Exit Time Table

4.5. First round results

First round of the process contains 64 simulations as previously described in the simulation list. For each of the simulations the output table illustrated above is derived from the system and inserted into Excel sheet. A downside of the output table is that it did not contain information about the number of fully fulfilled orders, and this process is recorded manually in the Excel sheet.

Investigation of the first 8 simulation results proceeds next. Referring to the simulation list, the first 8 simulations should test all the 4 considered storage policies with a fixed warehouse configuration of 5 bays in 2 levels, with x3 and x1 of frequency of orders. Output indexes provided below.

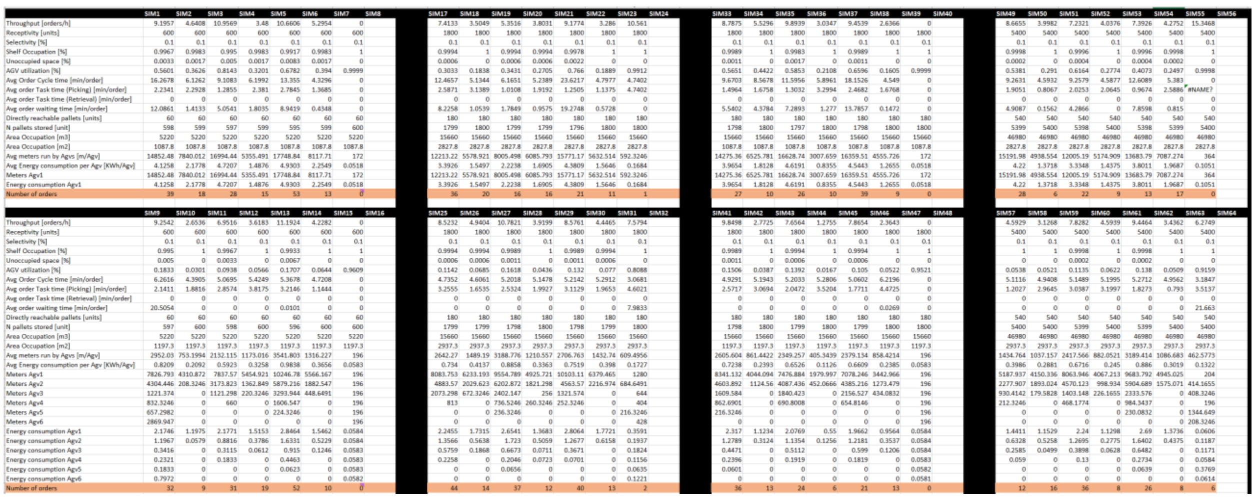
	SIM1	SIM2	SIM3	SIM4	SIM5	SIM6	SIM7	SIM8
Throughput [orders/h]	9.20	4.64	10.96	3.48	10.66	5.30	0.00	0
Receptivity [units]	600.00	600.00	600.00	600.00	600.00	600.00	600.00	600
Selectivity [%]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.1
Shelf Occupation [%]	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1
Unoccupied space [%]	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0
AGV utilization [%]	0.56	0.36	0.81	0.32	0.68	0.39	1.00	0.9999
Avg Order Cycle time [min/order]	16.27	6.13	9.11	6.20	13.36	4.33	0.00	0
Avg order Task time (Picking) [min/order]	2.23	2.29	1.29	2.38	2.78	1.37	0.00	0
Avg order Task time (Retrieval) [min/order]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Avg order waiting time [min/order]	12.09	1.41	5.05	1.80	8.94	0.43	0.00	0
Directly reachable pallets [units]	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60
N pallets stored [unit]	598.00	599.00	597.00	599.00	595.00	599.00	600.00	600
Area Occupation [m3]	5220.00	5220.00	5220.00	5220.00	5220.00	5220.00	5220.00	5220
Area Occupation [m2]	1087.80	1087.80	1087.80	1087.80	1087.80	1087.80	1087.80	1087.8
Avg meters run by Agvs [m/Agv]	14852.48	7840.01	16994.44	5355.49	17748.84	8117.71	172.00	172
Avg Energy consumption per Agv [KWh/Agv]	4.13	2.18	4.72	1.49	4.93	2.25	0.05	0.0518
Meters Agv1	14852.48	7840.01	16994.44	5355.49	17748.84	8117.71	172.00	172
Energy consumption Agv1	4.13	2.18	4.72	1.49	4.93	2.25	0.05	0.0518
Number of orders	39	18	28	15	53	13	0	0

Table 9. 8 Simulation Output Indexes

Execution of automated order generation and past historical transaction data resulted in abnormal data for the storage policy with the Association Rule, as can be seen from Simulation 7 and Simulation 8. Several precautions and modifications in the setup of the model has been performed to fix the issue, however giving the same abnormal outcome for repeatedly conducted runs. Therefore, the study further focused only on the 3 storage policies and their performance indicators.

Although the first run already generated precise and useful data to conduct first step of statistical analysis, with a purpose of creating bigger and diverse dataset, no data analysis carried out at this point.

Excluding output data related to Association Rule, meaning that omitting statistical info of 2 simulations in every 8 set, for the first round we had 48 successfully run simulations with processable indexes. The full list of the first round results, even though difficult, is represented in the screenshot below.



	SIM1	SIM2	SIM3	SIM4	SIM5	SIM6	SIM7	SIM8
Throughput [orders/h]	9.1957	4.6408	10.9569	3.48	10.6606	5.2954	0	
Receptivity [units]	600	600	600	600	600	600	600	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9967	0.9983	0.995	0.9983	0.9917	0.9983	1	
Unoccupied space [%]	0.0033	0.0017	0.005	0.0017	0.0083	0.0017	0	
AGV utilization [%]	0.5601	0.3626	0.8143	0.3201	0.6782	0.394	0.9999	
Avg Order Cycle time [min/order]	16.2678	6.1262	9.1083	6.1992	13.355	4.3296	0	
Avg order Task time (Picking) [min/order]	2.2341	2.2928	1.2855	2.381	2.7845	1.3685	0	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	12.0861	1.4133	5.0541	1.8035	8.9419	0.4348	0	
Directly reachable pallets [units]	60	60	60	60	60	60	60	
N pallets stored [unit]	598	599	597	599	595	599	600	
Area Occupation [m3]	5220	5220	5220	5220	5220	5220	5220	
Area Occupation [m2]	1087.8	1087.8	1087.8	1087.8	1087.8	1087.8	1087.8	
Avg meters run by Agvs [m/Agv]	14852.48	7840.012	16994.44	5355.491	17748.84	8117.71	172	
Avg Energy consumption per Agv [KWh/Agv]	4.1258	2.1778	4.7207	1.4876	4.9303	2.2549	0.0518	
Meters Agv1	14852.48	7840.012	16994.44	5355.491	17748.84	8117.71	172	
Energy consumption Agv1	4.1258	2.1778	4.7207	1.4876	4.9303	2.2549	0.0518	
Number of orders	39	18	28	15	53	13	0	

	SIM17	SIM18	SIM19	SIM20	SIM21	SIM22	SIM23	SIM24
Throughput [orders/h]	7.4133	3.5049	5.3516	3.8031	9.1774	3.286	10.561	
Receptivity [units]	1800	1800	1800	1800	1800	1800	1800	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9994	1	0.9994	0.9994	0.9978	1	1	
Unoccupied space [%]	0.0006	0	0.0006	0.0006	0.0022	0	0	
AGV utilization [%]	0.3033	0.1838	0.3431	0.2705	0.766	0.1889	0.9912	
Avg Order Cycle time [min/order]	12.4657	5.1344	6.1651	5.2389	23.6217	4.7977	4.7402	
Avg order Task time (Picking) [min/order]	2.5871	3.1389	1.0108	1.9192	1.2505	1.1375	4.7402	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	8.2258	1.0539	1.7849	0.9575	19.2748	0.5728	0	
Directly reachable pallets [units]	180	180	180	180	180	180	180	
N pallets stored [unit]	1799	1800	1799	1799	1796	1800	1800	
Area Occupation [m3]	15660	15660	15660	15660	15660	15660	15660	
Area Occupation [m2]	2827.8	2827.8	2827.8	2827.8	2827.8	2827.8	2827.8	
Avg meters run by Agvs [m/Agv]	12213.22	5578.921	8005.498	6085.793	15771.17	5632.514	592.3246	
Avg Energy consumption per Agv [KWh/Agv]	3.3926	1.5497	2.2238	1.6905	4.3809	1.5646	0.1684	
Meters Agv1	12213.22	5578.921	8005.498	6085.793	15771.17	5632.514	592.3246	
Energy consumption Agv1	3.3926	1.5497	2.2238	1.6905	4.3809	1.5646	0.1684	
Number of orders	36	20	16	16	21	11	1	

	SIM33	SIM34	SIM35	SIM36	SIM37	SIM38	SIM39	SIM40
Throughput [orders/h]	8.7875	5.5296	9.8939	3.0347	9.4539	2.6366	0	
Receptivity [units]	1800	1800	1800	1800	1800	1800	1800	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9989	1	0.9983	1	0.9989	1	1	
Unoccupied space [%]	0.0011	0	0.0017	0	0.0011	0	0	
AGV utilization [%]	0.5651	0.4422	0.5853	0.2108	0.6596	0.1605	0.9999	
Avg Order Cycle time [min/order]	9.6703	8.5678	11.5956	5.8961	18.1526	4.549	0	
Avg order Task time (Picking) [min/order]	1.4964	1.6758	1.3032	3.2994	2.4682	1.6768	0	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	5.5402	4.3784	7.2893	1.277	13.7857	0.1472	0	
Directly reachable pallets [units]	180	180	180	180	180	180	180	
N pallets stored [unit]	1798	1800	1797	1800	1798	1800	1800	
Area Occupation [m3]	15660	15660	15660	15660	15660	15660	15660	
Area Occupation [m2]	1087.8	1087.8	1087.8	1087.8	1087.8	1087.8	1087.8	
Avg meters run by Agvs [m/Agv]	14275.36	6525.781	16628.74	3007.659	16359.51	4555.726	172	
Avg Energy consumption per Agv [KWh/Agv]	3.9654	1.8128	4.6191	0.8355	4.5443	1.2655	0.0518	
Meters Agv1	14275.36	6525.781	16628.74	3007.659	16359.51	4555.726	172	
Energy consumption Agv1	3.9654	1.8128	4.6191	0.8355	4.5443	1.2655	0.0518	
Number of orders	27	10	26	10	39	9	0	

	SIM49	SIM50	SIM51	SIM52	SIM53	SIM54	SIM55	SIM56
Throughput [orders/h]	8.6655	3.9982	7.2321	4.0376	7.3926	4.2752	15.3468	
Receptivity [units]	5400	5400	5400	5400	5400	5400	5400	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9998	1	0.9996	1	0.9996	0.9998	1	
Unoccupied space [%]	0.0002	0	0.0004	0	0.0004	0.0002	0	
AGV utilization [%]	0.5381	0.291	0.6164	0.2774	0.4073	0.2497	0.9998	
Avg Order Cycle time [min/order]	9.2631	4.5932	9.2579	4.5877	12.6089	5.383	0	
Avg order Task time (Picking) [min/order]	1.9051	0.8067	2.0253	2.0645	0.9674	2.5886	#NAME?	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	4.9087	0.1562	4.2866	0	7.8598	0.815	0	
Directly reachable pallets [units]	540	540	540	540	540	540	540	
N pallets stored [unit]	5399	5400	5398	5400	5398	5399	5400	
Area Occupation [m3]	46980	46980	46980	46980	46980	46980	46980	
Area Occupation [m2]	2827.8	2827.8	2827.8	2827.8	2827.8	2827.8	2827.8	
Avg meters run by Agvs [m/Agv]	15191.98	4938.554	12005.19	5174.909	13683.79	7087.274	364	
Avg Energy consumption per Agv [KWh/Agv]	4.22	1.3718	3.3348	1.4375	3.8011	1.9687	0.1051	
Meters Agv1	15191.98	4938.554	12005.19	5174.909	13683.79	7087.274	364	
Energy consumption Agv1	4.22	1.3718	3.3348	1.4375	3.8011	1.9687	0.1051	
Number of orders	28	6	22	9	13	17	0	

	SIM9	SIM10	SIM11	SIM12	SIM13	SIM14	SIM15	SIM16
Throughput [orders/h]	9.2542	2.6536	6.9516	3.6183	11.1924	4.2282	0	
Receptivity [units]	600	600	600	600	600	600	600	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.995	1	0.9967	1	0.9933	1	1	
Unoccupied space [%]	0.005	0	0.0033	0	0.0067	0	0	
AGV utilization [%]	0.1833	0.0301	0.0938	0.0566	0.1707	0.0644	0.9609	
Avg Order Cycle time [min/order]	6.2616	4.3905	5.0695	5.4249	5.3678	4.7208	0	
Avg order Task time (Picking) [min/order]	2.1411	1.8816	2.8574	3.8175	3.2146	1.1444	0	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	20.5054	0	0	0	0.0101	0	0	
Directly reachable pallets [units]	60	60	60	60	60	60	60	
N pallets stored [unit]	597	600	598	600	596	600	600	
Area Occupation [m3]	5220	5220	5220	5220	5220	5220	5220	
Area Occupation [m2]	1197.3	1197.3	1197.3	1197.3	1197.3	1197.3	1197.3	
Avg meters run by Agvs [m/Agv]	2952.03	753.1994	2132.115	1173.016	3541.803	1316.227	196	
Avg Energy consumption per Agv [KWh/Agv]	0.8209	0.2092	0.5923	0.3258	0.9838	0.3656	0.0583	
Meters Agv1	7826.793	4310.872	7837.57	5454.921	10246.78	5566.167	196	
Meters Agv2	4304.446	208.3246	3173.823	1362.849	5879.216	1882.547	196	
Meters Agv3	1221.374	0	1121.298	220.3246	3293.944	448.6491	196	
Meters Agv4	832.3246	0	660	0	1606.547	0	196	
Meters Agv5	657.2982	0	0	0	224.3246	0	196	
Meters Agv6	2869.947	0	0	0	0	0	196	
Energy consumption Agv1	2.1746	1.1975	2.1771	1.5153	2.8464	1.5462	0.0584	
Energy consumption Agv2	1.1967	0.0579	0.8816	0.3786	1.6331	0.5229	0.0584	
Energy consumption Agv3	0.3416	0	0.3115	0.0612	0.915	0.1246	0.0583	
Energy consumption Agv4	0.2321	0	0.1833	0	0.4463	0	0.0583	
Energy consumption Agv5	0.1833	0	0	0	0.0623	0	0.0583	
Energy consumption Agv6	0.7972	0	0	0	0	0	0.0582	
Number of orders	32	9	31	19	52	10	0	

	SIM25	SIM26	SIM27	SIM28	SIM29	SIM30	SIM31	SIM32
Throughput [orders/h]	8.5232	4.9404	10.7821	3.9199	8.5761	4.4465	7.5794	
Receptivity [units]	1800	1800	1800	1800	1800	1800	1800	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9994	0.9994	0.9989	1	0.9989	0.9994	1	
Unoccupied space [%]	0.0006	0.0006	0.0011	0	0.0011	0.0006	0	
AGV utilization [%]	0.1142	0.0685	0.1618	0.0436	0.132	0.077	0.8088	
Avg Order Cycle time [min/order]	4.7352	4.6061	5.2018	5.1478	5.2142	5.2912	3.0681	
Avg order Task time (Picking) [min/order]	3.2555	1.6535	2.5324	1.9927	3.1129	1.9653	4.6021	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	0	0	0	0	0	0	7.9833	
Directly reachable pallets [units]	180	180	180	180	180	180	180	
N pallets stored [unit]	1799	1799	1798	1800	1798	1799	1800	
Area Occupation [m3]	15660	15660	15660	15660	15660	15660	15660	
Area Occupation [m2]	2937.3	2937.3	2937.3	2937.3	2937.3	2937.3	2937.3	
Avg meters run by Agvs [m/Agv]	2642.27	1489.19	3188.776	1210.557	2706.763	1432.74	609.4956	
Avg Energy consumption per Agv [KWh/Agv]	0.734	0.4137	0.8858	0.3363	0.7519	0.398	0.1727	
Meters Agv1	8083.753	6233.193	9554.789	4925.721	10103.11	6379.465	1280	
Meters Agv2	4883.57	2029.623	6202.872	1821.298	4563.57	2216.974	684.6491	
Meters Agv3	2073.298	672.3246	2402.147	256	1321.574	0	644	
Meters Agv4	813	0	736.5246	260.3246	252.3246	0	404	
Meters Agv5	0	0	236.3246	0	0	0	216.3246	
Meters Agv6	0	0	0	0	0	0	428	
Energy consumption Agv1	2.2455	1.7315	2.6541	1.3683	2.8064	1.7721	0.3591	
Energy consumption Agv2	1.3566	0.5638	1.723	0.5059	1.2677	0.6158	0.1937	
Energy consumption Agv3	0.5759	0.1868	0.6673	0.0711	0.3671	0	0.1824	
Energy consumption Agv4	0.2258	0	0.2046	0.0723	0.0701	0	0.1156	
Energy consumption Agv5	0	0	0.0656	0	0	0	0.0635	
Energy consumption Agv6	0	0	0	0	0	0	0.1221	
Number of orders	44	14	37	12	40	13	2	

	SIM41	SIM42	SIM43	SIM44	SIM45	SIM46	SIM47	SIM48
Throughput [orders/h]	9.8498	2.7725	7.6564	1.2755	7.8654	2.3643	0	
Receptivity [units]	1800	1800	1800	1800	1800	1800	1800	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	0.9989	1	0.9994	1	0.9994	1	1	
Unoccupied space [%]	0.0011	0	0.0006	0	0.0006	0	0	
AGV utilization [%]	0.1506	0.0387	0.1392	0.0167	0.105	0.0522	0.9521	
Avg Order Cycle time [min/order]	4.9291	5.1943	5.2033	5.2806	5.0602	6.2196	0	
Avg order Task time (Picking) [min/order]	2.5717	3.0694	2.0472	3.5204	1.7711	4.4725	0	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	0	0	0	0	0	0.0269	0	
Directly reachable pallets [units]	180	180	180	180	180	180	180	
N pallets stored [unit]	1798	1800	1799	1800	1799	1800	1800	
Area Occupation [m3]	15660	15660	15660	15660	15660	15660	15660	
Area Occupation [m2]	1197.3	1197.3	1197.3	1197.3	1197.3	1197.3	1197.3	
Avg meters run by Agvs [m/Agv]	2605.604	861.4422	2349.257	405.3439	2379.134	858.4214	196	
Avg Energy consumption per Agv [KWh/Agv]	0.7238	0.2393	0.6526	0.1126	0.6609	0.2385	0.0583	
Meters Agv1	8341.132	4044.094	7476.884	1979.997	7078.246	3442.966	196	
Meters Agv2	4603.892	1124.56	4087.436	452.0666	4385.216	1273.479	196	
Meters Agv3	1609.584	0	1840.423	0	2156.527	434.0832	196	
Meters Agv4	862.6901	0	690.8008	0	654.8146	0	196	
Meters Agv5	216.3246	0	0	0	0	0	196	
Meters Agv6	0	0	0	0	0	0	196	
Energy consumption Agv1	2.317	1.1234	2.0769	0.55	1.9662	0.9564	0.0584	
Energy consumption Agv2	1.2789	0.3124	1.1354	0.1256	1.2181	0.3537	0.0584	
Energy consumption Agv3	0.4471	0	0.5112	0	0.599	0.1206	0.0584	
Energy consumption Agv4	0.2396	0	0.1919	0	0.1819	0	0.0583	
Energy consumption Agv5	0.0601	0	0	0	0	0	0.0582	
Energy consumption Agv6	0	0	0	0	0	0	0.0581	
Number of orders	36	13	24	6	21	13	0	

	SIM57	SIM58	SIM59	SIM60	SIM61	SIM62	SIM63	SIM64
Throughput [orders/h]	4.5929	3.1268	7.8282	4.5939	9.4464	3.4362	6.2749	
Receptivity [units]	5400	5400	5400	5400	5400	5400	5400	
Selectivity [%]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Shelf Occupation [%]	1	1	0.9998	1	0.9998	1	1	
Unoccupied space [%]	0	0	0.0002	0	0.0002	0	0	
AGV utilization [%]	0.0538	0.0521	0.1135	0.0622	0.138	0.0509	0.9159	
Avg Order Cycle time [min/order]	5.1116	4.9408	5.1489	5.1995	5.2712	4.9562	3.1847	
Avg order Task time (Picking) [min/order]	1.2027	2.9645	3.0387	3.1997	1.8273	0.793	3.5137	
Avg order Task time (Retrieval) [min/order]	0	0	0	0	0	0	0	
Avg order waiting time [min/order]	0	0	0	0	0	0	21.663	
Directly reachable pallets [units]	540	540	540	540	540	540	540	
N pallets stored [unit]	5400	5400	5399	5400	5399	5400	5400	
Area Occupation [m3]	46980	46980	46980	46980	46980	46980	46980	
Area Occupation [m2]	2937.3	2937.3	2937.3	2937.3	2937.3	2937.3	2937.3	
Avg meters run by Agvs [m/Agv]	1434.764	1037.157	2417.566	882.0521	3189.414	1086.683	462.5773	
Avg Energy consumption per Agv [KWh/Agv]	0.3986	0.2881	0.6716	0.245	0.886	0.3019	0.1322	
Meters Agv1	5187.937	4150.336	8063.946	4067.213	9683.792	4945.025	204	
Meters Agv2	2277.907	1893.024	4570.123	998.934	5904.689	1575.071	414.1655	
Meters Agv3	930.4142	179.5828	1403.148	226.1655	2333.576	0	408.3246	
Meters Agv4	212.3246	0	468.1774	0	984.3437	0	196	
Meters Agv5	0	0	0	0	230.0832	0	1344.649	
Meters Agv6	0	0	0	0	0	0	208.3246	
Energy consumption Agv1	1.4411	1.1529	2.24	1.1298	2.69	1.3736	0.0606	
Energy consumption Agv2	0.6328	0.5258	1.2695	0.2775	1.6402	0.4375	0.1187	
Energy consumption Agv3	0.2585	0.0499	0.3898	0.0628	0.6482	0	0.1171	
Energy consumption Agv4	0.059	0	0.13	0	0.2734	0	0.0584	
Energy consumption Agv5	0	0	0	0	0.0639	0	0.3769	
Energy consumption Agv6	0	0	0	0	0	0	0.0614	
Number of orders	12	16	36	8	26	8	6	

Image 14. First Round Simulation Results

4.6. Obtaining the final simulation results

The establishment of a fixed framework of simulations made it possible to successfully run the simulations for 5 times for each configured scenario. It is possible to divide such scenarios into 8, each having 6 (instead of 8, due to the elimination of the Association Rule) simulations and each scenario is described below.

Scenario 1. The storage capacity of the warehouse is 600 (5x2x3x2x10) pallets while having 1 AGV in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 2. The storage capacity of the warehouse is 600 (5x2x3x2x10) pallets while having 6 AGVs in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 3. The storage capacity of the warehouse is 1800 (15x2x3x2x10) pallets while having 1 AGV in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 4. The storage capacity of the warehouse is 1800 (15x2x3x2x10) pallets while having 6 AGVs in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 5. The storage capacity of the warehouse is 1800 (5x6x3x2x10) pallets while having 1 AGV in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 6. The storage capacity of the warehouse is 1800 (5x6x3x2x10) pallets while having 6 AGVs in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 7. The storage capacity of the warehouse is 5400 (15x6x3x2x10) pallets while having 1 AGV in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Scenario 8. The storage capacity of the warehouse is 5400 (15x6x3x2x10) pallets while having 6 AGVs in action. Variables here are 3 storage policies with 2 various order frequency rates. This scenario is repeated five times and the results are recorded accordingly.

Total of 240 recordings were saved for the next step – statistical analysis, instead of planned 320. 75% of initial plan has been completed. In the next chapter, first we will have a quick look on the data, then we go deeper using the data analysis platform explained above.

5. DISCUSSION OF OBTAINED RESULTS

In this chapter we will discuss the obtained results in 3 steps. First of all data obtained by the simulations is studied according to storage policy classification, calculating the average performance indicators. In the next stage we focus on the important KPIs that we aimed at the beginning of the simulation. As the final part of the analysis we will compare the important performance indicators of all the storage policies tested and come up with data analysis conclusion.

5.1. Statistical analysis

In order start presenting the results, there should be set a framework of delivery, because despite the fact that there are only 3 storage policies studied in depth, there are several input factors considered in low and high levels: shelves, bays, number of AGVs and order inter-arrival time. Moreover, for each of the low-high input levels scenario, as described above, there were 5 different simulations run to reach higher level of confidence and accuracy for the obtained results. The following 3 sub-chapters will discuss the **average performance indicators** (of 5 simulations) for 3 different storage policies. Each scenarios are codified with the following formula (depending on the input warehouse parameters):

Warehouse parameters = SHELVESxBAYS_NofAGVs_INT-ARR-TIME

Example: Scenario with 2 shelves, 5 bays, 1 AGV and 3 times of inter-arrival time would be as:

2x5_1_x3

To make the process simpler and more straightforward, we also eliminate some of the indicators from the Table7. All the simulations are run under the time frame of 8 hours (1 standard shift) so the decisions should be made accordingly.

5.1.1. Data analysis of Class Based storage policy

To start evaluation of the performance of the warehouse with a Class Based storage policy, we first look at the case with only 1 AGV in action. The results table with important outputs to consider is given below.

Class Based								
Warehouse parameters	**2x5_1_x1**	**2x5_1_x3**	**2x15_1_x1**	**2x15_1_x3**	**6x5_1_x1**	**6x5_1_x3**	**6x15_1_x1**	**6x15_1_x3**
Throughput [orders/h]	9.75	3.44	8.65	2.68	9.29	3.31	8.22	3.60
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.62	0.25	0.48	0.16	0.57	0.24	0.51	0.26
Avg Order Cycle time [min/order]	12.20	4.89	13.02	5.09	13.12	5.93	10.25	5.49
Avg order Task time (Picking) [min/order]	2.25	2.20	1.99	2.38	1.86	2.19	1.98	2.05
Avg order waiting time [min/order]	8.08	0.68	8.78	0.95	8.86	1.71	5.97	1.08
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	15224.22	5540.71	14138.82	4115.79	14876.67	4788.19	14207.70	5481.70
Avg Energy consumption per Agv [kWh/Agv]	4.23	1.54	3.93	1.14	4.13	1.33	3.95	1.52
Meters Agv1 [m]	15224.22	5540.71	14138.82	4115.79	14876.67	4788.19	14207.70	5481.70
Energy consumption Agv1 [kWh]	4.23	1.54	3.93	1.14	4.13	1.33	3.95	1.52
Number of orders	42.20	15.00	33.40	11.20	32.20	11.20	30.00	10.80

Table 10. Average values of 5 simulations outputs for Class Based storage policy (1 AGV)

There are several constant indicators for specific scenarios for all the 3 storage policies, and the analysis starts with declaring such values. Looking at the table it is easily noticeable that Receptivity and the Area Occupation is constant over the change in inter-arrival time, increasing respectively as the number of shelves and bays are increasing. Therefore in the following next two chapters these indicators are disregarded.

As the number of bays are increasing from the low value 5 to the high value 15, there is a noticeable change of throughput from 9.75 [orders/h] to 8.65 [orders per hour] in case of 2 levels, as well as from 9.29 [orders/h] to 8.22 [orders/h] in case of 6 levels. This is understandable in the first case, because of an increasing average cycle time, but in the second scenario, such trend cannot explain the decrease of the throughput, because the time needed to complete the order is decreased. The AGV utilization in the table is directly related to the number of orders as higher number of orders completed during 8 hours of the shift, he higher is the efficiency from the vehicle. The average order cycle time includes picking and waiting times, and therefore directly related to them – the higher is the wait times, the higher is the cycle time.

Another important KPI to follow is the average energy consumption per AGV, that is directly related to the average meters run and orders completed. As can be seen in the table, as the order inter-arrival time is lower (x1) more orders are completed in any of the warehouse configurations, also resulting in the higher energy consumption by the vehicle. Since in this scenario we are assuming that there is only 1 vehicle completing all the orders, the average and the total meters run and energy consumption is the same.

The average highest number of orders completed in this case is with 2 levels of 5 bays in the lower order inter-arrival time (x1) and it is 42.2. Accordingly, the longest distance covered and the energy consumed is also in this case with 15224 meters and 4.23 kWh accordingly.

Class Based								
Warehouse parameters	2x5_6_x1	2x5_6_x3	2x15_6_x1	2x15_6_x3	6x5_6_x1	6x5_6_x3	6x15_6_x1	6x15_6_x3
Throughput [orders/h]	8.04	3.01	8.79	3.92	8.71	3.52	8.05	2.77
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.13	0.07	0.11	0.05	0.12	0.05	0.10	0.03
Avg Order Cycle time [min/order]	5.09	4.71	5.01	4.61	5.02	5.02	5.21	4.90
Avg order Task time (Picking) [min/order]	2.31	2.58	2.76	2.13	2.34	2.61	2.40	2.83
Avg order waiting time [min/order]	4.10	11.33	0.01	0.00	0.00	0.00	0.00	0.00
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	2357.54	864.11	2605.50	1033.24	2451.68	1043.49	2434.46	846.00
Avg Energy consumption per Agv [KWh/Agv]	0.66	0.24	0.72	0.29	0.68	0.29	0.68	0.24
Meters Agv1 [m]	6986.55	3574.35	7931.67	4743.23	7574.41	4943.81	7352.19	3772.89
Meters Agv2 [m]	4043.07	1436.52	4616.70	1236.95	4414.61	1134.15	4280.53	1021.78
Meters Agv3 [m]	1628.49	173.77	2154.05	178.46	2006.92	183.01	2204.94	236.11
Meters Agv4 [m]	653.95	0.00	620.23	40.80	585.63	0.00	715.49	45.22
Meters Agv5 [m]	259.20	0.00	263.94	0.00	128.50	0.00	53.61	0.00
Meters Agv6 [m]	573.99	0.00	46.40	0.00	0.00	0.00	0.00	0.00
Energy consumption Agv1 [kWh]	1.94	0.99	2.20	1.32	2.10	1.37	2.04	1.05
Energy consumption Agv2 [kWh]	1.12	0.40	1.28	0.34	1.23	0.32	1.19	0.28
Energy consumption Agv3 [kWh]	0.45	0.05	0.60	0.05	0.56	0.05	0.61	0.07
Energy consumption Agv4 [kWh]	0.18	0.00	0.17	0.01	0.16	0.00	0.20	0.01
Energy consumption Agv5 [kWh]	0.07	0.00	0.07	0.00	0.04	0.00	0.01	0.00
Energy consumption Agv6 [kWh]	0.16	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Number of orders	28.40	12.60	35.00	11.60	30.40	14.20	28.20	11.20

Table 11. Average values of 5 simulations outputs for Class Based storage policy (6 AGVs)

Looking at the simulation output data for the Class Based storage policy with 6 AGVs in the table above, it is possible to note the sharp decrease of average order cycle time, since now there are more vehicles available and the wait times are very low. This applies to all the warehouse rack configuration and for the both cases with different inter-arrival time.

Observing the distance travelled by AGVs, one can deduct that not all the time all 6 AGVs are used under different rack configurations and with the considered order frequency. In fact, only in 2 cases out of 8, all the vehicles were used. This in turn also affected to the AGV utilization, resulting in the maximum of 13%, almost 5 times less than in the case of a single AGV, from the previous table.

Energy consumption of a single vehicle and distance travelled is also distributed among 6 shuttles accordingly. Since the AGV utilization rates are comparatively low in the case of longer inter-arrival times, it can be suggested to decrease them from 6 to 4.

5.1.2. Data analysis of Dedicated Slot storage policy

Now we consider again that in the warehouse there is only one shuttle in operation, therefore as in the previous storage policy data table, average and total meters run, energy consumed coincide with each other, as can be noted in the table below. Comparing the throughput in the current policy, on average it is giving higher numbers than in the case of Class Based storage setting, while having almost the same number of orders. Comparing the total orders completed between low and high inter-arrival time, the values are relative to each other, following the ratio of 3 for each rack configuration – another proof that the code is running correctly generating 3 times less orders when commanded so.

Dedicated Slot								
Warehouse parameters	**2x5_1_x1**	**2x5_1_x3**	**2x15_1_x1**	**2x15_1_x3**	**6x5_1_x1**	**6x5_1_x3**	**6x15_1_x1**	**6x15_1_x3**
Throughput [orders/h]	9.55	3.92	9.16	4.29	8.87	3.49	8.01	3.86
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.67	0.26	0.70	0.32	0.64	0.25	0.62	0.25
Avg Order Cycle time [min/order]	11.58	5.13	15.29	4.90	10.66	4.21	12.21	5.13
Avg order Task time (Picking) [min/order]	2.03	2.39	1.79	1.98	2.17	1.82	2.19	2.24
Avg order waiting time [min/order]	7.48	0.84	10.93	0.68	6.31	0.77	7.76	0.82
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	15000.26	6012.22	14786.08	5834.79	14676.85	4658.15	12707.74	5754.15
Avg Energy consumption per Agv [KWh/Agv]	4.17	1.67	4.11	1.62	4.08	1.29	3.53	1.60
Meters Agv1	15000.26	6012.22	14786.08	5834.79	14676.85	4658.15	12707.74	5754.15
Energy consumption Agv1	4.17	1.67	4.11	1.62	4.08	1.29	3.53	1.60
Number of orders	36.60	13.60	31.00	13.80	31.80	11.40	27.60	12.80

Table 12. Average values of 5 simulations outputs for Dedicated Slot storage policy (1 AGV)

In terms of the performance of the AGV, first we consider the case of more frequent order generation. The utilization ratio is always higher than 60%, up until 70% with 2 levels and 15 bays, where it reached its maximum amount, also resulting the higher order cycle time and wait times. According to the rule already defined, higher wait times for each rack configuration is generating the higher order cycle time, which ranged from 10.66 minutes per order to 15.29 minutes per order. Another relationship between the KPIs is that the higher number of orders fulfilled is directly connected to the longer distance travelled by the vehicle, because in the first rack configuration where on average 36.6 orders entered and exited the system, there is the highest value for the distance travelled – 15 kilometers. Energy consumption is following the same trend, having the maximum amount in the first case – 4.17 kWh with the most orders and 3.53 kWh (its minimum) with the least orders.

While looking at the data generated with lower order frequency, its maximum throughput is 4.29 orders per hour, about 2 times less than in the case of higher order frequency. Therefore, all the other important KPIs are also around 2-2,5 times less: AGV utilization, total meters run and energy consumed. What is more interesting here is the fact that average order wait time is always less than 1 minute, meaning that the AGV is not waiting at all to complete the order. This is also mirrored in the average order cycle time ranging from 4.21 minutes to 5.13 minutes, again 2-2,5 times less than in the case of more frequent orders.

Dedicated Slot								
Warehouse parameters	**2x5_6_x1**	**2x5_6_x3**	**2x15_6_x1**	**2x15_6_x3**	**6x5_6_x1**	**6x5_6_x3**	**6x15_6_x1**	**6x15_6_x3**
Throughput [orders/h]	9.70	3.09	7.95	3.80	9.43	2.82	8.29	4.27
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.14	0.05	0.12	0.05	0.15	0.04	0.13	0.06
Avg Order Cycle time [min/order]	5.31	4.87	5.28	4.99	5.07	4.85	5.03	4.89
Avg order Task time (Picking) [min/order]	2.65	2.79	2.51	2.54	2.40	2.85	2.27	2.41
Avg order waiting time [min/order]	0.05	0.00	0.02	0.00	0.01	0.00	0.00	0.00
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	2988.52	960.87	2460.90	1124.18	2896.40	735.18	2594.53	1167.37
Avg Energy consumption per Agv [KWh/Agv]	0.83	0.27	0.68	0.31	0.80	0.20	0.72	0.32
Meters Agv1	8950.34	4363.36	7248.76	4807.76	8684.37	3421.75	8044.66	5349.73
Meters Agv2	5047.80	1137.56	4704.67	1514.68	5477.20	857.26	4593.37	1384.74
Meters Agv3	2498.73	221.12	1903.33	276.99	2331.92	89.22	1946.52	269.76
Meters Agv4	997.53	43.20	657.27	93.66	754.82	42.83	847.84	0.00
Meters Agv5	359.63	0.00	200.13	52.00	85.23	0.00	134.83	0.00
Meters Agv6	77.10	0.00	51.26	0.00	44.86	0.00	0.00	0.00
Energy consumption Agv1	2.49	1.21	2.01	1.34	2.41	0.95	2.23	1.49
Energy consumption Agv2	1.40	0.32	1.31	0.42	1.52	0.24	1.28	0.38
Energy consumption Agv3	0.69	0.06	0.53	0.08	0.65	0.02	0.54	0.07
Energy consumption Agv4	0.28	0.01	0.18	0.03	0.21	0.01	0.24	0.00
Energy consumption Agv5	0.10	0.00	0.06	0.01	0.02	0.00	0.04	0.00
Energy consumption Agv6	0.02	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Number of orders	37.40	12.40	29.00	14.00	35.60	10.60	30.20	13.00

Table 12. Average values of 5 simulations outputs for Dedicated Slot storage policy (6 AGVs)

The table above illustrates performance indicators of the warehouse with a Dedicated Slot storage policy under the operation of 6 vehicles. The throughput and the number of orders completed do not differ too much from the case, in which there was only 1 AGV in action. Throughput is ranging from 7.95 orders per hour to 9.7 orders per hour with higher frequency of order generation, while with longer inter-arrival time the minimum and maximum values are 2.82 and 4.27, accordingly. There is not much difference from the previous setting of this policy, as expected, since the number of AGV is not related to the order generation.

Having a deeper look for the performance of vehicles, we observe that all the 6 vehicles were used in case of x1 order inter-arrival time, except for the last rack configuration of 6 levels and 15 bays. The availability of unoccupied shuttles has an impact on the average order cycle time, always a little longer than 5 minutes per order, therefore decreasing it for almost 3 times in the case of a single AGV. The distance travelled and the energy consumed is also distributed among 6 machines. When the system was accepting orders at a slower rate, ranging from 10.6 orders to 14 orders in the whole 8-hour shift, the efficiency of having 6 shuttles is not very high. In fact, only in one case 5 of the AGVs were used, while for the other 3 rack settings, only 4 of the AGVs were always enough. Distance travelled and the energy consumed by the system is distributed accordingly.

5.1.3. Data analysis of storage policy by Weight

As per the logic we followed in the last 2 chapters, for the last type of storage policy, we start analyzing the indicators in the participation of a single vehicle. The table below represents the data obtained for the current policy. The current setting in inspection also follows the rule: the higher the number of orders completed in the 8-hour shift, the higher is the throughput. As seen in the table, with an average number of orders of 40.40 with the rack setting 1 (2 levels and 5 bays), there is a higher throughput of 9.38 orders per hour than in the second setting of the same order frequency (2 levels and 15 bays) where the throughput has a value of 7.93 orders per hour, of total of 25.2 orders in the single shift, on average.

Other indicators, such as average order cycle time, AGV utilization, energy consumption and total distance travelled follow the same trends as in the case of the previous 2 policies, therefore it is not discussed in depth in this chapter, since there will be more analysis in terms of the comparison of storage policies in the next chapters of this report.

By Weight								
Warehouse parameters	2x5_1_x1	2x5_1_x3	2x15_1_x1	2x15_1_x3	6x5_1_x1	6x5_1_x3	6x15_1_x1	6x15_1_x3
Throughput [orders/h]	9.38	3.12	7.93	3.59	9.80	3.09	8.84	3.90
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.68	0.21	0.59	0.25	0.71	0.20	0.57	0.27
Avg Order Cycle time [min/order]	11.65	4.81	12.72	5.96	13.51	5.03	16.91	5.33
Avg order Task time (Picking) [min/order]	2.37	1.89	1.79	2.09	2.17	2.23	1.73	2.71
Avg order waiting time [min/order]	7.29	0.45	8.32	1.47	9.13	0.71	12.36	0.71
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	15735.33	5023.95	13546.65	5980.83	16977.71	5249.55	16456.48	6454.20
Avg Energy consumption per Agv [KWh/Agv]	4.37	1.40	3.76	1.66	4.72	1.46	4.57	1.79
Meters Agv1	15735.33	5023.95	13546.65	5980.83	16977.71	5249.55	16456.48	6454.20
Energy consumption Agv1	4.37	1.40	3.76	1.66	4.72	1.46	4.57	1.79
Number of orders	40.40	9.60	25.20	13.20	37.20	11.60	26.80	16.40

Table 13. Average values of 5 simulations outputs for storage policy by Weight (1 AGV)

Similar results are obtained for the warehouse performance with 6 vehicles, difference of which related to the other policies will be discussed in the next chapters. The full data is presented in the table below. Another solid conclusion from by looking at the data is that, not always all of the 6 AGVs are used with the current order list and both order generation frequencies.

By Weight								
Warehouse parameters	2x5_6_x1	2x5_6_x3	2x15_6_x1	2x15_6_x3	6x5_6_x1	6x5_6_x3	6x15_6_x1	6x15_6_x3
Throughput [orders/h]	9.53	3.60	8.97	3.82	7.86	3.08	8.47	3.16
Receptivity [units]	600.00	600.00	1800.00	1800.00	1800.00	1800.00	5400.00	5400.00
AGV utilization [%]	0.14	0.05	0.14	0.05	0.11	0.04	0.13	0.05
Avg Order Cycle time [min/order]	5.17	3.90	5.18	4.96	5.12	5.19	5.34	5.24
Avg order Task time (Picking) [min/order]	2.89	1.79	2.73	3.14	2.60	3.19	2.58	2.67
Avg order waiting time [min/order]	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01
Area Occupation [m3]	5220.00	5220.00	15660.00	15660.00	15660.00	15660.00	46980.00	46980.00
Avg meters run by Agvs [m/Agv]	3015.55	1033.06	2838.02	1022.90	2415.37	984.70	2884.56	1046.66
Avg Energy consumption per Agv [KWh/Agv]	0.84	0.29	0.79	0.28	0.67	0.27	0.80	0.29
Meters Agv1	9073.42	4522.63	8729.11	4637.86	7505.21	4259.45	8610.36	4953.10
Meters Agv2	5577.11	1329.35	5085.32	1311.28	4149.38	1326.52	5019.59	1276.46
Meters Agv3	2598.90	301.50	1931.34	188.26	1886.71	280.55	2455.37	50.42
Meters Agv4	755.74	44.86	943.07	0.00	723.18	41.66	1082.75	0.00
Meters Agv5	88.13	0.00	287.23	0.00	227.75	0.00	139.26	0.00
Meters Agv6	0.00	0.00	52.06	0.00	0.00	0.00	0.00	0.00
Energy consumption Agv1	2.52	1.26	2.42	1.29	2.08	1.18	2.39	1.38
Energy consumption Agv2	1.55	0.37	1.41	0.36	1.15	0.37	1.39	0.35
Energy consumption Agv3	0.72	0.08	0.54	0.05	0.52	0.08	0.68	0.01
Energy consumption Agv4	0.21	0.01	0.26	0.00	0.20	0.01	0.30	0.00

Energy consumption Agv5	0.02	0.00	0.08	0.00	0.06	0.00	0.04	0.00
Energy consumption Agv6	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Number of orders	42.20	10.00	34.20	14.60	29.40	13.00	31.80	12.60

Table 15. Average values of 5 simulations outputs for storage policy by Weight (6 AGVs)

5.2. Results on Important KPIs

After generation of simulation data and averaging the 5 repetitions for each type of rack configuration, order frequency and storage policies, there is a study of the most important indicators of output. This stage of the data analysis is very important, because the simulation model is now performed with the real world order list. The outcomes can be assessed in many possible ways, so focusing only on the significant factors helps us better evaluate the warehouse, and the most importantly, the new technology performance. Following sections will go deeper in the study of such KPIs.

5.2.1. Throughput

Starting with the results obtained during high season, we can see how each of the storage policies did with 4 different warehouse structure in the following diagram.

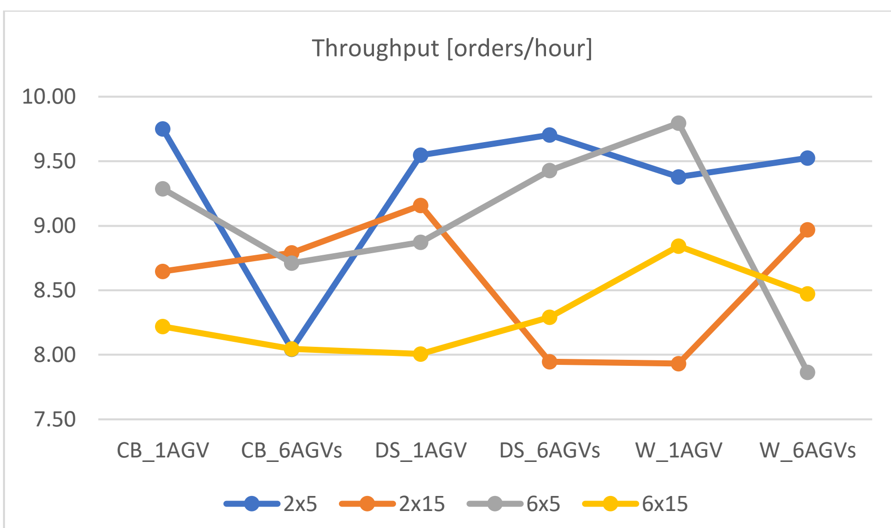


Figure 13. Throughput values for high order frequency

The diagram illustrates throughput values of the 4 rack structure as levels x bays in 4 different colors, for each storage policy (CB – Class Based, DS – Dedicated Slot, W – by Weight) and number of AGVs (1 and 6).

Having a warehouse of 2 levels and 5 bays is clearly a dominant strategy in terms of throughput, whose value is stable around 9.5 orders/hour, only except for the Class Based policy with 6 vehicles. While 2 levels x 15 bays and 6 levels x 5 bays layouts are fluctuating in the inverse way, from a little lower than 8 orders/hour to 9.7 orders/hour, the least favorable dimension is to have 6 levels and 15 bays, where its throughput is always between 8 and 8.5 orders/hour on average. This trend tells us that the bigger is the warehouse, the more complicated it is for it to have higher rates of throughput, because there will be more waiting times and travel times.

Comparing the structures with storage policies, it can be seen that 2x5 works better with Dedicated Slot, 2x15 with Class Based, 6x5 also with Dedicated Slot and 6x15 with the storage policy by Weight in terms of the efficient throughput rate. However, this data is not enough to decide which policy is better for the warehouse with the current order list, and it will be studied in the last section of this chapter.

Now we consider that the warehouse is operating in the low season, with less frequent orders. The values of throughput rate which follow the same logic of representation explained previously is described in the graph below.

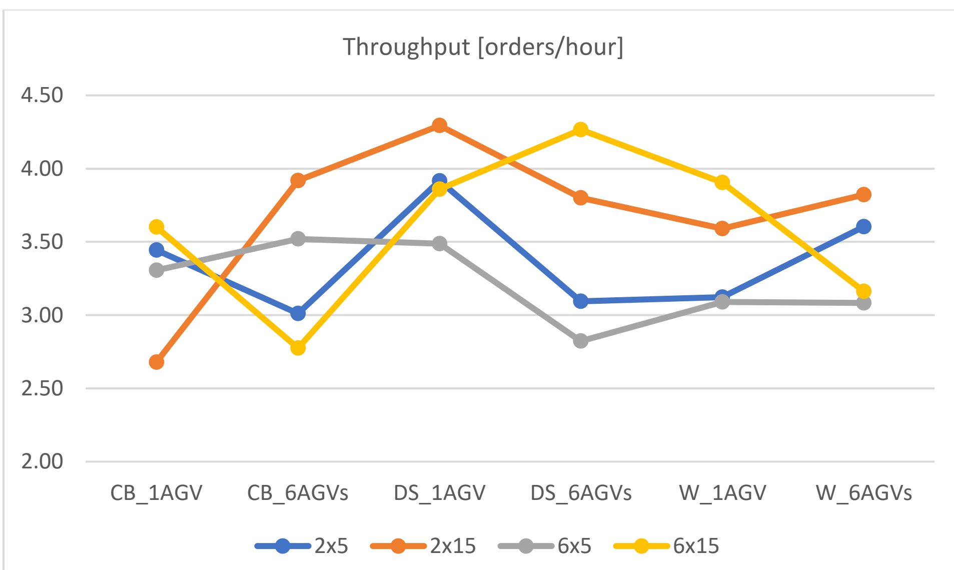


Figure 14. Throughput values for low order frequency

Unlike the case of high-rotation orders, in low seasons there is not one dominant strategy for all the cases, since the best results are shared equally by the warehouse layout consisting of 2 levels x 15 bays and 6 levels x 15 bays. The best throughput rate is always higher than 3.5 orders/hour on average and is close to 4.5 orders/hour at its peak, with the storage policy of Dedicated Slot having 1 active vehicle. However, the lowest rate is also recorded by the rack configuration of 2x15 with an amount of slightly higher than 2.5 orders/hour. Having 5 bays in both 2 and 6 levels showed average result of 3.5 orders/hour, with a slight dominance of lower level warehouse structure in terms of throughput indicator.

As per the storage policies, 2x5 configuration gave better results when it was combined with the Dedicated Slot logic. Same level of warehouse with 15 bays had the best throughput when coupled with the same policy. The dominance of Dedicated Slot is also observed with the rack dimension of 6x15, and it only underperformed with 6x5 structure, the best rate in which was achieved using the Class Based locating strategy.

5.2.2. Order cycle time

The next indicator – order cycle time is studied in the same type of the graph, first looking at the warehouse in operation under high-season, i.e., with high frequency of orders and in the case of 3 storage policies, each having 1 and 6 vehicles in action, separately. The graph below shows information about the order cycle time in minutes per order, having 4 types of rack structure in 4 various colors.

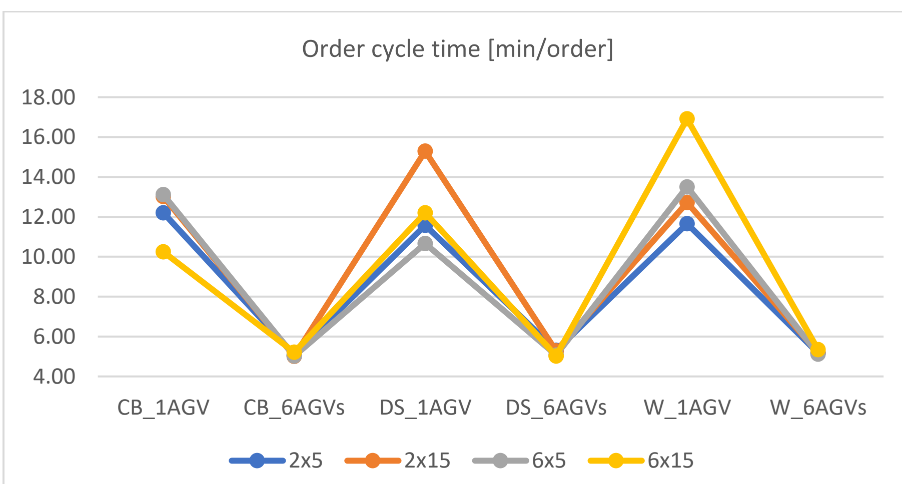


Figure 15. Order cycle time values for high order frequency

The trend that is notable at once is that, no matter the rack structure and the storage policy, having more AGVs in action is always decreasing the time needed to complete and order. In fact, on average the cycle time with 6 AGVs is at least 2 times less than the cycle time with a single vehicle. It is natural, since we are analyzing the case of higher item rotation and since there is only 1 shuttle to fulfill orders, some other orders need to wait until the previous one is done.

In order to make the comparison easier, we can omit the cases with 6 AGVs, because all the structures are having the cycle time of approximately 5 minutes in all the 3 storage logics. The idea of having 5 bays in 2 levels performed stable at around 12 seconds of cycle time with a single shuttle in all the 3 storage policies. Another 2 level structure with 15 bays fulfilled orders at around 13 minutes on average at its best case with storage policies by Weight and Class. However in the case of a Dedicated Slot, the longest cycle time was recorded, just below 16 minutes. Clearly, 6x5 rack structure has the favorite positioning logic of Dedicated Slot, having the cycle time of a little over than 10 minutes, while in the remaining 2 cases, this structure performed worse, around 13 minutes. The last warehouse dimensions of 15 bays in 6 levels fulfilled orders in the best rate of 10 minutes for Class Based storage logic, and having worse and worse indicators in the next two policies, 12 minutes in Dedicated Slot and 17 minutes (the longest cycle time needed throughout the whole simulations) in the policy by Weight.

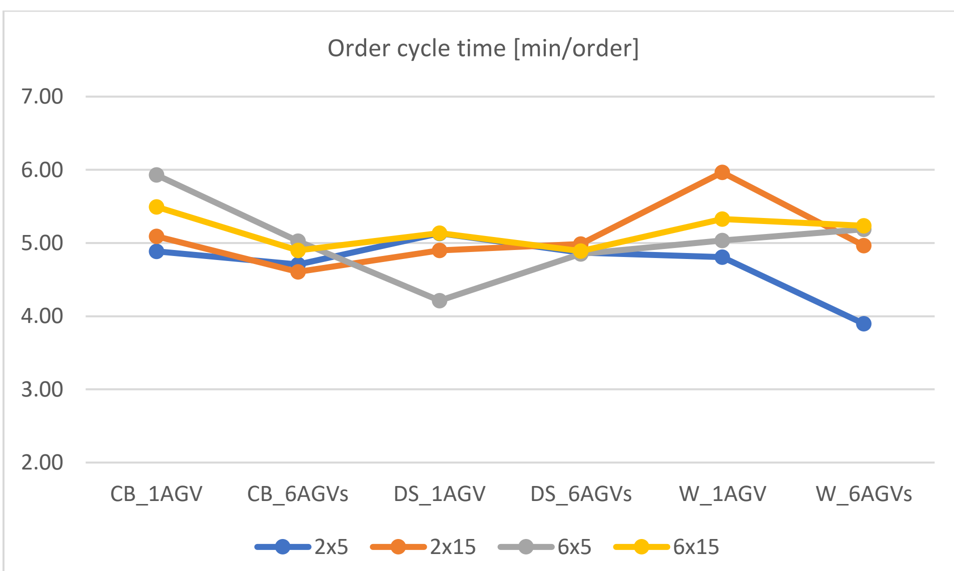


Figure 16. Order cycle time values for low order frequency

Looking at the table above, we can see the order cycle time values of the warehouse that is operating in the low season – with less frequent orders. There is not much surprise that almost all of the structures under various storage policies are operating within the time frame of 4 to 6 minutes, because in case of order generation of a slow rate, only 1 AGV is enough to fulfill the orders without waiting times.

The smallest warehouse structure 2x5 is again performing better than other rack configurations, understandably because of the fewer need of inventory. In fact, such dimension when coupled with a Class Based and by Weight storage policies showed the best time compared to other dimensions. However, in the case of the Dedicated Slot policy, 6x5 rack structure took the lowest amount of time to fulfill orders on average.

5.2.3. Energy consumption

Observing the simulation data in the tables of the previous chapter we understood that the energy consumed by AGVs is a little difficult to discuss and relate them on the rack structure. The scenario with a single vehicle is straightforward – there is only one agent that consumes energy, and all of the orders are fulfilled by only single shuttle. However, in the case of multiple AGVs, there is not output of the model, that shows the possession of each AGV in terms of orders fulfilled. We cannot assess the performance of a single shuttle (in case of multiple shuttles), because we do not know consuming a certain amount of energy, how many orders each AGV completed.

In the case of a single vehicle, let us learn the relationship of the energy consumed by each shuttle and the throughput in that scenario. The scatterplot graph of such a relationship is described in the figure below. Bottom left corner of the graph contains indicators relating to the orders fulfilled according to the slower order generation taking into account 4 rack structures. As anticipated, when the warehouse system receives less orders, a shuttle performs the fulfillment process with a smaller cycle time, however this overall results to the lower throughput, thus the vehicle burns less energy. On the top right corner, similar traction is observed when the warehouse was receiving high frequency orders. The throughput is high and because the single AGV is active in the system, the energy consumed is higher too.

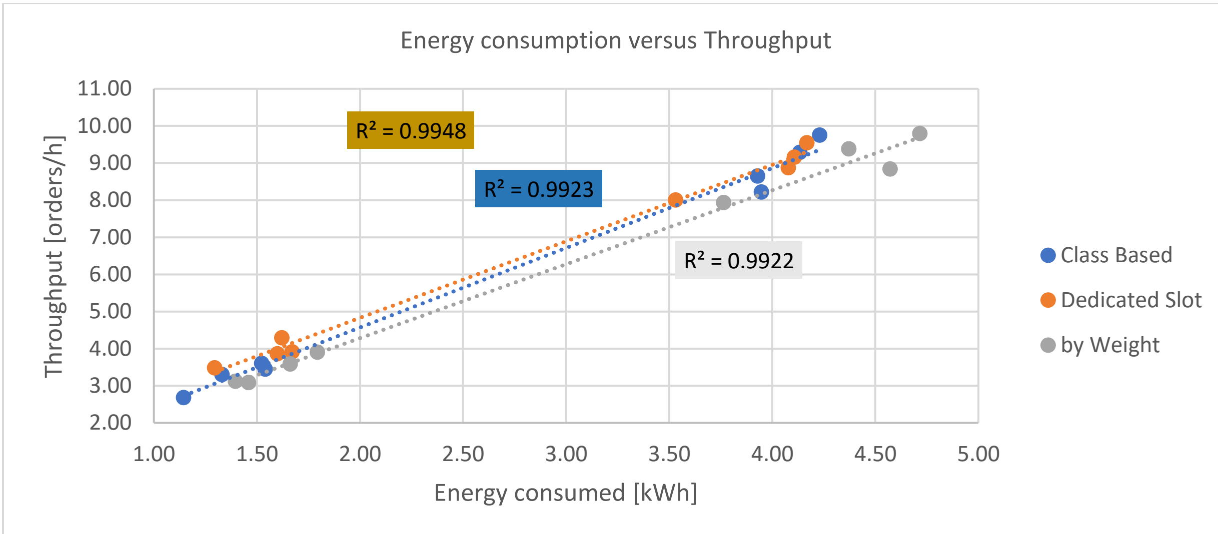
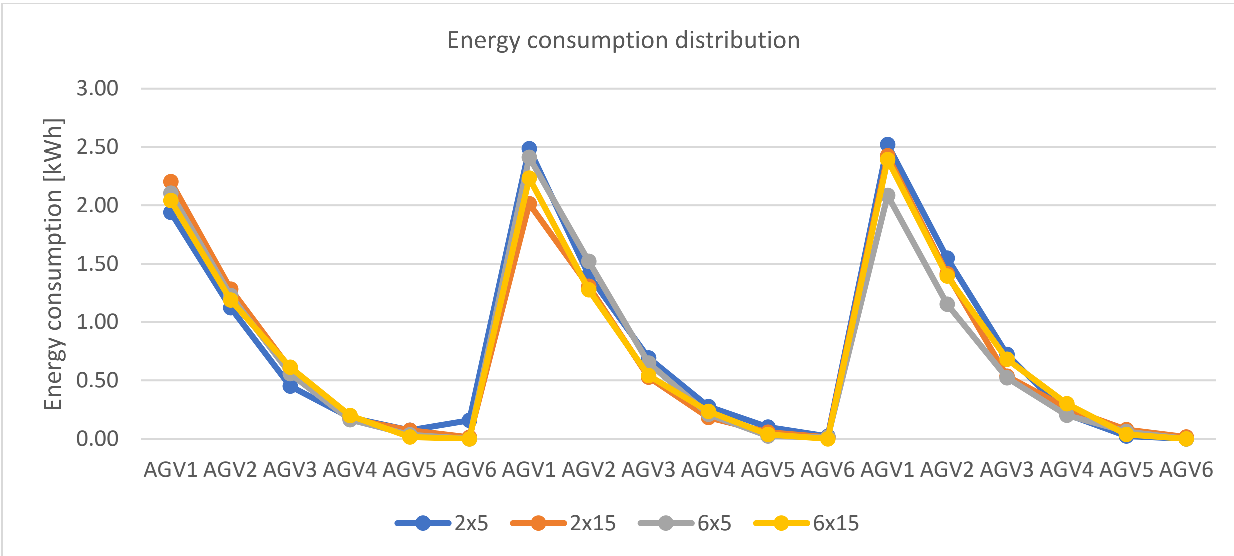
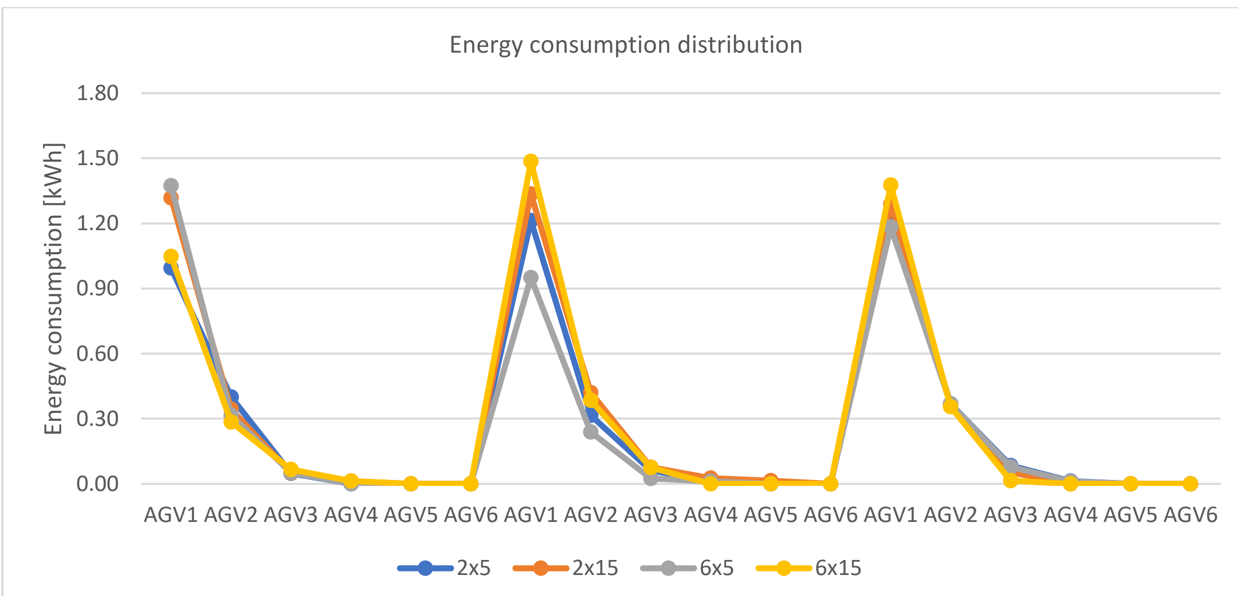


Figure 17. Energy consumption of a single AGV and the system throughput

The graph also shows the trendline for all 3 storage policies, and all of them have the R value very close to 1, which signals us again, that the higher throughput requires more energy. Concerning the storage policies, whose datapoints are represented in 3 types of colors according to the legend, Dedicated Slot has higher [orders/hour] for each [kWh] consumed. The Class Based storage policy had almost the same efficiency ratio, while the storage policy by Weight has a considerably low orders fulfilled per hour per energy consumed.

In the case of 6 active AGVs in high season and low season, not always all the 6 vehicles were used, as can also be seen from the figures below.





Figures 17&18. Energy consumption of 6 AGVs

The colors represent the various rack dimensions in levels x bays, first 6 AGVs belong to the Class Based storage policy, next 6 belong to the Dedicated Slot and the last 6 belong to the storage policy by Weight. As expected, the first AGV that starts the first order consumed more energy both in the first case with higher rate and in the second case with the lower rate of inventory turnover. The conclusion that is worth to highlight from learning this data is that even for the high season, with the current order list in test and for all the rack configurations, and storage policies, 6 is an excessive amount for a shuttle. This statement has its solid proof in the scenario with a low inventory turnover, where AGV4, AGV5 and AGV6 was almost never used.

5.2.4. Orders per energy consumed

There is another interesting set of data, which should be derived from the output table and that is the ratio of total number of orders fulfilled to every energy unit consumed during 8 hour standard shift. This is an important KPI, also because we can properly assess the performance of each rack structure and its combination with all 3 types of storage policies in question both in low and high season, because we are simply dividing the total number of orders to energy consumed. The only downside of considering such data is that it is possible to learn the behavior of this ratio only in the case of a single AGV. The reason, as mentioned above, is that the system does not provide information about how any orders each AGV fulfilled in the case of a warehouse operating with multiple shuttles. The ratio in analysis is illustrated in the figure below.

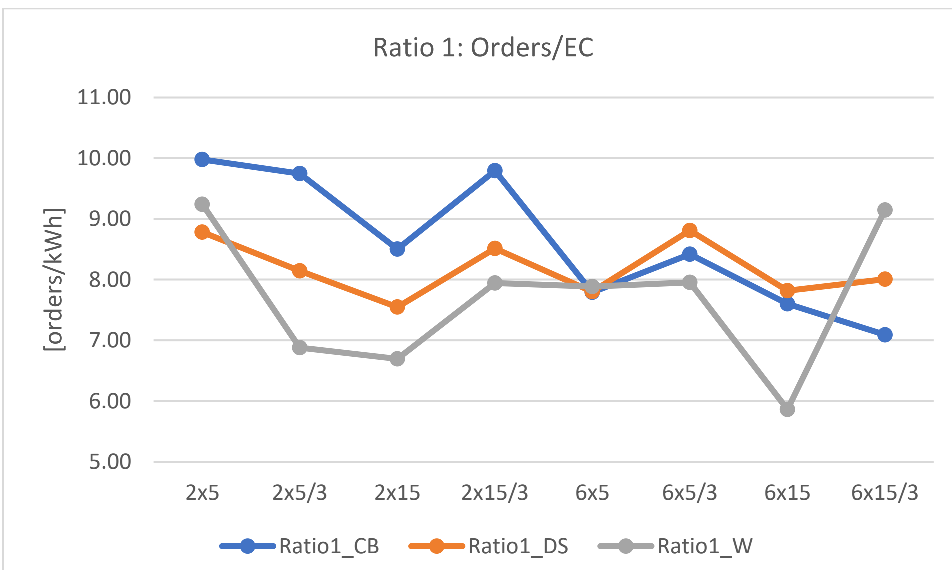


Figure 19. Ratio1: Number of orders per energy consumed

The rack configuration with 2 levels either with 6 or 15 bays resulted in the highest ratio value when deployed under Class Based storage policy. More precisely, the value is stable with 2x5 structure at 10 orders per kWh consumed, while with 2x15 rack structure its value fluctuated from 8.5 orders per kWh to 10 orders per kWh, still having the highest amount compared to other storage policies. As the levels increased in the warehouse from 2 to 6, the ratio is decreased as an overall trend. In the case of 6 levels with 5 bays, the Dedicated Slot storage policy was dominant over the other 2 policies with a value of up to 9 units/kWh. The last rack structure of 6 levels and 15 bays is shared between the Dedicated Slot and the storage policy by Weight in terms of indicating the highest rate of orders per energy consumed, approximately 8 orders/kWh and 9 orders/kWh respectively.

5.3. Comparison of storage policies

This study aimed at developing an assessment framework for the performance of various storage policies in an automated warehouse that uses the new technology named EUROFORK. Initially the research set 4 policies under analysis: Class Based, Dedicated Slot, by Weight and Association Rule. However, due to the order list and the simulation model, the Association Rule policy provided incompetent results to analyze its performance, hence was opted out. This is due to the fact that not enough transaction history was obtained for this specific simulation model, so that it would generate a logic for the fulfillment of orders in the case of item location according to the Association Rule. Considering all of the above, the study finalizes assessment in a single table, taking into account all the variables. The table is illustrated in the figure below.

		RACK CONFIGURATION							
		2x5	2x5/3	2x15	2x15/3	6x5	6x5/3	6x15	6x15/3
Throughput	1AGV	CB	DS	DS	DS	W	DS	W	W
	6AGVs	DS	W	W	CB	DS	CB	W	DS
Cycle time	1AGV	DS	W	W	DS	DS	DS	CB	DS
	6AGVs	CB	W	CB	CB	CB	DS	DS	DS
Throughput/EC	1AGV	CB	DS	DS	DS	CB	DS	DS	DS
Orders/EC	1AGV	CB	CB	CB	CB	DS	DS	DS	W
		CB		CB/DS		DS		DS	

Figure 20. Best storage policy for different scenarios

The input parameters we introduced in the early stage of the research: number of bays, number of levels, frequency of order generation and number of vehicles are all considered to make the full list of scenarios. During the simulation of abovementioned scenarios, the table presents which storage policy showed the best result in terms of important output parameters:

throughput, order cycle time, throughput over energy consumption, completed orders over energy consumption. In total, we have 48 scenarios, because the last two output indicators cannot generate accurate results for the case of multiple vehicles.

Generally, in 24 of 48 scenarios, Dedicated Slot storage policy produced the best result, followed by Class Based storage policy owning 14 scenarios with the best indicators. The storage policy by Weight had the best outcome in the rest of the scenarios – in total, 10. Such a decision, however, does not represent the most accurate intention to choose the storage policy, because there are 4 types of warehouse structure – in 4 sizes. In the case of 5 bays of 2 levels, with high inventory turnaround the Class Based policy recorded 4 favorable indicators out of 6, while in the low inventory turnaround of the same setting, storage policy by weight had the most favorable indicators. In total, however, Class Based storage policy had the most strong KPIs – 5 out of 12, compared to Dedicated Slot – 4 out of 12 and by Weight – 3 out of 12.

Following the same strategy the best storage policy for each setting is produced accordingly. To sum up, the company with the current order list, using the new technology in the automated warehouse should use Class Based storage policy if their warehouse layout has lower levels. In case of higher levels of inventory rack structure, the Dedicated Slot policy is recommended. The storage policy by Weight produced unstable results as far as the current transaction history is concerned, so it is the least recommended policy for this model. It should also be noted that considering the output indicator under improvement, the most preferred storage policy differs too.

6. CONCLUSIONS

The aim of this study was to continue the pre-existing work, that focused on analyzing the performance indicators of the new technology developed to be implemented in an automated warehouse. In the previous work, a simulation model has been developed and adjusted to test it under various storage policies of the conceptional warehouse. However, a generic order list and order creation model was used before, unlike this study that derived data from the existing order list from an Italian electronics manufacturer. Attracting the real-life data defined the novelty of this study.

Initially, several input parameters have been decided and the study aimed at observing the impact of changing those parameters. Various outcome KPIs have also been defined before starting running the simulation, as the key indicators to assess the performance of 4 main storage policies, initially considered. The simulation process was carried out using a Discrete Event Simulation methodology and a specific platform – FlexSim. An Excel sheet containing a historical order list was embedded to the system and the whole order generation, fulfillment process and inventory distribution were replicated as if it was a real life scenario. Data contained in the file was not accurate to calculate KPIs and run the simulation process for the conceptual warehouse with Association Rule storage policy, so that policy was discarded further. After running 64 different scenarios while changing the input parameters accordingly, with an aim of getting more precise data, the simulation is further repeated 4 times – obtaining 5 set of results for the 64 (48) scenarios. The output sheet of the simulation then was transferred to another helpful tool – Minitab which is a powerful Six Sigma platform – to calculate average values for the 48 cases. Each case is then further studied statistically, which is followed by a step of defining the best storage policy for the warehouse that uses the new technology in question.

Results showed that there is not a single policy that stood out of all the others under various circumstances, however, as relatively assessed, the Dedicated Slot policy deserved the title of the best policy in 50% of the cases (24 out of 48). The second favorable storage policy, according to the statistical analysis carried out, was the Class Based storage policy, outperforming the other location logics in 29% of the cases (14 out of 48). Lastly, the storage policy by Weight showed best results in the remaining 21% of the cases (10 out of 48).

Despite being unable to analyze the full content of intentioned policies, this research has proposed a systematic way for warehouse managers how to run assessment and measurement analysis when deciding about the storage policy. Moreover it took the previous attempts of analysis of the innovative technology consisting of a shuttle, a satellite and a robotic arm for picking activities to next step, by testing the technology under a real-life scenario. Further extension of the research can be carried out by involving several sets of realistic historical data from manufacturers. Another attempt to improve the study could be by making the input parameters more close to reality, i.e., obtaining warehouse rack configurations from real warehouses, as well as implementing analytical reasoning to choose the number of AGVs for each simulation. Because in the current study, there were only two cases in terms of the amount of vehicles representing the technology: 1 and 6. While having 6 vehicles showed accurate results when there was a high turnover of inventory in the warehouse, having a scenario with 6 AGVs and low order generation was not really a significant case. However, generally the study carried out provided enough data to assess the performance of various storage policies and to develop a framework of the process to help professionals in charge to decide which policy to use when implementing innovative technologies in an automated warehouse of AVS/RS type.

7. REFERENCES

[1] V. LOTOTSKY, R. SABITOV, G. SMIRNOVA, B. SIRAZETDINOV, N. ELIZAROVA, SH. SABITOV. Model of the Automated Warehouse Management and Forecasting System in the Conditions of Transition to Industry 4.0

[2] D.BATTINI, M.CALZAVARA, A. PERSONA, F. SGARBOSSA, 2016. Additional effort estimation due to ergonomic conditions in order picking systems

[3] E.ROMAINE, 2020. Automated Storage & Retrieval System (AS/RS) Types & Uses

[4] C.J. MALMBORG, 2003. Interleaving dynamics in autonomous vehicle storage and retrieval systems

[5] K. AZADEH, R. DE KOSTER, D. ROY, 2019. Robotized and Automated Warehouse Systems: Review and Recent Developments

[6] Y. JAGHBEER, R. HANSON, M.I. JOHANSSON, 2020. Automated order picking systems and the links between design and performance: a systematic literature review

[7] F.H. STAUDT, G. ALPAN, M. DI MASCOLO, C.M. RODRIGUEZ, 2015. Warehouse performance measurement: a literature review

[8] P.H. KUO, A KRISHNAMURTHY, C.J. MALMBORG, 2007. Design models for unit load storage and retrieval systems using autonomous vehicle technology and resource conserving storage and dwell point policies

[9] G. MARCHET, M. MELACINI, S. PEROTTI, E. TAPPIA, 2011. Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes

[10] G. MARCHET, M. MELACINI, S. PEROTTI, E. TAPPIA, 2013. Development of a framework for the design of autonomous vehicle storage and retrieval systems

[11] B.Y. EKREN, S.S. HERAGU, A. KRISHNAMURTHY, C.J. MALMBORG, 2014. Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system

[12] S. ARIANO, F. LOMBARDI, G. BRUNO, A. FAVETO, 2021. Design of Innovative Transport Systems for automated warehouses

[13] ERASMUS UNIVERSITY ROTTERDAM, Material Handling Forum

[14] J.M. JARVIS, E.D. MCDOWELL, 1991. Optimal Product Layout in an Order Picking Warehouse. IIE Transactions, 23, 93-102.

[15] F. CARON, G. MARCHET, A. PEREGO, 2010. Routing policies and COI-based storage policies in picker-to-part systems

[16] W. HAUSMAN, L.B. SCHWARZ, S.C. GRAVES, 1976. Optimal Storage Assignment in Automatic Warehousing Systems

[17] M.J. ROSENBLATT, A. EYNAN, 1989. Deriving the Optimal Boundaries for Class-based Automatic Storage/Retrieval Systems. Management Science, 35, 1519-1524.

[18] M. MILIJUS, 2006. Warehouse management and modeling

[19] M.G. KAY, 2015. Warehousing

[20] I.H. SARKER, F.D. SALIM, 2018. Mining User Behavioral Rules from Smartphone Data through Association Analysis

[21] H.L. CHAN, K.W. PANG, K.W. LI, 2011. Association Rule Based Approach for Improving Operation Efficiency in a Randomized Warehouse

[22] G. MANGANO, A. DE MARCO, 2014. The Role of Maintenance and Facility Management in Logistics: A Literature Review

[23] E. FRAZELLE, 2002. World-class warehousing and material handling

[24] A. AKPUNAR, B.Y. EKREN, 2017. Energy efficient design of autonomous vehicle based storage and retrieval system

[25] G. BRUNO, G. D'ANTONIO, M. DE MADDIS, 2016. Sustainability Analysis of Autonomous Vehicle Storage and Retrieval Systems

[26] M. EDER, 2020. An approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep storage

[27] B. ZOU, X. XU, Y.Y. GONG, R. DE KOSTER, 2016. Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems

[28] https://www.flexsim.com/

[29] https://www.educba.com/what-is-minitab/