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Real simulation of last mile e-fulfillment processes in a laboratory environment

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Abstract

This work is aimed at the study of the performance of the automated unit-load warehousing system installed in the DIGEP laboratory. In order to undertake this work, we conduct a literature review on automated warehouses to identify the metrics and key performance indicators. We specify the methodology to assess the performance of the warehouse and its operations, we present a descriptive analysis of the results as well as a benchmarking analysis to evaluate the market performance.

Key-words: automated warehouse, e-commerce, AS/RS, AGV, order picking, order kitting, INCAS, WMS.

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List of abbreviations

WMS	Warehouse management system
AS/RS	Automated storage and retrieval system
S/R	Storage/retrieval machine
AGV	Automated guided vehicle
KPI	Key Performance Indicator
AMR	Autonomous mobile robots
UDC	Unità di carico: storage keeping unit
UDS	Unità di spedizione : order keeping unit
B2B	Business to business
B2C	Business to consumer
C2C	Customer to customer
MRO	Maintenance, repair and operations
AIDC	Automatic identification and data capture
WES	Warehouse execution system
WCS	Warehouse control system
DIGEP	Dipartimento di Ingegneria Gestionale e della Produzione

General introduction

Warehouses have changed dramatically in recent years and they are continuing to evolve day by day. To respond to the growing needs in terms of demand and flexibility, they have been updated, remodelled and modernized. Traditional pallets, racks and forklifts are now upgraded with connected sensors, artificial intelligence or robots.

The expanding growth of e-commerce has significantly shaped this trend. In the first three months of 2021 alone, online sales reached $ 876 billion worldwide, up 38% from the previous year. In some countries like France, nearly one in six tangible goods is now purchased online, and it doesn't look like it will stop. In the United Kingdom, Japan and the United States, studies show that consumers are preferring more and more online shopping, including for their groceries.

It is evident that e-commerce platforms work 24/7, without interruption. It must therefore always be operational and able to take orders at any time. And since it is unthinkable to make warehouse employees work all the time, warehouse managers have to develop new solutions, automation is one of the preferred options to meet these new needs. It is the most popular choice as it helps manufacturers gain productivity, helps to respond to HR issues such as difficult recruitment, or reduce the level of hardship of employees by supporting them on the most repetitive or difficult tasks such as the picking and the packaging of products. For the vast majority of e-merchants, automation is simply a matter of common sense. While the sales processes sometimes differ from buyer to buyer, most are repetitive. The automation of e-commerce workflows allows online merchants to keep their platform running smoothly while focusing their resources on processing related to business development and improving the customer experience.

Automated Storage and Retrieval systems (AS/RS) are computer and robot assisted systems, they can retrieve items and objects for storage in specific locations. They are recommended by the industry in order to maintain a competitive advantage, especially in times of accelerated globalization. These systems help speed up production tasks, save time and decrease costs.

This project is part of this precise framework of warehouse automation. Its objective is to study the performance of the Automated Storage and Retrieval System in order to determine its capabilities and throughput. To do this, we proceed as follows:

- By performing a literature review, we choose our performance indicators, namely the productivity indicators;
- We set up experiments and measure the performance of the several activities that are carried out in the automated warehouse on each station separately. The aim here is to evaluate the performance of the station independently from the next work station;
- We interpret the results obtained from the measurements of our performance test to determine the most accurate values;
- We generalize the experimental results obtained in order to benchmark the performance compared to the industry standards;

All of these elements are described in this report, which is made up of six chapters. In the first chapter, we present the basic concepts of our project, we study the logistics of e-commerce, we explain the constraints of e-logistics, then we describe the automation in e-commerce by presenting a market study of this sector. This chapter defines technically the automated storage and retrieval system and the automated guided vehicles. In the next chapter, we adapt a theoretical research approach that regards the performance studies of automated warehouses and performance indicators. We identify the research and articles that were produced in this field, study their objectives, assumptions and the developed approaches. The objective of this chapter is to synthesize the KPIs that were studied in the literature review, we classify them according to the dimension of time, productivity, quality and cost, then we run some adjustments to make them more coherent with our context. The technical study will be the aim of the third chapter. In the latter, we describe in detail the hardware used in our case study, we present the automated warehouse and all the tools that are installed, without forgetting the presentation of the software: the warehouse management system. In the fourth chapter, we start analysing the case study in which we explain how we initiate the warehouse to star the measurement tests, we define the assumptions and explain our approach, we include also a detailed study of the processes and flows in the warehouse. The rest of chapters are devoted mainly to the interpretation and discussion of results, the description of implications on our case study, limitation that were identified and possible future perspectives.

1. Introduction

This chapter is devoted to the presentation of the basic notions used in this project. It introduces the various concepts and approaches that we faced and the tools that we used in this thesis. First of all, we are interested in the themes of ecommerce and the logistics of e-commerce, we discuss the challenges, limitations and opportunities, then we focus on the automated storage and retrieval systems.

1.1. E-commerce

Technological advances are evolving at such a speed that it would be unwise not to take them into account. Faced with this, electronic commerce or e-commerce has established itself as a new form of commerce, this new form has led to new customer-supplier relationships, new management methods and new forms of organizations.

Electronic commerce, covers everything that allows to carry out online commercial operations in its most obvious form, it sells products online to consumers including any deal carried out by electronic means. E-commerce is simply the creation, control and development of online business relationships. Electronic commerce is the sale or purchase of goods or services carried out over computer networks using methods specifically designed for receiving or placing orders. Even if goods or services are ordered electronically, payment and delivery need not take place online. An electronic business transaction can take place between businesses, households, individuals, governments and other public or private organizations. These electronic transactions include orders placed over the web or the extranet. Orders placed by telephone, fax or hand-typed email are excluded.

Asia-pacific region is the world's largest e-commerce market, with sales reaching up to $2.992 trillion in 2021, 3 times greater than the total sales in North America and almost 5 times as much as the total sales in western Europe. The first spot is occupied by China, which accounts for 52.1% of all retail e-commerce market worldwide, outpacing the united states 19% market share. India on the other hand, holds the spot for the fastest growing market this year, followed by Brazil, Russia and Argentina (Abrams, 2021).

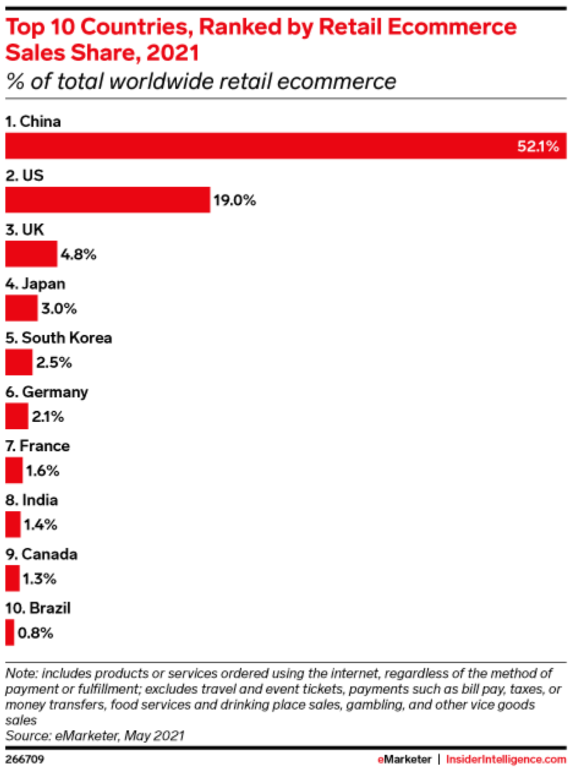

Figure 1: E-commerce sales share, 2021 (Abrams, 2021)

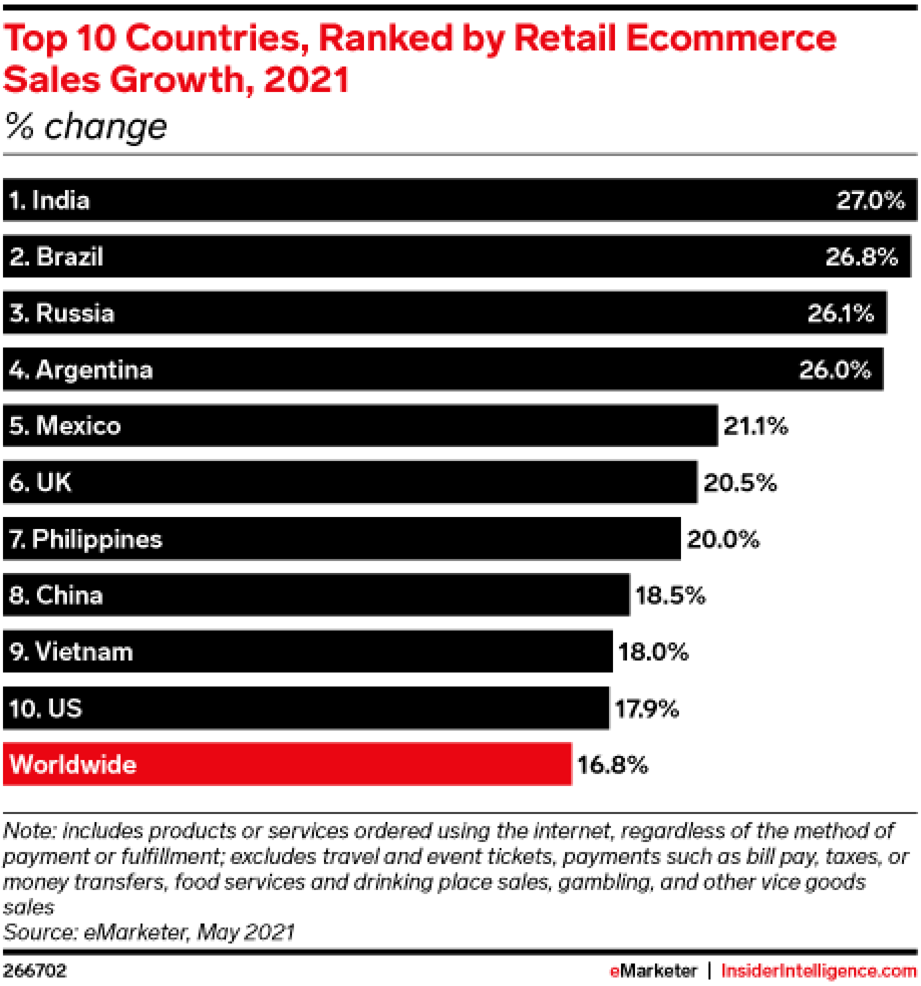

Figure 2: E-commerce sales growth, 2021 (Abrams, 2021)

Mainly there are two types of e-commerce:

- Business to business (B2B): Refers to electronic commerce carried out directly between companies based on the use of a digital medium for the exchange of information. The relationship between a company and its supplier can now be done without an intermediary. B2B is electronic commerce between businesses such as a manufacturer and a wholesaler or a wholesaler and a retailer. It is the exchange of products, services or information between businesses rather than between businesses and end consumers. The B2B e-commerce market was valued at US$ 14.9 trillion in 2020 and is projected to grow to US$ 35 trillion by 2025. Dominated by the Asia-pacific region with a share of 78% in 2020, It continues to grow at such a rapid pace and it is expected to reach 81% by 2025, followed by North America and Europe, respectively with 15% and 6.6% (Mehta & Senn-Kalb, 2021);
- Business to consumer (B2C): Refers to electronic commerce aimed at consumers. This is the most common and well-known form. We are talking about business online stores. Although business-to-end consumer e-commerce is the subject of much attention, business-to-business transactions far exceed business-to-consumer transactions. B2C ecommerce sales were valued around US $ 4.9 trillion in 2019, after a 11% increase compared to 2018, with top spots held by China, the US and the UK (UNCTAD, 2021). In B2C ecommerce, products are sold to the customers through the use of online cart software, that users fill by checking the online catalogue of products. This trade was still only a small part of all electronic commerce, but it continues to

grow. Business-to-consumer e-commerce is most prevalent in Norway, Denmark, Sweden, the United Kingdom and the United States and involves mainly computer products, clothing and digital products;

- There are also other types of e-commerce such as: Business to Administration (B2A), Business to Employers (B2E), Customer to Customer (C2C) etc.

1.2. Logistics

A few years ago, logistics was seen as a secondary function in the company. The role of logisticians was limited to the physical organization of the transport of raw materials or finished products, and even if considerable sums were involved, there was hardly any need for a reflection and a global analysis bearing on all the internal or external flows of the company. The economic crisis and increasingly fierce productivity imposed on entrepreneurs have accelerated the evolution of the function, which has become one of the fundamental keys to the competitiveness of companies.

The term logistics in its most common sense refers to the management of flows within the business. In 1948, the Definitions Committee of the American Marketing Association proposed a first definition: "Movement and handling of goods from the point of production to the point of consumption or use." In their book "Corporate logistics", (Tixier, et al., 1998) proposed the following definition: "Logistics is the strategic process by which the company organizes and supports its activity. As such, the related material and information flows are determined and managed, both internal and external, as well as upstream and downstream". Logistics is the set of methods and resources relating to the organization of a business including: handling, transport, packaging, supplies. Its role is to ensure the best possible treatment of goods and to optimize storage, transport and distribution to customers. It corresponds to the operation which aims to optimize flows in the production system, both for distribution and for industry. The logistics function includes the management of physical flows of raw materials and products as well as that of information flows, i.e. transport, warehouses, import-export, IT, travel and removals, etc. Logistics includes distribution, production, support, storage and industrial logistics. Currently, companies are forming more and more networks. Each network is made up of a company and a set of suppliers. The concept of logistics chain or supply chain has succeeded in bringing together all the different areas of logistics. Indeed, the supply chain is the entire organization and process that aims to deliver the right product, at the right time, to the right place to a customer. It integrates information flows, infrastructures and the overall organization of the company and the processes of purchasing-supplying, production, distribution and after-sales management.

The logistics chain brings together the links relating to supply logistics including purchasing, procurement, inventory management, transport, handling.

1.3. Logistics and e-commerce: strategic relevance and connected issues

Once an online purchase process is made by the Internet user, a delivery process is required to be executed as a next step, to deliver this order to its owner, it is an essential step which becomes an integral part of the “cyber-product”. At the beginning, most sites offered free delivery, which is almost no longer the case, except under special conditions such as having a minimum value of the order or being subscribed to a premium delivery service). In 2000, this situation was completely reversed, since now all the companies insist on the importance of the logistics factor. More and more start-ups are studying the upstream logistic aspect of their project, in the early stages of project development, immediately after studying the IT architecture and secure payment. It became normal that many sites show their delivery offers on the first page of their site, along with the product offer.

Faced with the growing interest in logistics as a key success factor for a website, a new concept is being developed: e-logistics. We can then ask ourselves whether this is really new logistics, specific to electronic commerce, or simply a generalization of current practices. If we look closely at the logistics failures that are most observed in e-commerce, such as the too long delivery dates (a customer who orders in a few clicks may feel frustrated having to wait a fortnight for delivery), a short but unreliable dates (announcing 48 hours and delivering in 10 days is one of the surest ways to lose a customer), unavailability of products, too high delivery fees, insufficient or incomplete information given to the customer on the progress of his order. As we can see, all of these dysfunctions relate to the problem of logistics. The problem here is that the customer is not a company but millions of individual users, each one of them has his own impression on the efficiency of logistics depending on their own constraints.

The difficulties of logistics related to online sales are linked to both order preparation and physical distribution. The e-customer can be a universal customer, who wishes his order to be delivered to his home, usually he has a strong expectation in terms of service, especially since he has paid for his product in advance, he wants a suitable solution to be offered to him because selling on the net comes under the same regulations as distance selling and the customer has, among other protections, the possibility of withdrawing within 7 days after the purchase. This issue is underpinned by two families of constraints or difficulties: those related to order preparation and those related to physical distribution.

For the first constraint, if we consider, by way of example, the problem of order picking, we can easily illustrate the differences between the order picking model in the traditional logistics and e-logistics. In fact, in the classic model, the merchant obtains supplies from his suppliers for his stores and load them in large volumes shelves from which a customer comes to take his products, fill his basket or cart and carry it, by his own means to his home. In the ecommerce model, it is the order picker (of the online merchant or the service provider to whom he has entrusted this activity) who will collect the products, individually, from the warehouse shelves. This new offer brings about the following changes:

– Modification of the size of processed unit: we are moving from packaging big units as pallets and boxes to handling small boxes and units. Some sites also voluntarily choose to reduce the number of references offered, as a way to make the handling process less complicated and more efficient, at least at the start of their activity. The counterpart of this choice is surely the risk of losing customers, who see diversification and availability of other choices as a premium, hence the competitive advantage that would be lost;
– The problem of splitting orders: in the majority of cases, orders are made up of several different items. Some of them may have very long waiting and availability time. The e-merchant may, for obvious customer service reasons, choose to deliver part of the order. He can also choose to reserve the available products, as not to risk additional delays. This gives rise to new information in the logistics system, "partially fulfilled" orders and "pending stocks". The increase of these particular cases tends to interfere with the order preparation system and it could be the source of errors due to the co-existence of several order preparation spaces and the handling of the same order successively, by several preparers.

The second constraint is related to the final distribution: The main characteristic of B to C e-commerce is the need to deliver individually to final customers. Suddenly there is the problem of the “last mile” or last kilometre to be travelled to deliver a small package to its final recipient. E-commerce introduces new challenges: order splitting, high service requirements, delivery difficulties related to approaching the home of individuals. The difficulties associated with this new form of distribution can be summarized mainly in 3 points:

- Home delivery: In addition to the classic obstacles to delivery in urban areas (traffic problems and parking difficulties), the delivery of parcels to the home of the customer poses several specific problems, such as the limited time window when the customer is at his home, or even not being home at all, as well as the difficulties of identifying the home address (incomplete or incorrect address, no elevators, etc.);

- The splitting of order deliveries: Regarding deliveries to end customers, and even more during the start-up phase of the activity, the volumes to be delivered are relatively low and impose an Express delivery. The company is therefore required to manage a much larger fleet of small vehicles (vans);
- Geographic extent: the geographic extent of the market open to online merchants is global. the Internet modifies the rules of competition and helps to lower the barrier to having an international and diverse customer base compared to the traditional customer. It is necessary to deliver a single customer's order no matter what the destination is; sometimes, e-commerce sites limit their delivery offer to national or regional geographic areas. This restriction is, in most cases, temporary.

We can say that in e-commerce, the three essential components are: price, choice and delivery time. For the price, the operational performance and the logistician's margin have of course a direct impact. For the choice, it is always related to a delivery time. For the same sector, some brands have decided to stock a large number of references in order to be able to deliver them very quickly, while others offer even more references but with longer delivery times. This difference corresponds to the time required for the goods to be transported by the manufacturer. A seller can make his offer via a third-party website and have the goods delivered from a logistics platform. These three actors are therefore quite distinct. The logistics of e-commerce therefore consists in detaching the delivery part of goods from the part that sells. In terms of geographic scope, on the Internet, the barrier to selling internationally is much lower than in the case of selling through a network of stores. It therefore becomes necessary to deliver orders anywhere. Some logistics providers are in particular able to offer cyber sellers solutions to deliver their customers anywhere in Europe or even globally. They can also be called upon to offer advanced stocks.

1.4. Automation in logistics and e-commerce

Automation is currently revolutionizing and reconstructing logistics operations, thanks to the decreasing expenditures and the swift returns on investment. Three factors explain the increased use of automation in logistics operations and warehouse facilities. First, COVID resulted in increased absenteeism, which raised the issue of labour availability. Second, technology is continuing to improve, it helps to expand capabilities and reduce costs. Finally, labour-intensive operations, especially in e-commerce, are growing rapidly. The benefits of this technology are significant for e-commerce players, who are considered to be the early adopters of automation. This dramatic transformation cannot be overstated: What was supposed to happen in several years happened in just a few months. As a result, various logistics players in the industry are investing heavily in automation.

Currently, the state of warehouse automation is limited because of the high cost and the slow return in investments. The costs of moving into fully automated facilities are 4 to 5 times higher than the costs of moving into a non-automated facility (Bldg, 2020). Other factors include planning difficulties and the need for operational flexibility, as well as some issues related to downtime and integration during implementation. Automation is mainly present in e-fulfilment centres. E-commerce is three times more labour intensive than traditional logistics operations (Bldg, 2020), with sales volatility twice that of traditional retail, and it is growing rapidly, making it a preferable target for investments that are going likely to improve productivity at work. Automation enables high-quality sites to be opened closer to end consumers, making it easier to expand direct-to-home delivery. In many cases, the choice of site today constitutes a compromise between the availability of labour and proximity to the end consumer. With adopting automation, we would be able to focus on the proximity to customer factor, which will lead to shorter delivery time and lower transportation costs.

Automation is about improving efficiency. When it is done right, automated sites are more productive, perform better, have shorter processing times, improve worker safety, and are more efficient in terms of total cost. Key logistics operations typically include the unloading, receiving, storage, warehousing, order picking, packaging, loading and shipping, and the logistics industry come to the point of enhancing and optimizing these functions thanks to the use of automated racks and forklifts.

The automation adapted in commerce and logistics can be fixed or mobile: the fixed automation involves the use of conveyors, automatic sorters, automated storage and research systems. The mobile and semi-mobile automation consists of adapting robotic solutions, among the most common are the automatically guided vehicles (AGVs) such as autonomous forklifts, the autonomous mobile robots (AMR) such as some co-bots. Logistics players invest in automation primarily to improve productivity and labour efficiency. Therefore, rates of automation use are correlated to the labour force. E-commerce operations will employ more than three people for 93 square meters (Bldg, 2020). Almost 15% of players in logistics in mid-2020, have adopted one or more forms of automation in their facilities. In contrast, traditional execution operations employ on average just over one employee per 93 square meters. The use of automation by these users is very low. Current rates of automation use vary considerably by technology. A 2019 survey of U.S. customers in the logistics industry indicated that about 30% of those surveyed worked in facilities that included a conveyor belt or vertical lift storage, which are the most commonly used technologies. Around 8-10% of the workplaces of those surveyed are equipped with automatically guided vehicles or autonomous mobile robots, with a similar percentage of deployment of pick-to-light or pick-to-voice technologies. Automated station systems (AS/RS, automated sorting) are relatively infrequent, affecting 3 to 5% of respondents.

We move now to explaining why the use of automation today is limited, and why its adaptation rates are slow, well it has some complications, including the high costs and long payback periods. Many traditional forms of automation are heavily customized for specific uses, increasing initial costs and limiting secondary use. In addition to that, when the size of the labour force in logistics facilities is limited, the cost of adopting automations cannot be covered by the economic benefits obtained through labour savings. There are also the IT issues and poor data quality. Automation systems are complex and require the integration of several existing systems. The complexity of the processes and the challenges of planning is also one of the reasons. The use of automation is more widespread when processes are repetitive, with low variability and high volume. While ecommerce is known to have a great volatility and variability, it makes it even harder to respond to the challenges posed by long-term investments in automation. However, the benefits are particularly evident during holidays and other peak periods when labour requirements are great. Added to that, automation fosters opportunities for expansion in markets where labour availability is limited. This disconnection between labour force and logistics activities are usually identified in remote facilities. However, reducing transport costs and reducing the distance between consumers is essential for most users of logistics services.

1.4.1. Automated storage and retrieval system (AS/RS)

Thanks to the development of information and communication technologies, e-commerce occupies an increasing place on the sales market. This trend is expected to intensify in the coming years, as consumers are becoming more confident are trusting of online shopping increasingly, therefore, more packages are being shipped every day, firing up the demand for automation solutions in warehouses. The automated storage and retrieval systems market was estimated to be around 2.4 trillion U.S. dollars in 2020 and it is forecasted to grow by 71% by 2028 reaching 4,2 trillion US dollars as a market value (LogisticsIQ, 2019).

These figures can be primarily explained by the increase in industrial warehousing automation efforts, in the face of the increase of online sales orders and the labour shortage resulting from the Covid-19 pandemic. On the other hand, like virtual reality glasses and portable devices with increased performance, it appears that mobile, collaborative and autonomous robots are a popular solution to quickly gain productivity in warehouse workspaces. The study cites that automatic guided vehicles (AGVs) and autonomous mobile robots (AMRs) will have a 15% share of the automation market by 2025 (LogisticsIQ, 2019). We can see also that in the warehousing industry, robotics has moved from an exploration phase to a now more mature market. All suppliers in the ecosystem have accompanied this evolution, expanding the range of solutions, where software and integration have become important factors of business differentiation, it is forecasted to have a share of 9% by 2025.

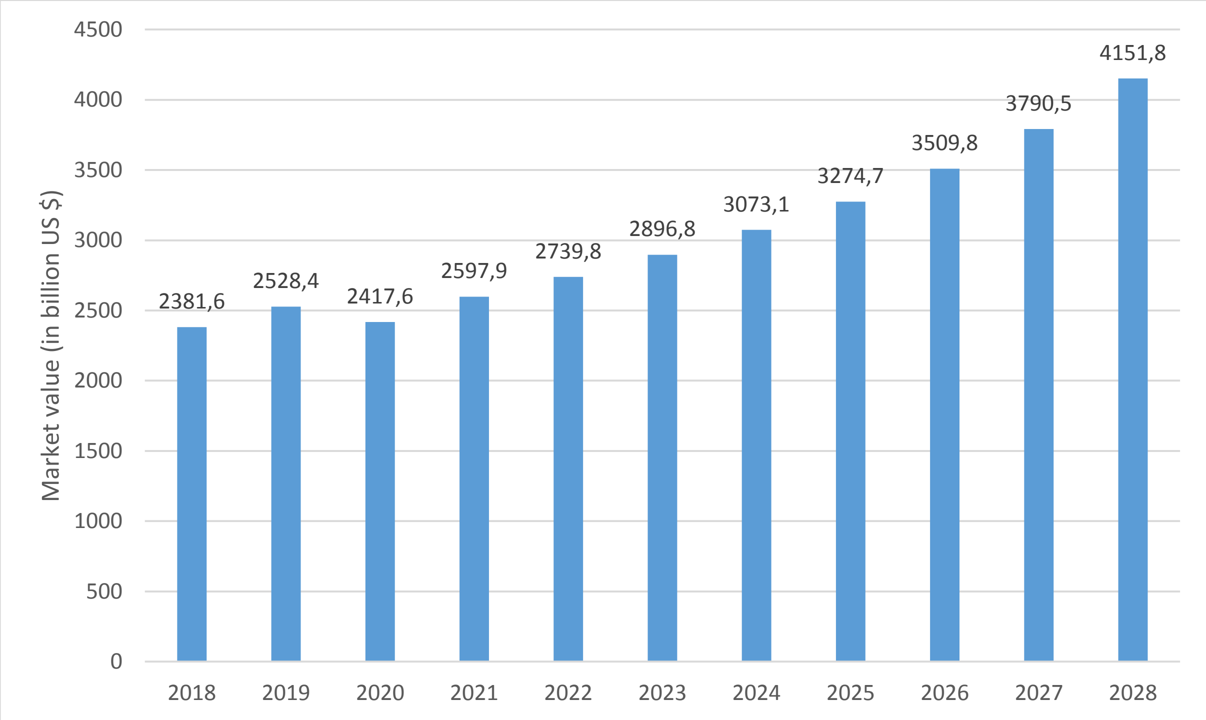

Figure 3: Size of the automated storage and retrieval systems (ASRS) market worldwide from 2018 to 2028 (in billion U.S. dollars)

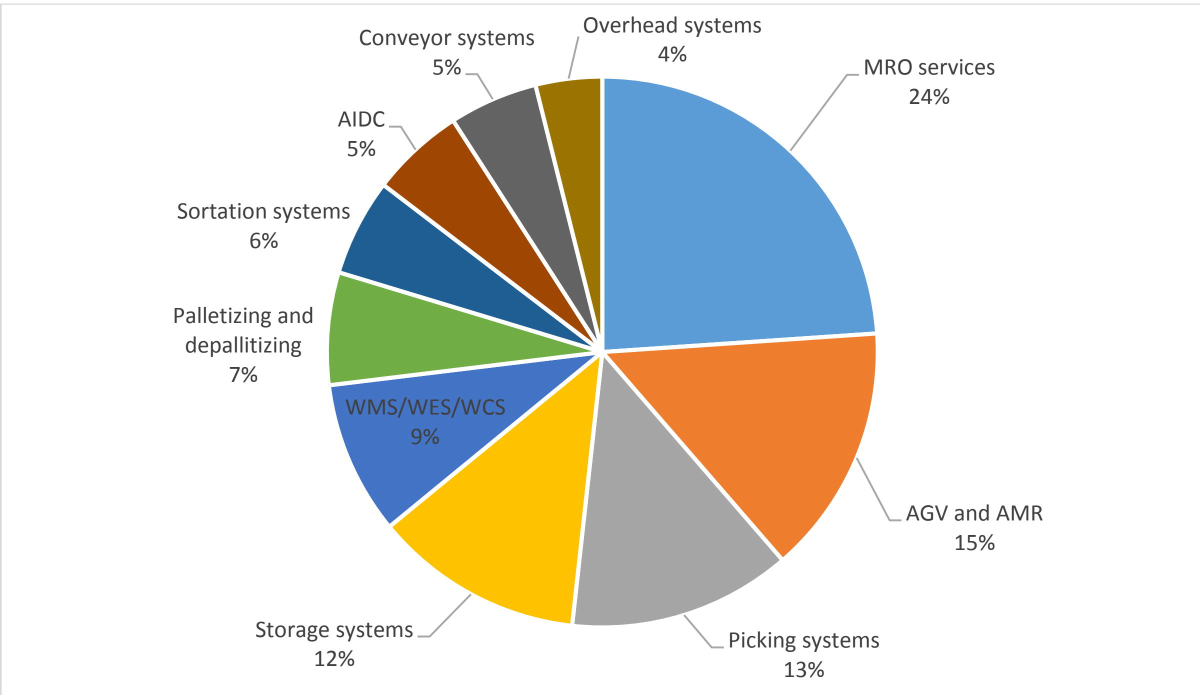

Figure 4: Forecasted global warehouse automation market share in 2025, by technology

After presenting the market for automated warehouses and AS/RS, we focus now on the key terms and concepts of AS/RS. We describe the AS/RS, we benchmark on their functionality and components as well as their advantages and disadvantages.

Automated Storage and Retrieval systems (AS/RS) are computer and robot assisted systems, they can retrieve items and objects for storage in specific locations. Material Handling Institute defines an automated storage/retrieval system as follows: "It is a combination of equipment and control systems that supports, stores and retrieves products with precision, accuracy and speed under a certain degree of automation" (MaterialHandlingInstitute, 1977).

The system is usually made up of machines that can follow established routes to get items. The routes of the system must be minimized to have an economical stock in terms of time and costs. These systems help speed up production tasks, generally they are used when large loading units need to be moved quickly and accurately.

Automated storage and retrieval systems eliminate human assistance in performing sets of operations which include the storage and retrieval of the product which is done by the S/R machine and the transport of items from the locker to the delivery station also called the entry and exit station. These operations are controlled by a microcomputer and the appropriate software.

An AS/RS is made up of storage racks each formed by a set of lockers, a set of aisles each placed between two racks, deposit/delivery stations or input/output stations, storage machines/destocking, and a control system supervising everything.

- Storage rack: This is a set of cells or lockers lying next to each other forming a row and one above the other forming a column. In each cell, one or more products can be stored in multiple layers;
- Bay: It is the height of the storage rack on the ground to the ceiling;
- Row: a series of bays installed side by side;
- Deposit/delivery station: The deposit/delivery station also called entry/exit station is the point through which all the products entering or leaving the system will pass. It is the interface between the S/R machine and the transfer system external to the AS/RS. The transfer of products from AS/RS to other production systems is done either manually or by using transfer systems such as: automated guided vehicles (AGVs) and conveyors;
- Storage/retrieval machine (S/R): The storage/retrieval machine also called stacker crane is a mobile structure used to store or retrieve products in a rack, often at great height. The horizontal sides slide on rails fixed along the aisles (one on the ground and the other on the ceiling). While on the vertical sides slides a sliding plate with two degrees of freedom (linear, vertical and horizontal perpendicular to the aisle) allowing to load and unload the pallets (SARI, 2003). The new generation of these machines has been specially designed to ensure very high speeds and therefore increase efficiency and productivity. They are used to carry out storage and retrieval operations which can be long or even dangerous for human intervention. These machines can move simultaneously in the horizontal and vertical direction. The S/R machine can operate in single or double cycle. In a simple cycle, it performs an operation that is either storage or removal from storage: it then moves from the deposit/delivery station to the storage or destocking locker, deposits or retrieves the product and returns to this same station. In a double cycle, it carries out the two operations at the same time, a storage followed by a destocking: the latter moves from the entry/exit point to the storage rack deposits the product to be stored then it moves from the storage rack to the destocking bin, collects the product to be removed from storage and returns to the delivery station;
- Pallets, container or loading units: These are unit loading containers used to store products in stock. The above items include pallets, special pots and drawers, steel wire containers and baskets;
- Input and output stations, also known as Pick up/drop-off (P/D) station, are the places where inventory enters and leaves the AS/RS. Usually, they are located at the end of the paths for quick

access from the external handling device. The location and number of P/D stations depending on the point of origin of incoming loads and the destination of outgoing loads;
- Control system: It allows real-time control in the production system. It is made up of microprocessors endowed with memory and greater or lesser computing power; software: developed for each type of operation, they are the heart of the control system; Databases, information transmission systems, sensors: They allow the transmission of information such as the storage locations of different products;

The basic form of an AS/RS, known as the unit load AS/RS, consists of two racks separated by a service aisle, each rack having a number of bins. The aisle is served by an S/R machine for storing and removing products from and to the lockers.

Advantages and disadvantages of an AS/RS:

According to (SARI, 2003), automated storage and retrieval systems offer a variety of advantages:

- Reduced space required: an AS/RS can greatly reduce the space required for storage. The space thus recovered can be used to increase production;
- Capacity increase: for the same space, an AS/RS considerably increases the storage capacity. A company whose storage system is saturated can, by choosing an AS/RS, increase its storage capacity, without investing in new premises;
- Improved stock management and control: at any time, the AS/RS control system can accurately give the typical quantities and qualities of products, present in stock, those delivered within the hour, the day, the week etc.;
- Reduction in response times: AS/RS systems have very short response times, for locating, storing or removing items from stock, compared to conventional storage systems;
- Stock reduction: Due to better stock management and control, and reduced response times, it is possible to reduce the quantity of products in stock;
- Reduction of the risks of stock shortage: Thanks to better stock management, which can be done in real time. Stock-outs are virtually non-existent, or of very short duration when unavoidable;
- Reduction of manpower: The automation of the majority of operations in AS/RS makes it possible to reduce human intervention, whether in administration or execution;
- Reduction of deterioration: Automation reduces the risk of product breakage;
- Reduction in operating costs: given the high degree of automation, operating costs are reduced as much as possible (reduction of personnel, light, heating, etc.);
- Increase in production efficiency: Thanks to the increase in the productivity of workstations, the AS/RS allow to increase efficiency of the production system;
- Increased security: AS/RS being autonomous and closed areas, without human intervention, security is greatly improved and theft of products by personnel, or others, is very reduced;
- Just-in-time production (JIT): AS/RS make it possible to have the right product, tools, pallet and support in the right place at the right time thanks to the points mentioned above. This makes it possible to make a significant contribution to achieving just-in-time production.

AS/RS have also some disadvantages:

- AS/RS systems require knowledge, skills and experience. They require significant investments of the capital of the company, in particular for the maintenance and the update of the various subsystems;
- The initial investment is very high. For example, for an AS/RS of 10,000 storage bins, 5 S/R machines and a 60m conveyor, the initial investment varies between 2 and 3 million US$ (Reza, 2000).

1.4.2. Automated guided vehicles

An AGV is an automatically guided vehicle that is able to follow by itself a predefined path through the use of algorithms, artificial intelligence and electromagnetic and optical sensors hardware that are installed. It can handle a variety of tasks such as the delivery of pallets or keeping units from one work station to the other.

AGVs manage their missions autonomously under the automatic control of software linked to the company's ERP or WMS. AGVs first appeared among manufacturers, mainly to supply production lines at the right rate. In recent years, they have evolved to handle less regular and less predictable flows thus meeting logistics needs. These vehicles are most often forklifts capable of moving full or empty pallets on a dock or in a warehouse. These AGVs know how to adapt to the presence of other vehicles and operators nearby. They are programmed to know their surroundings and the different locations where they must pick up or drop off the pallets. These vehicles are also equipped with different types of sensors (barcode readers, 3D cameras, laser curtain scanners, GPS, etc.). These tools allow them to locate themselves in relation to their environment with precision, but also to send a feed-back to the central system with information on the status or configuration of stocks. AGVs must also be able to detect any obstacles, dangers or operators to avoid accidents. The more sophisticated they are, the faster the vehicle can move and deal with obstacles and people working in the same space. Geolocation systems are therefore an essential element for the productivity and proper functioning of AGVs. The applications of AGVs are diverse, for example, they can take care of loading and unloading of trucks, transportation of a pallet to a conveyor, placing a pallet in stock, optimization of overnight storage, moving empty pallets, etc. The cost of an AGV today is around 100,000 €. Thanks to economies of scale and shorter and less complex settings, this price could be dropped to around € 60,000 (GS1, 2019).

AGVs can be useful in industrial environments that needs the transport of material from one place to the other, in situations that are not suitable, complicated, boring or repetitive to operators. They also can be relied on in cases that are considered to be risky or dangerous to human health. For examples, when dealing with materials that are highly toxic, AGVs prevent the risk of human contact with these substances. They have low error rates, high productivity and flexibly to adapt to new tasks and non-familiar situations (like for examples dealing with new products, extension of the industrial facility…). They are energy and environmental friendly because they can operate in conditions that do not require heating systems and lighting which helps to reduce the energy consumptions and costs. They are characterised by their high availability, in fact they are able to operate for longer work shift compared to operators, they also have high efficiency due to their continuous flow in transporting keeping units without any stops. Because they are equipped with a state of the art sensors, the risk of collision is at minimum thus decreasing the rate of product defects in the warehouse.

1.5. Objective of the thesis

The objective of this work is to study the automated warehousing systems installed in the DIGEP laboratory in Politecnico di Torino from a managerial point of view and to present a benchmarking and a performance measurement of a warehouse that is likely to be exploited in a real industrial environment by developing a performance dashboard which allow the estimation of several indicators.

From an industrial point of view, the research interest can be justified by the fact that AS/RS represent a major investment and that we must seek to maximize their productivity. Although the cost of acquiring an AS/RS is high, it is becoming increasingly popular thanks to the high efficiency they can offer. Technologically, they are becoming more flexible, more mobile, and less tied to the physical characteristics of buildings than they were in the past. It is important to say that automation brings the opportunity of having access to new places closer to the end customer, with a low barrier related to the location of the workforce. Thus, it allows supply chains to project themselves into the future more quickly; a future where dynamic, productive and well-located logistics facilities will help customers deliver goods well.

It has already been the subject of scientific work and has been present in academic literature since the end of the 1970s. We also note, depending on the frequency of publication of the field, that scientific interest remains sustained for this type of technology. However, there appear to be several shortcomings in terms of AS/RS systems performance measurement approaches. Indeed, the majority of previous studies are based on analytical models, medialisations and simulations whose validity rests on a large number of simplifying assumptions. This reality raises questions as to the validity of the approaches and results of the literature when we want to apply them to real systems. In order to tackle this problem, we propose the study of a real complex, strongly interrelated and dynamic system. In the literature, some simulation models have been proposed. However, these are very poorly documented and their validity is generally linked to a very particular configuration.

To achieve our objective, we identified through a literature review the performance indicators used in inventory management and performance benchmarking, we classified these indicators according to similarity criteria. Then we moved to the measurement phase carried out on the real system under real operating conditions.

Conclusion

In this chapter we described the key concepts and ideas related to our research. In the next part, we go through a literature review to understand the research that was conducted about the performance of AS/RS.

2. Literature review

This section is dedicated to the literature review, first we discuss broadly about the automation in the warehouse, then we are interested in the works of researchers that have been studying the performance evaluation measures of AS/RS. Finally, we identify the main key performance indicators that were discussed in the literature, then, and finally.

2.1. Automated warehouses in the literature

The degree of automation is a variable that greatly impacts the performance of warehouses and their order preparation systems (Gu, et al., 2010). (De Koster, et al., 2007) classify order picking systems as follows:

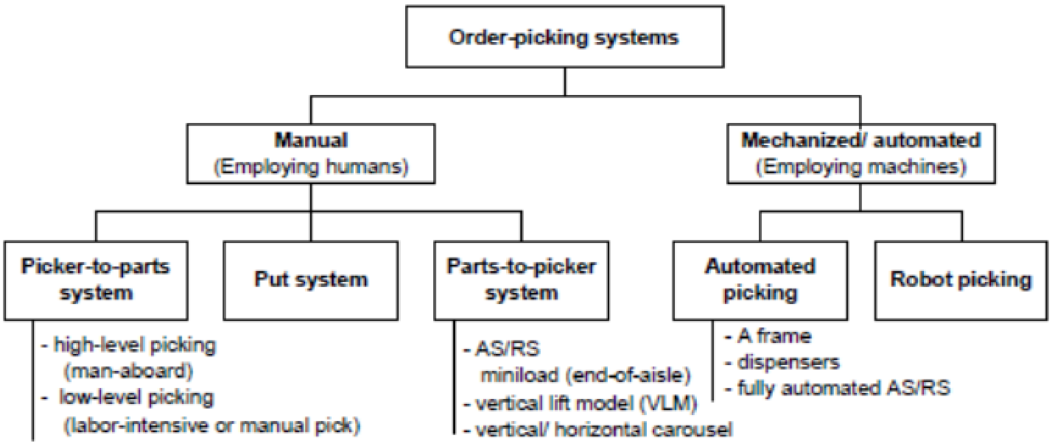

Figure 5: Classification of order picking systems (Gu, et al., 2010)

This classification first distinguishes picking systems according to the presence or absence of a person to perform order picking. The least frequent case is the system without employing a picker, where the order picking is fully automated. In this case of total automation of the order preparation system, two cases arise, either the use of robots, where articulated arms take the products from the stock to place them directly in the boxes/pallets which will be placed in the zone of dispatch, or by the use of automated order picking machines. In the second case, a system using an order picking machine coupled with conveyor systems are used. The machine places the products on the conveyor which takes them to the shipping area. It should be noted that these systems are still very little used in the majority of warehouses because they require a colossal initial investment, and therefore an extremely large number of orders to be carried out to make the automated system profitable.

The second type of order picking system is the one where there is the presence of order pickers. In such a case, the way in which the order picker moves in relation to the products to be collected makes it possible to characterize the system used:

- The order picker moves to the products; this system is called Picker-to-Parts. In this case, the operator is responsible for the preparation of orders, he moves in the aisles to look for the products to be collected. It can be on foot or by vehicle;
- The products are brought to the order picker; this system is called Parts-to-Picker. This case requires the use of automated storage systems, called Automated Storage and Retrieval Systems (AS/RS);

- We can note that there are also systems combining Picker-to-Parts and Parts-to-Picker. This system is called Put-system.

The classification of AS/RS depends on several parameters, we mention a few:

- Size or dimensions of the products to be stored: width, height, depth, weight. The products can be small parts, pallets, containers, etc.;
- The products must be stored one per rack or in multiple layers;
- Number of S/R machines used;
- Number and positions of entry/exit points;
- Dimensions racks: width, height, depth;
- Total number of racks;
- Yield: the number of storage / retrieval per unit of time;
- Number of aisles, shelves, etc.;
- Type of cycle performed by the machine S/R: single cycle, double cycle, multi-address cycle, etc.;
- Machine utilization rate.

Based on this classification criteria, we can identify the main types of AS/RS that are studied in the literature and adapted in the industry as follow:

- Unit load AS/RS: The unit load AS/RS is made up of several aisles, each placed between two adjoining racks and served by an S/R machine. Each locker has a unit capacity. This type of AS/RS is used when the loads to be stored are palletized or in a container. The weight of the load exceeds 250kg. S/R machines are designed to be able to withstand large weights and volumes. Unit load system control is managed by computer with appropriate software. Unit load AS/RS is the standard; other types of AS/RS are just variations of this one;
- AS/RS at mini load or at reduced load: A system at reduced load is used to store small identical or different loads such as: tools, spare parts, ... which are contained in lockers of the storage system (a rack can contain one or more multi-layered products). In the event of storage or removal from storage, the S/R machine is designed to remove the entire container which is moved to an operator who will select the products to be removed from or stored. Once the operation is completed, the container or locker is returned to its place in the system;
- Multi-aisle AS/RS: A multi-aisle AS/RS consists of a set of racks, arranged two by two in parallel and separated by aisles. Each of these aisles, called the service aisle, gives access to two racks. A common aisle placed perpendicular to the racks connects all the service aisles. This type of system is composed of a single storage/retrieval machine which serves all the racks, this S/R machine moves along three axes: vertically, along the columns forming the racks, horizontally, along the racks. service aisles and transversely, along the common aisle, one end of which is equipped with a drop-off/delivery station (P/D). The topology of the multi-aisle AS/RS is similar to that of the unit-load AS/RS with the addition of a common aisle connecting all the service aisles allowing the S/R machine to circulate;
- AS/RS with sliding racks: The AS/RS with sliding racks also called AS/RS with mobile racks are a variation of the AS/RS multi aisles. They are composed of a set of racks arranged in parallel and a single storage/retrieval (S/R) machine. The particularity of these systems is that the service aisles only appear when a storage or retrieval operation is planned in the corresponding racks. The racks forming the system slide sideways on rails so that an aisle can be opened between any two adjoining racks. At rest, there is only one service aisle, which can be placed between any two adjoining racks by sliding the racks. At rest, there is only one service aisle, which can be opened between any two adjoining racks;
- AS/RS with gravitational conveyor: The AS/RS with gravitational conveyor is made up of: A rack which itself is made up of compartments, each compartment is made up of several storage layers, it is fitted with a gravitational conveyor based on rollers or freewheels inclined so as to allow the

sliding of the products from one end of the rack to the other, therefore from one face to the other of the rack; A deposit station located on the storage side, where the storage machine collects the products to be stored; A delivery station located on the destocking side, where the destocking machine deposits the products for delivery. The deposit station and the delivery station are located respectively at the bottom corner of the storage face and the destocking face; A storage machine on the front face of the rack and a destocking machine on the rear face. The two machines can move simultaneously on two axes. These two axes form the x-y plane parallel to the two sides of the rack. These two machines are linked together by a restocking conveyor allowing the S/R machine to access products for restocking; A restocking conveyor which is a gravitational conveyor, tilted in the opposite direction, connecting the two sides of the rack. It allows the products to be restocked to be transferred to the deposit station;

- AS/RS on board: This type of system allows several small loads to be stored in each locker. A person located on a mobile platform, chooses the products to be removed from the lockers, and stores the products to be stored in the corresponding locker. This system makes it possible to reduce storage/retrieval times thanks to the possibility of storing/retrieving several products in a single operation. The operator, after removing them from storage, loads the products onto the S/R machine which transports them to the deposit/delivery station;
- AS/RS with carousel: The AS/RS with carousel is composed of a set of c-mounted racks carrousel and moving horizontally to one end of the rack where the storage and release operation will be performed. In these systems, it is the lockers that move to the end of the rack where an operator stores or retrieves the products;
- AS/RS with deep shelves: In AS/RS with deep shelves, several unit loads can be stored in the same compartment one after the other and having the same address. At each bin, the products can move horizontally. They are stored on one side of the locker and taken out of storage on the other side. This movement is possible thanks to a movable plate which moves from the S/R machine to the entry of the bin. So this type of AS/RS is only a variation of the unit load AS/RS offering in addition the possibility of storing several unit loads in multilayers in the same location.

2.2. AS/RS performance measurement

AS/RS hold a very important place in the industry today, in all fields and sectors. New tools, new methods and new equipment are being developed, all of which have the common objective of improving the performance in terms of efficiency and effectiveness of storage in warehouses, while facilitating industry-related activities and keeping up with the technological development rate and the human activities modernization. They have been the subject of several studies.

The expected travel time of the S/R machine is considered to be the most important factor when evaluating the performance of an AS/RS system. Since 1976, research into the modelling of travel time has been widely studied. For this reason, several researchers have produced numerous articles in this field.

In several works, researchers have been interested in evaluating performance measures of AS/RS, mainly in the cycle time of the S/R storage/retrieval machine. We generally find the mathematical modelling of cycle time and the optimization of this criterion.

The literature on travel time modelling for a unit load AS/RS shows a variety of approaches. (Hausman, et al., 1976) were the first to propose the single-drive cycle travel time model. The authors assumed a continuous square rack over time. They compared the performance of random assignment, full turnover based assignment and class-based assignment. This study was extended by (Graves, et al., 1977) by modelling the dual control cycle travel time model for the same assumptions. The most interesting approach to this question has been proposed by (Bozer & white, 1984). They developed the expected single and double travel time models of rectangular rack under random storage and for different entry/exit positions. Added to that, numerous storage and retrieval strategies were studied.

Some researchers did not consider acceleration and deceleration of the S/R machine and the configuration of the rack. Therefore, (Hwang & Lee, 1990) presented travel time models that incorporated the operating characteristics of the S/R machine, including constant acceleration and deceleration rate, and maximum speed restriction. (Bozer & white, 1984) assumed constant speed, (Chang, et al., 1995) expand this study and consider the acceleration and deceleration. This work was extended by (Web, et al., 2001). (Chang & Wen, 1977) study the impact of rack configuration on expected travel time. Recently, (Brotolini, et al., 2015) extended the analytical models already proposed by the literature to calculate the expected travel time of (AS/RS) in a storage based on three-class-based storage rectangular-in-time storage systems.

(Sari, et al., 2005) presented mathematical models for the expected travel time for an AS/RS flow-rack, which used two S/R machines. The first model is developed using a continuous approach and compared to a discrete model for accuracy via simulation. The authors conclude that expressions based on the continuous approach are extremely practical due to the difference in computation time. After that, (Sari, 2010) carried out a comparative study between AS/RS at unit load and AS/RS with rack. The author considered two parameters of comparison: space use and travel time. (Xu, et al., 2015) develop the dual cycle and quadruple cycle travel time models for single deep and double deep dual shuttle AS/RS. By comparing the two systems, the researchers find that the double shuttle S/R machine is more efficient. In a recent article, (Hachemi & Besombes, 2013) extend the problem of sequencing the recovery of AS/RS flow-rack by integrating the product expiration date. They introduce an optimization method as a decision process, which performs real-time optimization in two phases and formulated as a whole program.

To reduce the travel time of the AS/RS flow-rack, many researchers have proposed different methods. (Sari, et al., 2007) studied the impact of Pickup/Drop off stations and restoration of conveyor locations on expected recovery time and ranked their optimal positions based on randomness of storage and retrieval. (Meghelli, et al., 2010) use a storage method based on two classes for the flow-rack AS/RS, where each element is assigned to the same bin as close as possible to the pick-up/drop-off station. (Bessenouci, et al., 2012) extend this work by implementing two metaheuristic algorithms (taboo search and simulated annealing) that were applied to control the flow rack of the AS/RS with a goal to decrease the retrieval cycle time. (Hachemi & Alla, 2008) present a method for optimizing recovery sequencing in order to find the best locations to destock in the rack, with a gravitational conveyor based on a coloured Petri network model.

In 2012, (Sari & Bessenouci, 2012) presented a new type of AS/RS flow-rack: using a single machine for storage and retrieval operations instead of two machines. They studied storage and retrieval machine analytic travel time models under random storage assignment. Two dwell points positions were investigated and compared in order to determine the best one. Usually, bins in a flow rack go in the same direction from the storage side to the retrieval side, instead, (Chen, et al., 2015) designed a bidirectional flow rack (BFR) in which the bins of adjacent columns tilt in opposite directions. As a result, dual commands operations can be executed in the same time of both sides. They developed a travel time model for BFR systems, providing a throughput baseline for different configurations of BFR.

(Gomri, et al., 2009) propose continuous models of single and dual cycle times of a multi-aisle AS/RS. (Lerher, et al., 2010) present multi-aisle AS/RS travel time analytical models for the travel time calculation for single-control (SC) and dual-control (DC) cycles, they take into account the operating characteristics of the storage and retrieval machine such as acceleration, deceleration and maximum speed, assuming a uniform distribution of locations of storage racks. In the research of (Ouhoud, et al., 2016), continuous and discrete travel time models are developed, for a Class Based Storage single-cycle trips of the S/R machine in a multi-aisle AS/RS. (Guezzen, et al., 2013) presented two analytical models for estimating the travel time of an AS/RS with mobile rack moving laterally on rails (M-AS/RS).

In summary, in the literature, several travel time models have been developed and different types of AS/RS have been presented.

2.3. Performance indicators

This section deals with the concept of indicator. After defining it in the most general sense, important related concepts and the roles of indicators in a management system are discussed. The relationships between indicators, objectives, actors and levers of action are discussed, as well as the characteristics making it possible to judge the quality of an indicator.

Indicators represent essential decision-support tools for all those who are in charge of managing any process, whatever it may be. It is impossible to drive a car efficiently without a dashboard that indicates speed, fuel level, etc., it is the same when it comes to manage a process properly, we have to measure its performance, monitor the system time and compare its performance to the set objective.

Generally, an indicator can be defined as an element, information that provides indications, information on the value of a quantity measured. Information, for its part, is data or a set of data articulated in order to construct a message that makes sense. Depending on the degree of importance given to an indicator or a group of indicators in the management system, they may be qualified as "key" performance indicators (Key Performance Indicator). These are the predominant indicators in the performance monitoring and control system and which require the most attention from managers. From this, the performance indicator can be defined as information that should help a "decision maker", individual or more generally a group, to lead the course of an action towards the achievement of an objective or to enable him to do so.

In the literature, the indicators used to measure the performance of the automated warehouse systems are very numerous and diversified. For this reason, we have grouped them into four classes: time indicators, productivity indicators, cost indicators and quality indicators. In each of the classes, the indicators are generally calculated by mathematical (analytical) formulas. We start with time indicators that represent information on the duration of operations in the warehouse, such as the unloading activity, storing, order picking and order preparation. In the literature, these indicators take several forms such as the order picking time (Mentzer & Konrad, 1991), the put away time (Mentzer & Konrad, 1991) and the dock to sock time (Ramaa.A, et al., 2012). We identified another indicator class, cost indicators, that represent measures for the expenses generated by the different warehouse operations or by part of these operations and equipment. The cost calculation generally includes the costs of the use of space and the costs of labour. Additional costs can sometimes be added such as overtime costs and non-conforming order charges. There is also the productivity and performance indicators that record the pace of operators in the warehouse. Performance measures give an idea of the fluidity of operations. They present information on the productivity of the system. In the literature, performance indicators are expressed in the form of an order preparation rate such as the number of product lines picked in a labour hour (Kiefer & Novack, 1999). Finally, we identified quality indicators that provide information on a specific problem that can take place while storing products and preparing customer orders. They are used to track these problems and errors. Through these measures, it is possible to identify the inefficient use of resources. Some quality indicators were identified in the literature review such as the receiving accuracy (Mascolo, et al., 2014), on time delivery (Voss, et al., 2005), and perfect order rate (Kiefer & Novack, 1999).

The key performance indicators were assessed according to their usability and relevance: the indicator must make it possible to “give a sign”, to easily guide us, or more generally the group of actors, to act and understand the factors of success or failure. We selected these that are the most significant and in line with the objectives of the thesis that can help us properly monitor the performance of the automated warehouse. We also evaluated the quality of the indicator with its operational relevance. This consists of verifying that the measurements carried out are the results of a precise and identified type of action, that the data used are trustworthy. The operational relevance of an indicator therefore concerns the validity of the results.

To evaluate the performance of an AS/RS, we can use several measurement indicators. The most important are: the utilization rate of the S/R machine, the cycle time is among the most important parameters of an AS/RS since it directly influences the performance of the overall system and the storage space used.

- The rate of use of the S/R machine: it corresponds to the number of storage requests or destocking requests processed over a period of time;
- The cycle time of the S/R machine: Average time required to serve a storage or retrieval request or the time that elapses from the appearance of the request until the end of its execution. The cycle time includes the waiting time if the request is not satisfied at the time of its appearance, the time of movement of the S/R machine from the deposit/delivery station to the storage/retrieval locker, and the travel time from the storage/retrieval locker to the drop-off/delivery station;
- Rate of requests satisfied per unit of time: it depends on the average cycle time but also on storage methodologies and system management techniques;
- Storage space used: the storage space used in the AS/RS or the quantity of products that can be stored (per unit of volume) in an AS/RS depends on the type of the latter.

The list of the key performance indicators can be found in table 1 and the full list of KIPs that were identified in the literature review is located in attachment 1.

Table 1: KPI list

KPI	Brief description	Related variables	References
Time Indicators			
Put away time Pu t	Lead time since a product has been unloaded to when it is stored in its assigned place	$Pu\ t = \frac{\sum \Delta t\ (Sto)}{LU}$ (hour/loading unit) Δt (Sto)= Time between the instant when product is unloaded until its storage (hour) LU: number of loading units (nb/month)	(Mentzer & Konrad, 1991)
Order picking time Pick t	Lead time to pick an order line	$Pick\ t = \frac{\sum \Delta t\ (Pick)}{OrderLi\ Pick}$ (hour/order line) Δt (Pick)= Time between the instants when operator starts to pick an order and when the picking finishes (hour) OrdLi Pick= number of order lines picked (nb/month)	(Mentzer & Konrad, 1991)
Picking to packaging time PtP t	Time between picking to packaging (before shipping)	$Ptp\ t = \frac{\sum \Delta t\ (Ship)}{Order\ Del}$ (hour/order) Δt (Ship)= Time between the instant when the order picking finishes and when the order is in the packing area (hour) Ord Del= number of orders delivered (nb/month)	(Campos, et al., 2004)
Productivity Indicators			
Labour productivity Lab p	Total number of items managed by the amount of item-handling working hours	$Lab\ p = \frac{item\ proc}{WH}$ (items/labour hour) Item Proc = number of items managed by the warehouse (inbound and outbound) (nb/month) WH = number of item-handling working hours (hour/month)	(DeMarco & Mangano, 2011)
Storage productivity Sto p	Number of **loading units** stored per labour hours in storage activity	$Sto\ p = \frac{LU\ Sto}{WH\ Sto}$ (Loading unit/labour hour) LU Sto = number of loading units stored (nb/month) WH Sto = sum of employee labour hours working in storage activity (hour/month)	(Mascolo, et al., 2014)
Average Stock S	The average quantity of products sored in the warehouse during a certain amount of time	$S = \frac{\sum s(i)}{N}$ N= the number of observed days S(i)= the stock measured the i-th day, expressed as a number of products or total weight	(Colla & Nastasi, 2010)
Receptivity Saturation Coefficient RSC	Express how much the warehouse has been exploited in a certain period of time	$RSC = \frac{S}{R}$ S= the average stock R= the receptivity, approximately equal to the maximum quantity of items that has been recorded In terms of boxes stored in the warehouse (n of boxes or n of products)	(Colla & Nastasi, 2010)

Picking productivity Pick p	Number of products picked per labour hours in picking activity	$Pick\ p = \frac{OrdLi\ Pick}{WH\ Pick}$ (**order line**/Labour hour) OrdLi Pick = number of order lines picked (nb/month) WH Pick = sum of employee labour hours working in picking activity (hour/month)	(Kiefer & Novack, 1999)
Equipment downtime EqD p	Percentage of hours that the equipment is not used	$EqD\ p = \frac{\sum HEq\ Stop}{\sum HEq\ avail}$ (%) HEq Stop = total number of hours during which equipment are stopped (hour/month) HEq Avail = total number of hours during which equipment are available to work (hour/month)	(Bowersox, et al., 2002)
Throughput Th p	Ratio between items and hours leaving the warehouse	$$Th\ p = \frac{Ord\ ship}{War\ WH}$$ Ord Ship = number of order shipped (nb/month) War WH = total number of hours during which the warehouse works (hour/month)	(Mentzer & Konrad, 1991)
Stock contraction	Percentage of the theoretical stock contraction compared to the current one	(Theoretical stock - Actual stock) / Theoretical stock	(Mecalux, 2021)
Out-of-stock rate	The amount of an assortment that is not in stock	Unfulfilled orders /Total orders x 100	(Mecalux, 2021)
Quality Indicators			
Storage accuracy Sto q	Storing products in proper location	$Sto\ q = \frac{Cor\ Sto}{LU\ Sto}$ (%) Cor Sto = number of loading units stored in proper location (nb/month) LU Sto = number of loading units stored (nb/month)	(Voss, et al., 2005)

Conclusion

In this chapter we dived in the literature review that was conducted about the subjects of automated warehouses, measuring their performance and classifications. Subsequently, we began the process to define the context of the project to clearly specify and delimit the problem.

3. The laboratory

This chapter is the first step of work with the case study of the thesis, it describes the model of the automated warehouse in our case as well as the warehouse management system that was used.

3.1. The physical system

3.1.1. The automated unit-load warehousing systems

In this thesis, we focus on a particular warehousing and handling technology: the unit-load automated storage and retrieval system (AS/RS). Broadly speaking, the term AS/RS englobes any type of warehousing system in which the physical management of products is integrated and automated, at least in some parts. Unit load automated warehousing system is a type of AR / RS that specializes in the storage and processing of product pallets. It is mostly found in high volume distribution and production environments. In its most general implementation, a unit load AS/RS has one or more aisles lined with storage shelves. Each location can accommodate a single pallet. The pallets are handled by a robot that can transport at most one pallet at a time. At the entrance to each aisle there is also an input and output (I / O) point for the pallets.

Figure 6: Front view of the AS/RS

The automated warehouse is installed in the DIGEP lab that has a total surface of 68,6 m² and is equipped with:

- Racks to store keeping units a capacity of 40 cells (1);
- An output conveyor related to the kitting station or the AGV docking station (2);
- Kitting racks equipped with gravity conveyor (3);
- Picking racks equipped with gravity conveyor (4);
- Output picking station or docking with the outbound AGV (5);
- A kitting station dedicated to the preparation of kits that can be processed by assembly (6);

- A picking station dedicated to the preparation of orders (7);
- Buffer for picking orders keeping units (8);
- Input area of keeping units (9);
- A mini-load stacker crane that moves keeping units from one position to the other in the racks, or between the input and output conveyors, by a vertical and horizontal movement, it can move storage keeping units with a weight up to 50 kg. (10);
- 2 entrances that allow technicians to perform maintenance procedures.

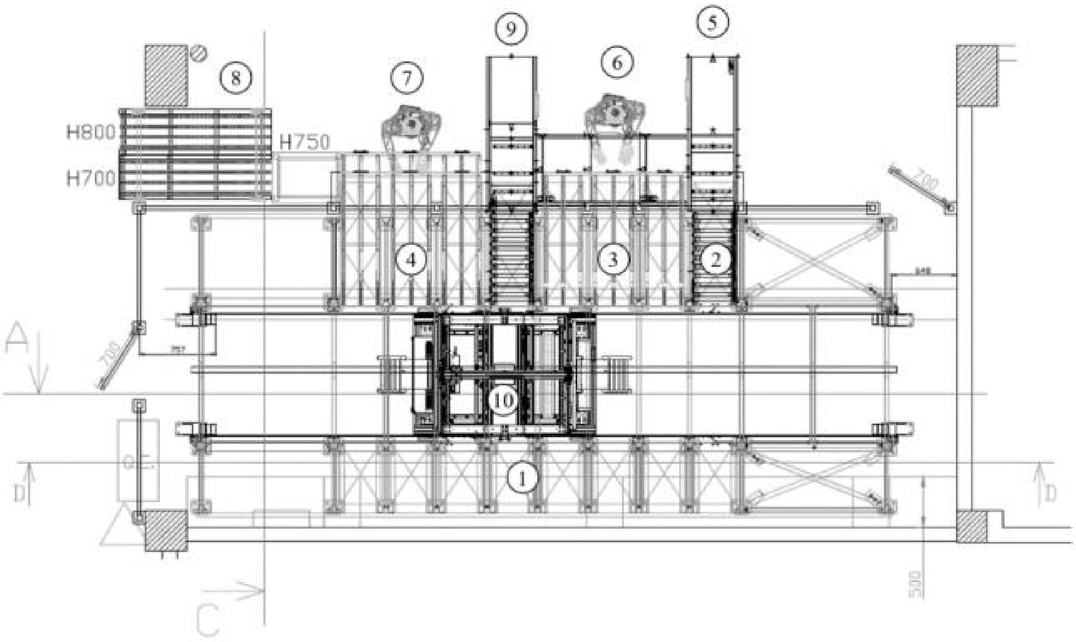

Figure 7:Top view of the automated warehouse

3.1.2. The automated guided vehicles

The laboratory is also equipped with 2 AGVs, they have a dimension of 890x580x352 mm and weight 62,5 kg, with a loading surface of 600x800mm, they can operate for 10 hours, transporting objects with a distance of 20 km if it is fully charged. Their forward speed is 1,5 m/s and their backward speed is 0,3 m/s. To reach 80% battery, they must be bulged in the charging station for 2 hours, 3 hours for 100%. They are equipped with 2 laser scanners for 360° visual field, 1 3D camera to detect obstacles and 4 ultrasonic scanners to detect transparent and glass objects.

Figure 8: the automated guided vehicle MIR

3.2. The warehouse management system (WMS)

Software systems are used to support warehouse processes. A WMS is a computerized information system for the preparation, monitoring and execution of warehouse activities of a transactional nature. It has been available since early computer systems where it provided simple functionality for the storage location. They can include complex technology, such as radio frequency identification (RFID) and speech recognition. The main use of the system is always the same, which is the logical control of the flow of materials in the warehouse. Improvements in WMS lead in the vast majority of cases to increased customer satisfaction thanks to reduced lead times and thanks to 100% reliable deliveries, as well as better productivity (a use of the resources of warehousing, reduced inventory and improved productivity). More and more companies are using this type of tool.

The INCAS WMS is located in a virtual machine that can be accessed through any computer by connecting to the private VPN network of Politecnico and by inserting the user credential.

Figure 9: The main functionalities of the WMS

The main functionalities are as follows:

- Receipt (the "Postazione carico" menu): This is a functionality that supports the receipt of goods in the warehouse. It offers a wide variety of scenarios depending on the nature and size of the flow to be processed. In conjunction with site management, it ensures perfect synchronization between logical entries and physical storage;

– Storage (“Gestione giacenza”): The primary function of a stock is to constitute a "reservoir" making it possible to bridge the differences between upstream and downstream flows. It contributes to the regularization of production and the distribution cycle and avoids breakdowns. It offers the advantage of flexibility with respect to demand, and therefore control of delivery times;
– Preparation of kitting and picking orders (“Postazione kit” & “Postazione Pick”): The preparation management ensures operations from taking into account the orders to be delivered until the provision of the prepared goods on the shipping docks;
– Monitoring and reporting (“Missioni di prelievemento”): Real "control tower" of the warehouse, the dashboards allow to supervise the logistics activity in a synthetic and detailed way;
– Traceability: Legal obligation present throughout all the logistics processes of the warehouse. This makes it possible to visualize all the events that have occurred on an item, a batch or a location and this in terms of both administrative and physical traceability.

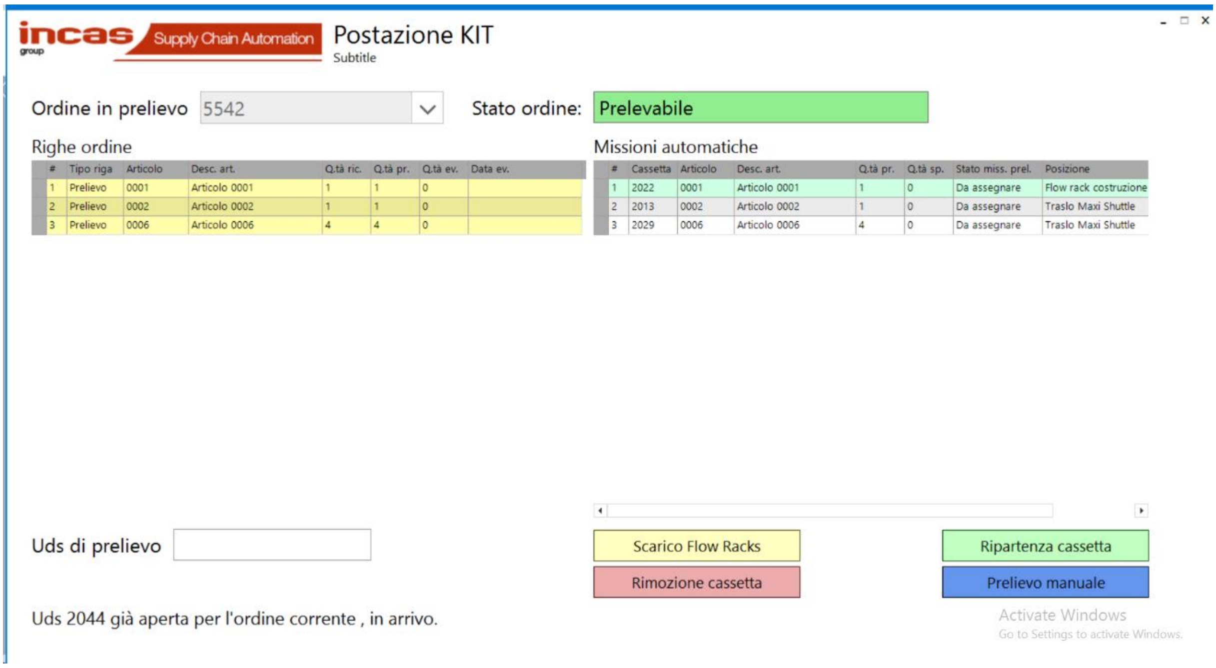

Figure 10: kitting order execution window on the WMS

To create new orders, In the section “Gestione uscite”, we click on “Ordini di prelevio (tutti)”, then on “ins. Ordine”. In the screen that opens, the order ID and order code are filled in automatically by the system and both of them are unique. In the section "Dati di base", we should choose the type of order "Pick" or “Kit”. We click then on the command "Inserici Testata", by doing this, we insert a new order in the queue. Now, we fill the order lines by clicking on “Editor righe” and on the symbol (+): we identify the article, the quantity and the lot of the product. At the end we confirm.

After creating the order, we click on the section “Gestione uscite” then on “Ordini di prelievo” and we look to the order characterized by the state “In acquisizione”. We should then highlight the order then we click on “Acquisisci ordine”, in this case the order should be “Acquisito (valido)”. From now on, the order can be activated from Easystor, by right-clicking on the order and choosing "Attiva". To deactivate an order, we select its header and click on "Disattiva".

When we want to withdrawal an order from the PICK station, we click on “Postazione Pick” or “Postazione Kit” (figure 9) depending on the type of the order, we choose first the reference of the order that we want to execute among the list, then the systems will elaborate it. If the order is executable, we discharge the flow rack and remove the keeping unit from the station and we confirm the execution of the order.

Figure 11: Functionalities of the WMS (on the left)

Conclusion

In this chapter we descripted the hardware and software that were used and studied in the thesis. The next step is to start setting up the experiments.

4. Experiment building

In this chapter, we discuss the assumptions that were taken, explain the development of experiments that took place in the warehouse and we specify how measurements were taken.

4.1. Initiation of warehouse

As a first step and before taking any measurements, we decided to clean the automated warehouse, so we can start basically from point zero, in the sense of closing all the customer orders that were executed in the past, recalling all loading unites that are stored inside the automated warehouse, stack them in the buffer areas near the input station, delete all the products that are defined in the warehouse management system and resetting the errors that were signalled by the system. By doing this, we were able to start from an initial state of the automated warehouse.

We begin by inserting 10 new products in the warehouse management system, we named them product 0001 to product 0010 with references ranging from 0001 to 0010. It was not important to define these products as real physical products, for example like a book, a bottle of water or even a smartphone. We assumed that these products can be anything, with small dimensions, to have an infinite quantities and to avoid the possibility of running out of stock in a latter phase of the work.

Then, we counted the total number of loading units available in the warehouse, there were 5 types of storage unites that had different dimensions: we had 130 in total. They were distributed as follow:

Table 2: Available keeping units

TYPE	Number of UDC
LTB6120	30
LTB6220	50
LTB4120	20
LTB4220	20
MF 6070	10
	130

Table 3: Dimensions of keeping units

Type	Length (cm)	Width (cm)	Height (cm)
LTB6120	60	40	12
LTB6220	60	40	22
LTB4120	40	30	12
LTB4220	40	30	22
MF6070	60	40	12

We defined also the maximum quantity of products that each unit can hold in relation to their dimensions, the bigger the size the more important the capacity. Their maximum capacities are shown in table 4.

Table 4: Capacities of keeping units

Box type	Capacity (Max quantities of products)
LTB6220	50
LTB4220	25
LTB6120	30
LTB4120	10
MF 6070	20

The automated warehouse can store up to 112 LTB 4220 units in total, with 90 compartments in both racks. We agreed to work with an 80% warehouse capacity because it was more efficient. In the guidelines, it is recommended to have some empty shelves so that the stacker crane can move up boxes from one location to another, in order to make the revival and storing of units more efficient and to give the system some degree of flexibility and freedom. The system can store up to 4 units in the same rack, and because the charging and discharging from the crane stacker to the storage position on the rack has the same entry and exit point for each position, the box that enters first will be blocked by the second box that is stored behind it. So in order to take the box that was first inserted in the rack, the system must remove the second box that is stored in front of it and store it in another position in the rack. As a result, this lead us to having 75 assigned positions and 15 empty position in the automated warehouse.

Table 5: Warehouse capacity

Compartments	90	
Total capacity	112	
% Filling	80%	
Number of boxes in	90	
Loading units	75	83%
Empty in	15	17%
Empty out	40	

Before inserting loading units in the warehouse, we had to add them logically into the warehouse management system. Then, we used the random function in Excel to assign, in a random way, each type of product to a specific loading units. We did not fill all the available loading units with products, we left some units empty intentionally because we will use them in a later step as order keeping units. 57,69% of total boxes were filled with products, 11,53% of unites were kept empty but were loaded inside the system and the rest were kept in the buffer areas. For example, for 30 boxes of type LTB6120, 18 boxes were loaded with mono-products such as product 0004, product 0008 and product 0010 (each box containing a single type of product), 3 units were empty and loaded in the warehouse and 9 unites were empty and stored in buffer area. Inventory records for LTB6120 can be seen in table 6.

Table 6: Inventory records for LTB6120 keeping units

BOX	CODE	CAPACITY	PRODUCT 1	TYPE
LTB6120	1001	30	4	LOADING UNITS
LTB6120	1002	30	4	LOADING UNITS
LTB6120	1003	30	4	LOADING UNITS
LTB6120	1004	30	9	LOADING UNITS
LTB6120	1005	30	4	LOADING UNITS
LTB6120	1006	30	6	LOADING UNITS
LTB6120	1007	30	8	LOADING UNITS

LTB6120	1008	30	5	LOADING UNITS
LTB6120	1009	30	7	LOADING UNITS
LTB6120	1010	30	5	LOADING UNITS
LTB6120	1011	30	10	LOADING UNITS
LTB6120	1012	30	7	LOADING UNITS
LTB6120	1013	30	10	LOADING UNITS
LTB6120	1014	30	8	LOADING UNITS
LTB6120	1015	30	3	LOADING UNITS
LTB6120	1016	30	5	LOADING UNITS
LTB6120	1017	30	5	LOADING UNITS
LTB6120	1018	30	3	LOADING UNITS
LTB6120	1019	30	0	EMPTY IN
LTB6120	1020	30	0	EMPTY IN
LTB6120	1021	30	0	EMPTY IN
LTB6120	1022	30	0	EMPTY OUT
LTB6120	1023	30	0	EMPTY OUT
LTB6120	1024	30	0	EMPTY OUT
LTB6120	1025	30	0	EMPTY OUT
LTB6120	1026	30	0	EMPTY OUT
LTB6120	1027	30	0	EMPTY OUT
LTB6120	1028	30	0	EMPTY OUT
LTB6120	1029	30	0	EMPTY OUT
LTB6120	1030	30	0	EMPTY OUT

Table 7: Total distribution of keeping unites in the warehouse:

TYPE	N UDC	%	EMPTY IN	LOADING UNITS	EMPTY OUT
LTB6120	30	23%	3	18	9
LTB6220	50	38%	6	29	15
LTB4120	20	15%	2	11	7
LTB4220	20	15%	2	11	7
MF 6070	10	8%	2	6	2
	130				

Afterwards, we used the WMS to insert the data logically. First, we insert the reference of the box, if the systems identify that the box is located outside and is indeed an empty storage keeping unit, it reserves this unit and we can choose which product we wish to fill it with, then we confirm the quantity.

Creation of picking and kitting orders:

In total, we created around 120 picking orders and 140 kitting orders. These orders contained products with references from 0001 to 0010 that were assigned randomly using excel. Some orders contained only one type of product and other orders contained several product references. We created orders containing 1 product, 2 products, until 10 products randomizing the possible product combinations in each order, by using the random function in excel to choose the orders that we will insert in the WMS. Each product had a quantity of 1.

The distribution of the number of product per each order was taken from an automated parcel lockers location problem study made in the city of Turin. In this study a questionnaire was submitted and answered by more than 1456 prospective user. The objective of this survey was to understand the behaviour of customers when they order products online. There were questions asking about information related to the customer in order to identify the sample's characteristics, such as: age, sex, job, postal code, and other questions related to the behaviour like: have you purchased at least one product online in the last month? last year? how many orders do you make online on average in a year? etc. One of the questions that were included in the survey and that was most relevant to our study was: "How many products do you buy on average for each order?". We had answers from 1 to 10 with some outliers. After cleaning and manipulating the data, we came out with the distribution in table 8.

Table 8: Product per order distribution

n of products per order	Number of occurrences	Distribution
1	653	48,99%
2	455	34,13%
3	151	11,33%
4	32	2,40%
5	22	1,65%
6	6	0,45%
7	2	0,15%
8	3	0,23%
10	9	0,68%
Total	1333	100%

We analysed this table statistically using Minitab software to verify if the data follow a normal distribution or another type of distribution. By analysing the p values we rejected the null hypothesis. The data did not follow a specific statistical distribution.

As mentioned before, 120 picking orders and 140 kitting orders were created in total. Before taking any measurements, we created a small number of orders that are going to be executed in the experiment, making sure that these orders were chosen randomly, and had random product combinations in each order, by following the product per order distribution. For example, for the first kitting measurement experiment, we decided to have around 50 kitting orders, loaded and ready to be executed in the WMS before taking any measurements, by employing the product per order distribution and rounding the results, we obtained 24 orders that contained a single product, 17 orders that contained 2 products that were assigned randomly, 5 orders that contained 3 products and 1 order for the remaining types of orders.

Table 9: Rounded number of orders

n of products per order	Distribution	N of orders on 50 orders	rounded number of orders
1	48,99%	24,495	24
2	34,13%	17,065	17
3	11,33%	5,665	5
4	2,40%	1,2	1
5	1,65%	0,825	1
6	0,45%	0,225	1
7	0,15%	0,075	1
8	0,23%	0,115	1
10	0,68%	0,34	1
	Total	50	52

Table 10: Product references that were assigned to each type of order (1, 2 & 3 products per order)

1 product per order	
order reference	reference of the 1st product
1	4
2	7
3	3
4	5
5	2
6	3
7	6
8	9
9	5
10	7
11	1
12	1
13	10
14	9
15	7
16	1
17	6
18	5
19	5
20	9
21	9
22	1
23	5
24	1

2 products per order		
order reference	reference of the 1st product	reference of the 2nd product
1	1	3
2	3	4
3	3	8
4	1	8
5	7	4
6	5	4
7	10	3
8	6	7
9	2	7
10	9	1
11	5	10
12	10	9
13	8	1
14	10	3
15	10	6
16	6	7
17	3	9

3 products per order			
order reference	reference of the 1st product	reference of the 2nd product	reference of the 3rd product
1	1	9	2
2	3	7	9
3	8	7	4
4	4	2	5
5	1	7	3

While creating kitting orders, we had to precise which type of order keeping unit we will use while executing the kitting order, this unit must be empty and loaded in the automated warehouse before launching the retrieval order. On the other hand, in the creation of picking orders, we did not specify the order loading unit.

4.2. Picking

One of the most important processes in logistics is the preparation of orders, the step of which occupies 50% of the total duration of the process. The process of picking is composed of several parts: the logical creation of picking order and launching them using the management software, as well as the waiting time in which the machine search for the right item and travel between the locations where the products are stored and where to be dropped in the picking station racks. Order preparation involves also allowing operators to collect a set of assorted items from their keeping unites and putting them on the order keeping unit following customer orders.

Figure 12: Picking station

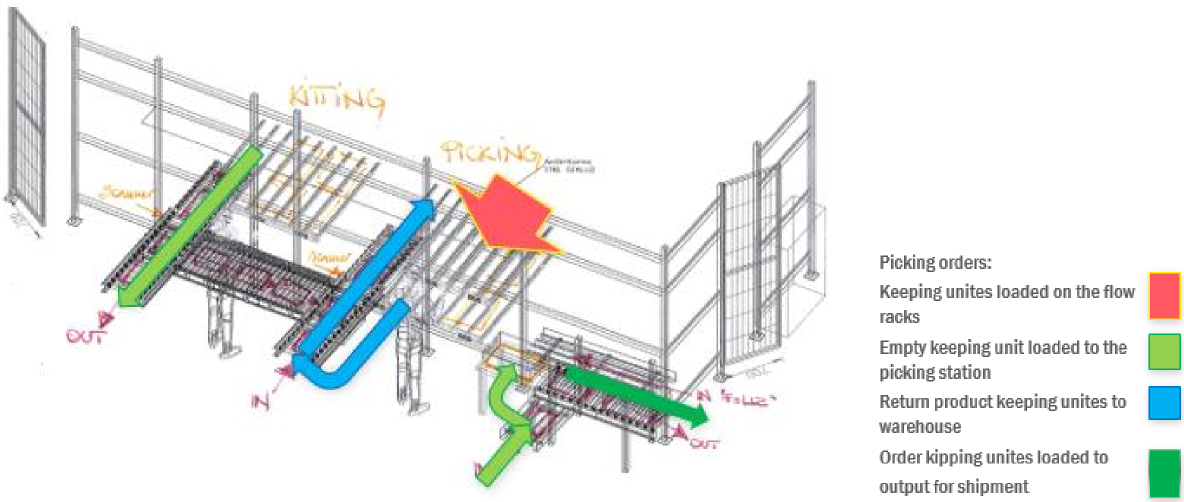

Figure 13: Flows in the picking process

The picking station (as well as the kitting station) is equipped with a Pick-to-Light system, that provides a visual aid to the operator by using small lights under the picking station flow racks, it displays in a comfortable manner and in the operator's field of vision the number of items that must be picked from the above loading unit. This system is connected with the WMS from which the order is sent. It improves efficiency, reduces picking errors and insures a paperless order preparation. This technique, which relies on visual signals, reduces errors as well as research time. The advantage of the pick-to-light is that it allows the operator to keep his hands free. Once the picking is finished, the operator confirms by pressing the confirmation button and the indicator light goes out. The change is immediately recorded in the management software.

Same as the kitting process, the operator can also execute a picking order, in which he has to retrieve loading units from the automated warehouse using the WMS, and then pick the products to prepare the customer order before delivery. Once a retrieval order is executed, the stacker crane moves the loading units from the storage racks and deliver them to the picking station. In one customer order, several retrieval operations are executed. In the case of the picking station, only the loading units that contain the required items will arrive on the flow racks of the picking station. The operator must take by himself the box that is going to contain the order. Once the retrieval is finished, the system updates its logical inventory by decreasing the number of items that were retrieved and signalling that the order is prepared.

It is important to note that the picking process is similar to the kitting, the difference here is that it is not required to insert or recall the box that is going to be used to hold customer's order once it is processed, the operator will simply take a box from a buffer near the picking station (terra) (light green line in figure 13) and insert its reference number in the picking UDC bar in the menu once the picking order is launched. Once the system verifies the availability of the requested items, the stack crane machine brings the required boxes, the operator picks the products, confirms the picking by pressing the buttons located near the pick-to-light system, then he discharges the flow racks, and reloads the boxes inside the automated warehouse (light blue line in figure 13). Once the order is prepared, he put them in the output conveyors (dark green line in figure 13). A MIR will be waiting for the UDS to deliver it to the outbound / packaging station.

To measure the performance of the picking process, we created picking orders based on product by orders distribution explained earlier: we created several orders randomly, then we allocated the number of products in each order based on the distribution, the reference of products was also chosen in a random way using an excel function:

= randombetween (1;10) (1)

We launch the WMS picking menu and then we execute random orders, that can contain 1 to 10 products and we measure how many orders we can launch in the duration one hour. We start the chronometer at the moment we confirm the launch of the order, until the moment in which we confirm the conclusion of the last order after one hour of working as a normal operator. This process includes the time the machine takes to pick up boxes from racks and load them in the flow racks, the time needed to pick the product by the operator, unloading the flow racks and then inserting the UDC in the automated warehouse. Two operator executed this experiment for 2 trials, one takes care of launching orders in the system, confirming the discharge of the flow racks logically and launching the next picking order, and the other operator takes responsibility of the physical picking task and discharging the flow racks. The output values of this experiment are the number of picking orders that were executed in one hour, number of order lines and the exact duration of picking.

Table 11: Picking experiment results

n of experiment	n of orders executed	Duration (hrs)	order lines
1	29	1	73
2	32	1	76

Table 12: Picking orders that were prepared for the first experiment

Alias	ID Ordine	Ordine	Descrizione Tipo	Tipo	Numero Righe
Uscita	280	5277	Acquisito (valido)	Pick	2
Uscita	288	5285	Acquisito (valido)	Pick	2
Uscita	290	5287	Acquisito (valido)	Pick	2
Uscita	293	5290	Acquisito (valido)	Pick	2
Uscita	298	5295	Acquisito (valido)	Pick	2
Uscita	302	5299	Acquisito (valido)	Pick	3
Uscita	309	5306	Acquisito (valido)	Pick	1
Uscita	310	5307	Acquisito (valido)	Pick	1
Uscita	311	5308	Acquisito (valido)	Pick	1
Uscita	312	5309	Acquisito (valido)	Pick	1
Uscita	313	5310	Acquisito (valido)	Pick	1
Uscita	314	5311	Acquisito (valido)	Pick	1
Uscita	315	5312	Acquisito (valido)	Pick	1
Uscita	319	5316	Acquisito (valido)	Pick	1
Uscita	322	5319	Acquisito (valido)	Pick	1
Uscita	323	5320	Acquisito (valido)	Pick	1
Uscita	327	5324	Acquisito (valido)	Pick	1
Uscita	328	5325	Acquisito (valido)	Pick	1
Uscita	330	5327	Acquisito (valido)	Pick	3
Uscita	340	5337	Acquisito (valido)	Pick	6
Uscita	344	5341	Acquisito (valido)	Pick	10
Uscita	346	5343	Acquisito (valido)	Pick	8
Uscita	347	5344	Acquisito (valido)	Pick	3
Uscita	348	5345	Acquisito (valido)	Pick	5
Uscita	349	5346	Acquisito (valido)	Pick	2
Uscita	351	5348	Acquisito (valido)	Pick	2
Uscita	352	5349	Acquisito (valido)	Pick	1
Uscita	353	5350	Acquisito (valido)	Pick	4
Uscita	355	5352	Acquisito (valido)	Pick	4

4.3. Kitting

Figure 14: Kitting station

To measure the performance of the kitting process, we created 52 orders in the first trial, we had to specify the type of box that will contain the order in the process of creating a kitting order. Using the same distribution of products per order: we create orders with 1, 2, 3… 10 products, then choose randomly the orders that we are going to execute. We then calculate the number of required UDC depending on the type of box, then we insert them logically in the management system then we load them as empty keeping unites in the automated warehouse and verify as a last step that the orders that we are going to launch have their assigned order keeping units loaded inside the warehouse.

The goal of this experiment is to measure how many orders we can execute in 30 minutes: we start the chronometer once we confirm the execution of the kitting order, and we start executing randomly kitting orders.

Table 13: Number of order keeping unites required for the kitting process

type of keeping unit	Number of units required
LTB 4120	5
LTB 4220	13
LTB 6120	3
LTB 6220	7
Total	28

Once a kitting order is launched, the system checks if the required items are available in the automated warehouse, and based on these quantities, it reserves this items. Once the components are retrievable and available in the demanded quantities, an empty loading unit is retrieved from the storage area and arrives to the kitting station through the output conveyor (light green path in figure 15). The type of the empty loading unit that arrived is not random, it was defined previously while creating the kitting order. This step can be emitted, and the operator can use an empty loading unit from the buffers near the kitting station. The stacker crane retrieves the required storage keeping units containing the components and loads them in the kitting flow racks (light blue path). Once the empty order keeping unit is detected by the sensors in the kitting station, the displays under the kitting racks turn on and identify the quantitates that should be taken from each box. The operator then, will identify the quantity, pick them up, then he will validate the picking by pushing the confirmation buttons. Once this is done, the operator will empty the flow racks logically and then physically, then, he will take out the UDS from the conveyer to the buffer area outside the automated warehouse and conclude the order. He then will launch another order.

Table 14: kitting process results

n of experiment	n of orders executed	Duration (mm:ss)	order lines
1	15	29:40	22
2	15	30:03	31
3	16	30:13	30
4	10	29:22	33

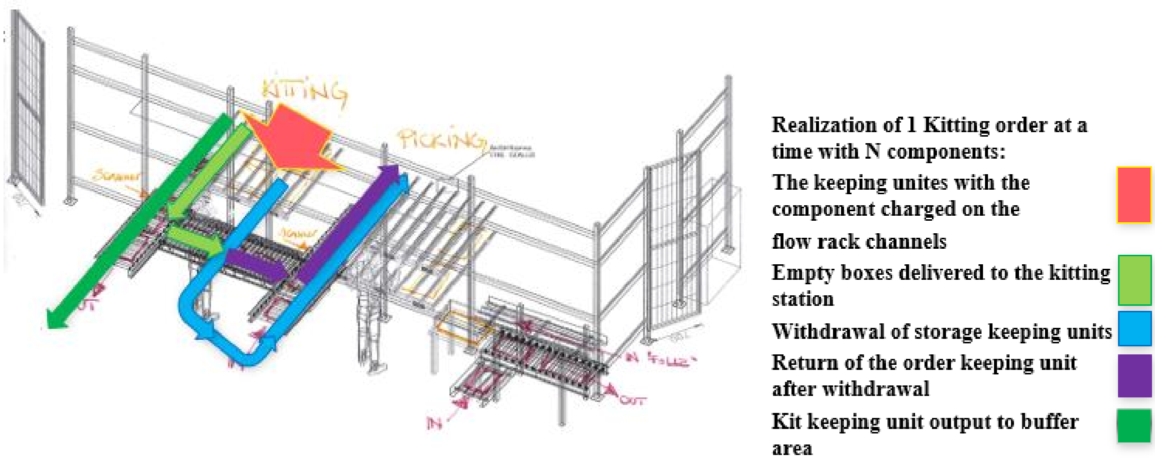

Figure 15: Flows in the kitting process

Table 15: WMS kitting orders list

Alias	ID Ordine	Committente	Numero Ordine	Descrizione Stato	Tipo	Causale	Descrizione Causale	Tipo cassetta raccolta	Numero Righe	Data Acquisizione	Data Attivazione	Data Evasione
Uscita	444	GEN	5441	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 6120	2	10/11/2021 14:12	12/11/2021 11:39	12/11/2021 11:42
Uscita	453	GEN	5450	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4120	3	10/11/2021 14:26	12/11/2021 11:36	12/11/2021 11:39
Uscita	431	GEN	5428	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4120	1	10/11/2021 13:58	12/11/2021 11:35	12/11/2021 11:36
Uscita	443	GEN	5440	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	2	10/11/2021 14:12	12/11/2021 11:33	12/11/2021 11:34
Uscita	417	GEN	5414	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4120	1	10/11/2021 13:49	12/11/2021 11:31	12/11/2021 11:32
Uscita	428	GEN	5425	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	1	10/11/2021 13:56	12/11/2021 11:24	12/11/2021 11:25
Uscita	432	GEN	5429	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	1	10/11/2021 13:58	12/11/2021 11:22	12/11/2021 11:23
Uscita	425	GEN	5422	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	1	10/11/2021 13:54	12/11/2021 11:20	12/11/2021 11:21
Uscita	421	GEN	5418	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 6220	1	10/11/2021 13:51	12/11/2021 11:16	12/11/2021 11:17
Uscita	434	GEN	5431	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	1	10/11/2021 14:00	12/11/2021 11:10	12/11/2021 11:13
Uscita	447	GEN	5444	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 6220	2	10/11/2021 14:14	12/11/2021 11:08	12/11/2021 11:10
Uscita	440	GEN	5437	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 6220	2	10/11/2021 14:10	12/11/2021 11:01	12/11/2021 11:05
Uscita	437	GEN	5434	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	2	10/11/2021 14:08	12/11/2021 10:57	12/11/2021 11:01
Uscita	430	GEN	5427	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 6220	1	10/11/2021 13:57	12/11/2021 10:53	12/11/2021 10:56
Uscita	427	GEN	5424	Prelevato	Kit	SCAORD	Scarico ordine (Incas)	LTB 4220	1	10/11/2021 13:56	12/11/2021 10:51	12/11/2021 10:52

4.4. Put away

Once supplies are prepared from the pallets, inserted physically in the loading units and logically in the warehouse management system by the operators, if there is still enough space inside the automated warehouse, a new position on the racks is going to be assigned to the new loading unit. Now, the loading unit can be delivered by the automated guided vehicles (MIRs) or by the physical human intervention from the preparation station (inbound station) to the automated warehouse (input conveyer) to be stored in. Once it is charged on the Mir, the automated vehicle knows its destination, and based on the logical map in its server, it calculates the best routes to reach this destination. With the help of sensors installed in the corners of the robot, it can detect obstacles and movements. Once they are present on the way, the vehicle stops and recalculate a new path. This is why it is called a smart mobile robot. When it reaches the input conveyer station, it docks with the conveyor, discharge the box to the AS/RS input conveyor, then returns to the inbound station to execute the following mission. If there is no mission pending in the queue, the guided vehicle returns to the charging station.

Figure 16: Path of the Mir in the Put away mission

When a loading unit is discharged from the MIR and is present on the input conveyor, the system detects its presence and identify its reference thanks to the detectors installed on the conveyors, and transfer it to the mini-load. This mini-load starts moving vertically and horizontally in a simultaneous way and charges the loading unit to deliver it to its specific assigned position on the rack. Once the mini-load reaches its destination, it unloads the box. Depending on what is inside the loading unit, the system updates its logical inventory to keep it coherent with its physical inventory. The loading unit can contain products, customer orders and kits. It can also be an empty loading unit, that is going to be used later to store customer orders.

Figure 17: MIR docking with the input conveyer

In this experiment, we want to measure how much time 2 MIRs take to deliver 10 keeping unites simultaneously from the inbound station to the input conveyor. We repeated 6 trials for better values. We start measuring the time once we confirm the launch of the first 'put away' mission and stop counting once the 10th keeping unit is discharged from the MIR to the input conveyor in the 10th mission. These measurements take into account the duration of different actions: departure from the charging station, loading of units, detection of surface and creation of path, transportation between inbound and input stations, docking and undocking with the input conveyor and discharging. We had also some small delays, in which, one of the MIRs stops from moving due to the presence of an obstacle in its path, we had several obstacles such as a person who was moving in the warehouse, or even the other MIR who interrupted the other robot's way, once interrupted, it recalculates a new path and moves around the obstacle to reach its destination.

Table 16: Put away experiment results

n°	n of keeping unites delivered	Duration (mm:ss)
1	10	15:01
2	10	14:50
3	10	14:42
4	10	15:23
5	10	16:20
6	10	16:42

4.5. Outbound process

Once customer orders are prepared in the picking station, they are loaded in the picking output conveyor. By the end of this conveyor, the UDS will be transferred to the outbound buffer, with the help of the MIRs that are able to dock with the output conveyers (figure 19) and discharge the loading unit to its final buffer station before delivery. This process is similar to the put away mission, the MIR will charge a box from the output conveyers of the picking station, then he will take it to the outbound/packaging area. The path of the MIR can be seen in figure 18. The packaging operator will take then the UDS from the MIR and do the packaging and put the box in the outbound station. We measured how much time is needed to deliver 10 order keeping unites from the picking station to the outbound station. We only used one MIR because the distance between the two stations was too short and it was not logical to work with two robots in such a small path, it would generate a large number of obstacle errors and the 2 MIRs would be constantly crossing each other's path.

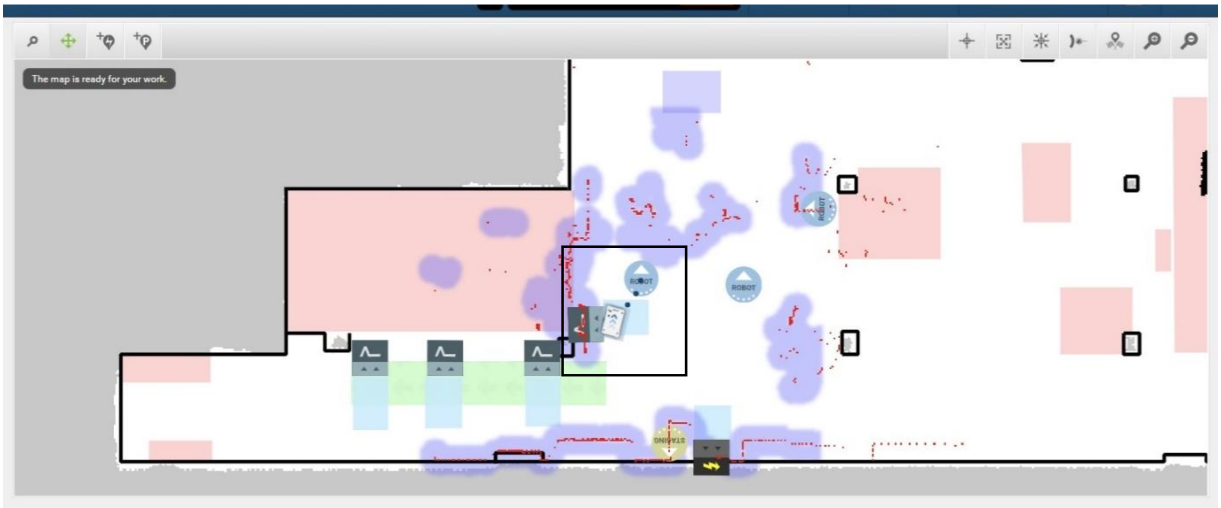

Figure 18: Path of the MIR in the outbound mission

Figure 19: MIR docking with the outbound conveyor

The measurements are recorded in table 17.

Table 17: Outbound process results

n°	n of boxes	Duration (mm:ss)
1	10	13:14
2	10	13:30
3	10	12:47
4	10	13:02
5	10	13:34
6	10	13:38

Conclusion

In this chapter we explained how we did the setup of the different experiments to measure the performance of the kitting and the picking processes in the automated warehouse, as well as the put away and the outbound missions. In the next chapter, we analyse the measurements, we identify the main trends and insights and we explain the reasons behind the range of values.

5. Analysis of results

In this section, we analyse the measurements we recorded in the experiments. First we analyse the kitting, picking, put away and outbound processes individually, then we compare the performances of the picking against the kitting, then the put away against the outbound. Afterwards, we conclude the global performance of the automated warehouse and we benchmark it with the performance of the industry.

5.1. Picking vs kitting

Piking and kitting are the main activities in the warehouse, their efficiency can give us a picture of the general warehouse management. They are influenced by the degree of automation in the warehouse, as its productivity and throughput dependent on the performance and the speed of the stacker crane. It can also be influenced by the productivity of operators, their efficiency in the handling process, and their knowledge in using the WMS to execute and confirm the orders. The difference between kitting and picking in an industrial environment is that kitting is more dedicated to the preparation of components that are going to be assembled together in the next station, it can be considered as an anticipation and preparation of the assembly task. In our context, we do not deal with manufacturing or assembly processes, therefore we can define kitting as another variant of the picking process, in other words: a type 2 picking operation that has its own station in the automated warehouse.

After converting the duration of the kitting process into seconds and hours, we used the productivity and the order kitting time formulas:

$$Kit\ p = \frac{OrdLi\ Pick}{WH\ Kit} \quad (2)$$

$$Kit\ t = \frac{\sum \Delta t\ (Pick)}{OrderLi\ kit} \quad (3)$$

Afterwards, we calculated the average and the standard deviations of these values. IT can be seen from the table below, that the kitting process has a productivity of 58,6 order line/labour hour, with a high standard deviation of 9,3: it means that it has a high variability and indicated the presence of outlier values. When we investigated the source of this high variability, we found that in some of our measurements, we had several machine errors. The kitting time is of value of 0,017 hour/order line or 62,8 s/order line.

Table 18: Kitting productivity and process time

	n°	n of orders executed	Duration (hh:mm:ss)	order lines	duration (s)	duration (H)	Kitting productivity (order line / Labour hour)	Order kitting time (hour/order line)	Order kitting time (second/order line)
kitting	1	15	00:29:00	22	1740	0,483	45,517	0,022	79,091
	2	15	00:30:03	31	1803	0,501	61,897	0,016	58,161
	3	16	00:30:13	30	1813	0,504	59,570	0,017	60,433
	4	10	00:29:22	33	1762	0,489	67,423	0,015	53,394
			avg	29	1779,5	0,494	58,602	0,017	62,770
			st dev				9,324	0,003	11,269

We calculated also the throughput of this process using the formula:

$$Th\,p = \frac{Ord\ pick}{War\ WH} \tag{4}$$

We can say that the kitting process has a throughput of 28,3 order/Labour hour. It means than in one labour hour in the kitting station, operators can execute around 28,3 kitting orders. This indicator measures the orders picked that are leaving the kitting station, and it takes into account the number of orders, not the number of order lines inside the order like in the productivity indicator.

Table 19: Throughput of the kitting process

	N°	n of orders executed	Duration (hh:mm:ss)	order lines	duration (s)	duration (H)	Kitting throughput (order /Labour hour)
kitting	1	15	00:29:00	22	1740	0,483	31,034
	2	15	00:30:03	31	1803	0,501	29,950
	3	16	00:30:13	30	1813	0,504	31,771
	4	10	00:29:22	33	1762	0,489	20,431
			avg	29	1779,5	0,494	28,297
			sd dev			0,010	5,297

For the picking process, we followed the same approach and we have identified a picking productivity of 74,5 order line/labour hour with an order picking time of 0,013 hour/order line (or 48,3 second/order line. The throughput of the picking station was around 30,5 order/labour hour.

Table 20: The picking process productivity and process time

	N°	n of orders executed	Duration (hh:mm:ss)	order lines	duration (s)	duration (H)	Picking productivity (order line /Labour hour)	Order picking time (hour /order line)	Order picking time (second /order line)
Picking	1	29	01:00:00	73	3600	1	73	0,014	49,315
	2	32	01:00:00	76	3600	1	76	0,013	47,368
			avg	74,500			74,500	0,013	48,342
			sd dev				2,121	0,000	1,376

Table 21: Throughput of the picking process

	N°	n of orders executed	Duration (hh:mm:ss)	order lines	duration (s)	duration (H)	Picking Throughput (order /Labour hour)
Picking	1	29	01:00:00	73	3600	1	29
	2	32	01:00:00	76	3600	1	32
			avg	74,5			30,5
			sd dev				2,121

When we compare the productivity and the process time between kitting and picking, we can say that picking is the better performing process. This process is indeed less complicated to execute. When we create a picking order, we don't have to specify the order keeping unit, the operator can launch his picking order, then he takes an empty loading unit from the buffer area near him and use it as a picking order keeping unit. For kitting, it is different, if we want to retrieve an empty keeping unit from the automated warehouse, there is an added waiting time in which the machine has to retrieve this box from storage and load it on the output conveyer to the kitting station.

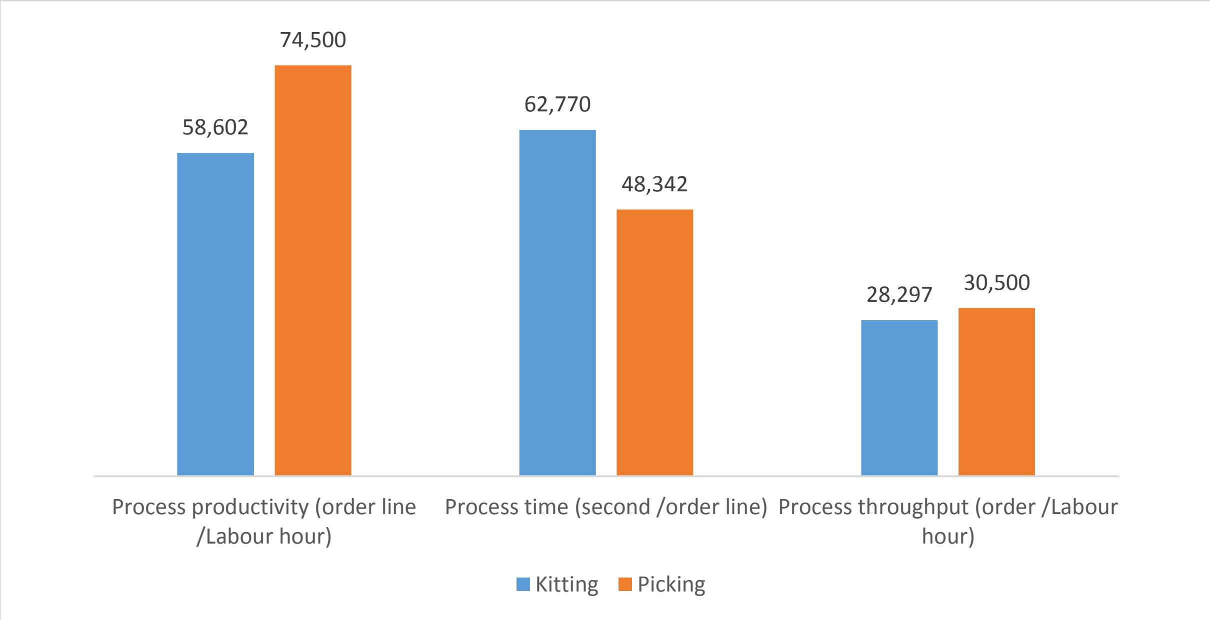

Figure 20: Kitting vs Picking

Even in cases where the level of automation in the warehouse is high, physical activities carried out by operators still need to be done, like loading keeping units on the conveyor, picking the products, double checking the quantities and moving the unit to the next process. These tasks are similar in kitting and picking, therefore when we compare these processes against each other's, we identified major differences, these differences can be explained by the performance of the automatic machine. We were able to extract more detailed data through the warehouse management system, we exported the orders list as a CSV excel file and we analysed the data after a cleaning process. We identified the time stamps that were recorded by the software when an order is launched ("Data Attivazione"), and when it is concluded ("Data Evasione"). By studying this two time stamps, we can identify the time in which the machine retrieves the keeping units and storage units.

If we consider the physical picking activity of products from the storage racks to the order keeping units that the operator does in the kitting and picking operation to be a physical process of a similar and constant duration, we can identify the performance of the automated warehouse without the human interference. By analysing the data, and based on a sample of 200 records of executed orders, we found out that, on average, the machine executes a kitting order in 159 s while it only takes around 117,6 s to execute a picking order. The 40 seconds duration difference between the two processes is due to the retrieval of the empty order keeping unit.

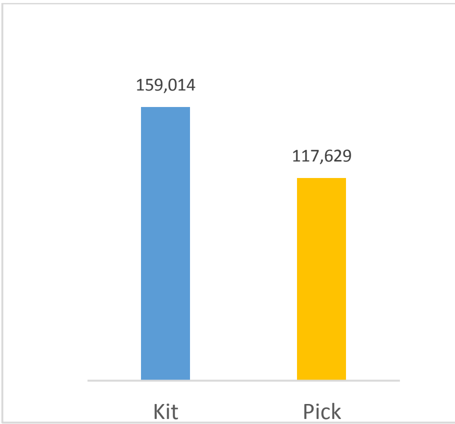

Figure 21: Machine average processing time (s)

By using the same sample, we added the dimension of order lines to analyse the machine processing time by the number of order lines and to study whether the number of products per order has a direct effect on the performance of the machine: we can notice the increasing trend, the bigger the order is, the more time it is required to prepare this order. We identified also two clusters; orders that have from 7 to 10 order lines have a similar processing time (red cluster in figure 22) of around 284 seconds, the same goes for orders from 1 to 6 order lines (yellow cluster) with an average of 137 seconds. Let's say for example, when we launch a kitting order of 5 products, the machine will retrieve all the 5 storage units at once on the flow racks, then it will signal to the operator that he can proceed with the manual picking activity. If we launch a kitting order that has 8 products, for instance, the machine will load 6 keeping units on the flow racks (the maximum capacity of flow racks), then it will signal to the operator to execute the picking activity and to discharge the flow racks, once it is done, the machine will proceed to the retrial of the remaining 2 storage units. As a matter of fact, the automated warehouse is equipped with 6 flow racks in the picking station and 3 flow racks in the kitting stations, each flow rack can load up 2 LTB6220 storage unites, or 4 LTB4220 storage units. Once storage units are retrieved from the warehoused, they are loaded in the multiple of 3s and of 6s in the same time. We can conclude that the range of the number of products per each order influences the performance of the machine.

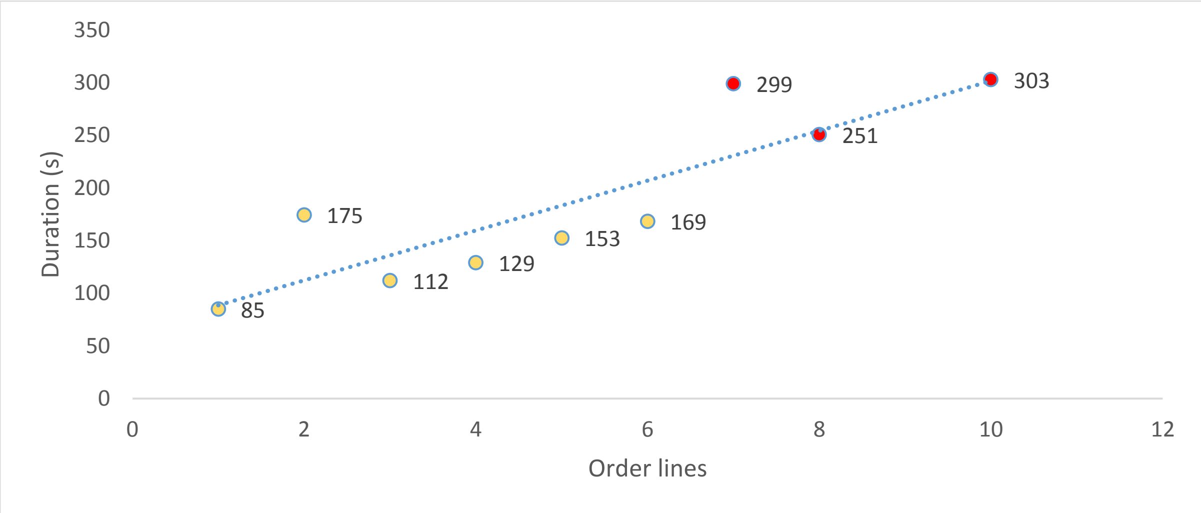

Figure 22: Cluster of the average machine processing time per the number of order lines (s)

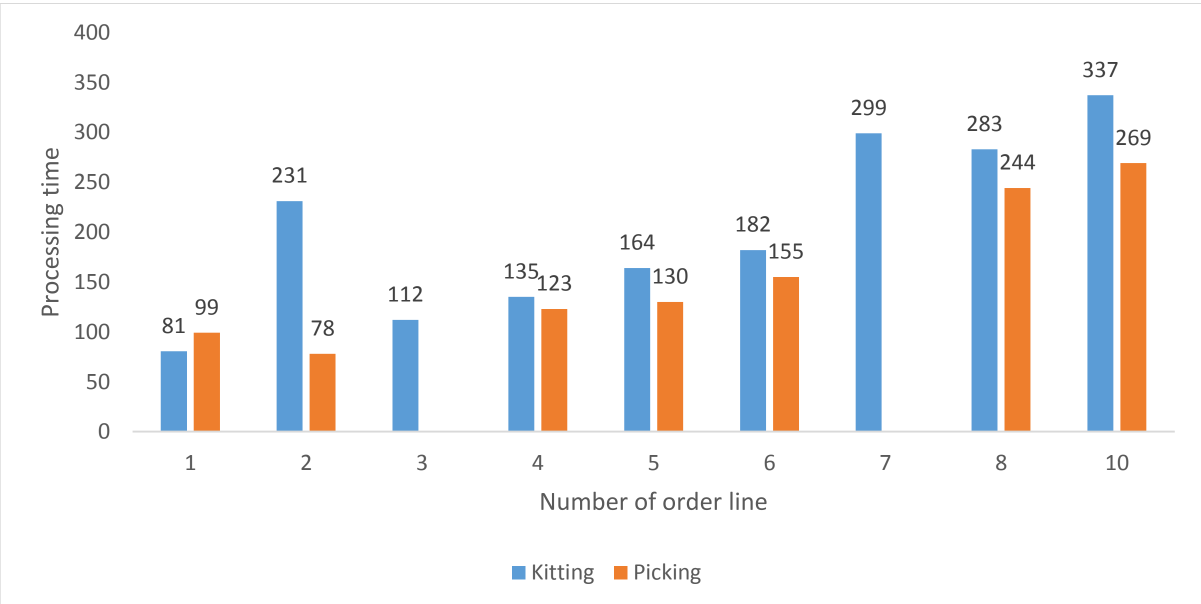

Figure 23: Machine average processing time per the number of order lines (s)

In figure 23 we notice the presence of an outlier value for kitting orders with 2 order lines. After returning to the data, we identified the source of the outlier value. The picking order with reference 5336 had an unusual long processing time of around 16 minute and 22 second, while executing this order we had a system error, in which the stacker crane stopped functioning, which required the intervention of the technician to solve this problem. After scraping this value from the data, the processing time of kitting orders that have 2 product lines decreased to 109 seconds. We notice also that kitting orders that have only one product per order have lower duration compared to the picking, when in reality it should be the opposite. When we investigated the data we identified that picking order with reference 5322 had also an unusually long duration of 530 seconds (around 9 minutes), this was due to a hardware malfunction, and as the same as for order 5336, it required the intervention of an operator. In the next graph we can see the final average processing time of the 2 processes.

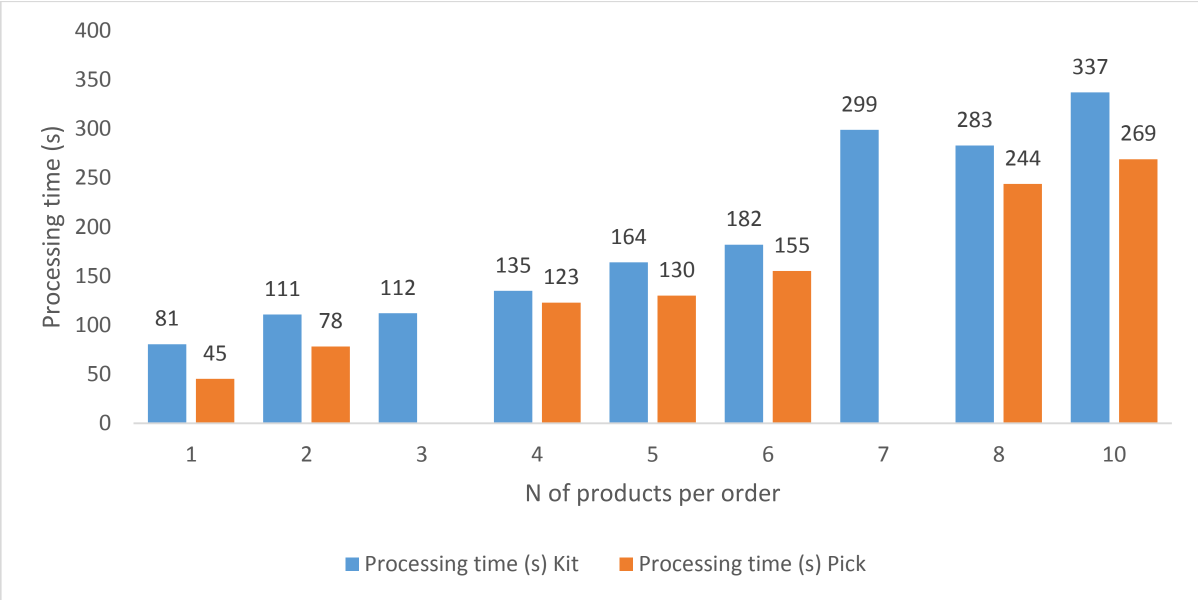

Figure 24: Machine average processing time per the number of order lines (s) after removing outliers

5.2. Put away and outbound process:

For the put away process, we calculated the put away time and the storage productivity using the following formulas:

$$Pu\ t = \frac{\sum \Delta t\ (Sto)}{LU} \qquad (5)$$

$$Sto\ p = \frac{LU\ Sto}{WH\ Sto} \qquad (6)$$

Table 22: the Put away process analysis

	n°	n of keeping unites delivered	Duration (hh:mm:ss)	duration (s)	Duration (H)	Put away time (hour /loading unit)	Put away time (second /loading unit)	Put away /storage productivity
Put away	1	10	00:15:01	901	0,250	0,025	90,100	39,956
	2	10	00:14:50	890	0,247	0,025	89,000	40,449
	3	10	00:14:42	882	0,245	0,025	88,200	40,816

	4	10	00:15:23	923	0,256	0,026	92,300	39,003
	5	10	00:16:20	980	0,272	0,027	98,000	36,735
	6	10	00:16:42	1002	0,278	0,028	100,200	35,928
			avg	929,667	0,258	0,026	92,967	38,815
			st dev			0,001	4,995	2,033

The put away process is an independent task compared to the other ones that are discussed in this part: it is basically about charging the warehouse of products that are available to be inserted in the inbound station, independently of customer orders. On the other hand, its productivity is highly influenced by the automation of the warehouse: the value added activities of the MIR and the input conveyor have a significant weight in adjusting this indicator. Based on the calculations that were made, we can say that this process has a storage productivity of 38,8 storage unit that can be loaded in the automated warehouse using the automated guided vehicle per labour hour, with a put away time of 0,026 hour/loading unit (or of 92,97 second/loading unit).

We followed the same approach used in the put away process, and we calculated the outbound time and the outbound productivity by using the following formulas:

$$Ptp\ t = \frac{\sum \Delta t\ (Ship)}{Order\ Del} \quad (7)$$

$$Outbound\ p = \frac{LU\ ship}{WH\ ship} \quad (8)$$

Table 23: The outbound process analysis

	n°	n of keeping unites delivered	Duration (hh:mm:ss)	duration (s)	Duration (H)	outbound time (hour /loading unit)	outbound time (second /loading unit)	Outbound productivity
Oubound	1	10	00:13:14	794	0,221	0,022	79,400	45,340
	2	10	00:13:30	810	0,225	0,023	81,000	44,444
	3	10	00:12:47	767	0,213	0,021	76,700	46,936
	4	10	00:13:02	782	0,217	0,022	78,200	46,036
	5	10	00:13:34	814	0,226	0,023	81,400	44,226
	6	10	00:13:38	818	0,227	0,023	81,800	44,010
			avg	797,500	0,222	0,022	79,750	45,165
			st dev			0,001	2,016	1,154

This process has an outbound productivity of 45,1 shipping unit per labour hour, this shipping units are loading unites that each contains an order that is picked and is ready to be delivered to the packaging station in the warehouse after passing through the output picking conveyor and being delivered by the MIR. The outbound time was estimated around 0,022 hour/loading unit (or 79,8 second/loading unit).

It is apparent that the productivity of the outbound process is higher than the one for the put away process. Even though in the less productive process, 2 automated guided vehicles were used instead of just one in the outbound process. This difference in performance can be explained by several reasons: first of all, the distance travelled in the put away process is longer, to be more precise, it is from the inbound station to the input conveyor station. Logically, it would take more time. Also, we noticed that the 2 MIRs were interrupted by obstacles several times, the longer path was narrow and when the two MIRs meet in this path, they always face each other's leading to halts, this path coincides also with the exist and entry door to the lab which means that the probability of a lab workers to be in the way of the robot was higher, thus a higher probability of facing an obstacle which will lead the MIR to stop and to recalculate a new path, thus a waiting time which slows the productivity. The discharge of loading units can also be another reason, we noticed that in the put away process, the MIR takes a quite long time to dock with the input conveyor, and sometimes it generates a docking error which will require the intervention of an operator to solve it and relaunch it all over again, this can be a technology or a software related issue. Sometimes, the performance of the automated warehouse can slow the docking process, due to the errors that can happen to the maxi shuttle and the input conveyor sensors, storage unites will accumulate on this conveyer, increasing the waiting time for the discharging process of the MIR. On the other hand, for the outbound process, one MIR was operating, leading to a less obstacle probability, we can add that the short path of the outbound station, is located in a separated area that has also a less probability of the presence of an obstacle. Usually in the outbound missions, the waiting time is at minimum, once the MIR arrives to the packaging station the operator takes the unit and the robot goes back to deliver the next order keeping unit.

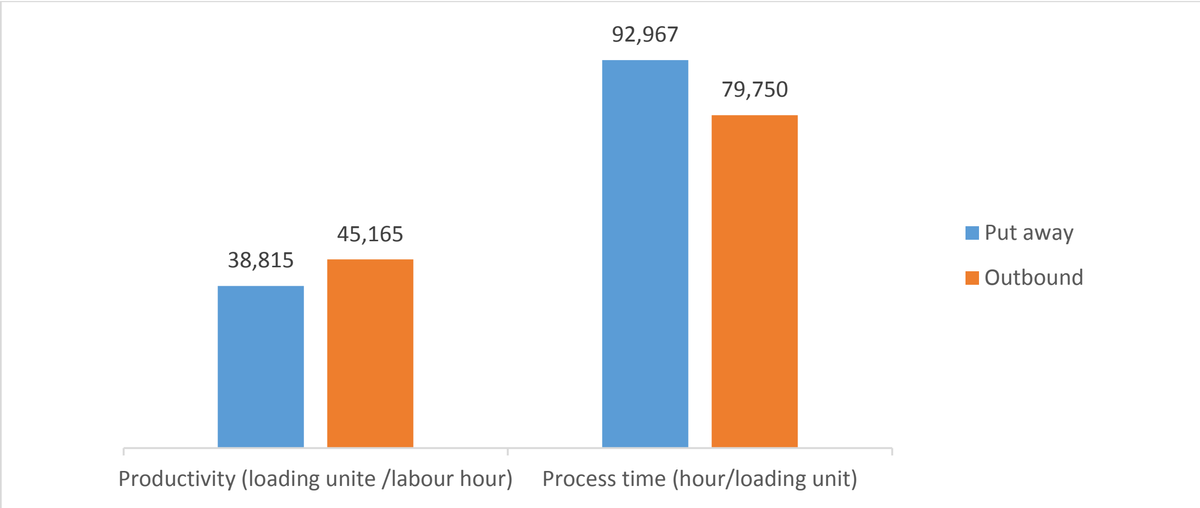

Figure 25: Put away VS outbound

5.3. Average stock and Receptivity saturation coefficient:

We assessed the average stock of items held in the inventory for a specified period. Logic would dictate that for a perfect average stock indicator, a reading must be performed daily in a real warehouse case scenario, which is even made easier with automated control systems that records the daily in/out movements of items. But in our case, the reading was only done after executing the kitting and picking orders that were simulated in the previous days in which products left the warehouse. At the beginning, we assumed at t=0, that the warehouse is loaded according to the maximum capacity of keeping units that were loaded into the system (see the warehouse initiation section). Then, we subtracted the quantities that left the warehouse and calculated the average stock for these two events by divining the quantity of items stored by the duration in days. We obtained an average stock value 50000 units per day. It is important to say that in our simulation, we did not deal with real physical products, we inserted a specific number of product units in the warehouse and based on these values and the requested products in customer orders we built this indicator. So to be more realistic, it better to calculate this indicator in a real case with real products inserted in a real inventory that is functioning at least 8 hours per day.

Table 24: The average stock

t	Stock (quantity)	Duration (s)	Duration (d)	Average stock
0	4300			
1	4151	7200	0,08333333	49812
2	4035	7118	0,08238426	48977,8028
	average stock	49395	unit of product/day	

We wanted also to see how much the warehouse has been exploited in time range of simulating, for this reason we calculated the receptivity saturation coefficient:

$$RSC = \frac{S}{R} \qquad (9)$$

With S being the average stock and R: the receptivity, approximately equals to the maximum quantity of items that has been recorded. The value of RSC = 11,9 based on the time window of the measurements. We believe that this indicator need more adjustments and require a real warehouse that is continuously operating in longer durations to give more realistic and accurate values.

5.4. The global warehouse performance

Previously, we studied the performance of operations individually. In this section, the focus is transformed to the performance of the warehouse as a whole. To compare the performances of the different operations, we chose the throughput KPI to measure the output productivity of each process. It is important to note that the output of the put away mission is different from the output of the other 3 missions: in fact, the picking and the kitting operation throughput indicator was calculated based on the number of orders executed in one labour hour, but for the put away and outbound process, the throughput is measured by calculating the number of keeping units that the automated guided vehicle can deliver to and from the automated warehouse. We already assumed that each order keeping unit that is going to be delivered to the outbound station contains only one order, but for the put away mission, the keeping units are not containing orders, instead they have the products that were loaded from the supplier's pallets and are going to be stored in the warehouse.

Graph 26 shows the global performance. It can be seen that the put away and the outbound processes are performing better than the kitting and picking. We can say that the good performance of one process doesn't guarantee the good overall performance, these processes are connected to each other's, the picking for example can be a bottleneck, it can slow down the performance that may otherwise be obtained. An increase of the waiting time of the MIR in the outbound process will lead to the loss of potential. The performance of all the processes should be improved and adjusted to be on the same level of throughput to avoid any influence or complication from one workstation on the next workstation. The performance of the warehouse therefore will follow the slowest operation in most cases. Indeed, the picking and kitting processes need more attention, they are basically the most time consuming operations because it requires the retrieval of the keeping units by the automated warehouse and the picking and kitting by the operator, as well as the margin between the kitting and picking that was studied in the previous section.

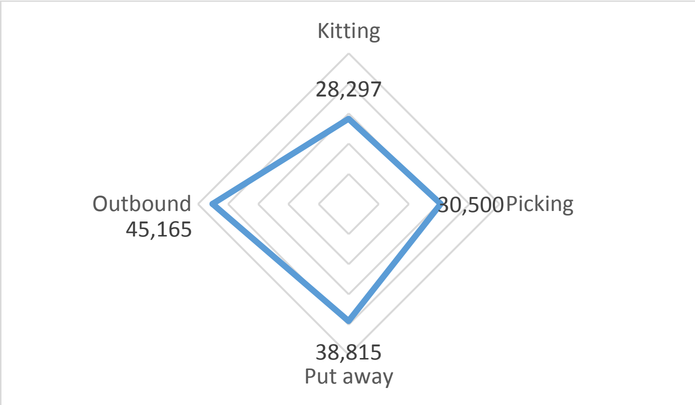

Figure 26: Productivity chart (order /Labour hour)

5.5. Competitive benchmarking

In this section, we are interested about comparing the performance of the automated warehouse of our case study to the performance of other industries in the market. Competitive benchmarking involves obtaining all kinds of data from the market and the industry as a whole, so that it can be considered as a comparison analysis of the performance. This type of benchmarking is very widely practiced in certain sectors of the industry. It is very often used for productivity and cost analysis that are common between companies.

However, it is quite difficult to practice real competitive benchmarking, due to the confidentiality of the data that was required to do this analysis. What is sometimes called competitive benchmarking is not really competitive after all, because in our case, we did not consider the type of products that we will be storing in the automated warehouse, and the competitors do not operate in the same sector and do not target the same end users. At the beginning, we searched how many fulfilment centres each company has, then we tried to identify the number of operators and the number of orders and products that were processed in these centres. In most cases, we did not find this information due to its confidentiality, but we tried to calculate the ratios based on generalized estimations and assumption.

Mainly we focused on companies that have ecommerce platforms, from sectors such as textiles, fashion, retailers, the food industry, distribution and logistics: the common thing about these companies is having fulfilment centres in which, picking operators do order picking operation with the aid of different forms of automated solutions and automated warehouses. The high performing companies have fulfilment centres that are scattered around the world, the average and small ones have mainly up to 3 fulfilment centres in a couple of cities, these centres have been working excessively to cove the increase in online orders. In order to be able to answer to this increase in demand, a lot of solutions were adapted such as the increasing of labour force in the picking activity, expanding the fulfilment facilities, installing new technologies and increasing automation.

In a benchmarking analysis, it is impossible not to talk about the giant Amazon, known also as the gold standard pioneer: its fulfilment centres are equipped with state of the art equipment, from advanced picking robots, to automated conveyers, highly qualified operators and advanced management systems, thanks to its high productivity, picking ratio can reach up to 800 picks per hour, a picking staff can execute manually 250 picks per hour and it can increase up to 450 if it was robot enabled (Trimmer, 2021). Orders productivity may differ from an amazon fulfilment centre to the other, estimating this indicator was quite difficult, we can assume that it is between 200 - 800 orders that can be executed in one hour.

Not far behind from amazon, Ocado, UK's online grocery's market leader implemented some improvements in its London fulfilment centre, which resulted in an increase from 600 to 700 picks per hour, leading to an order processing productivity of 650 order per hour. Tesco, one of the groceries and general merchandise retailer located in Welwyn Garden City in England can execute 180 orders per hours thanks to its 140 picking robots picking from 44,680 bins in 10 different picking stations.

In the United Kingdom, manual picking is estimated to be around 50-100 picking per hour, it increases to around 250-300 in facilities that adapt automations and robots and can reach up to 600 pick per hour in advanced and sophisticated fulfilment centres. The pick to light system can increase the picking ratio from 100 to 600 picks per hour (Trimmer, 2021).

The pharmaceutical sector has always been an automation market leader and is considered to be one of the early adopters of installing automation solutions in its manufacturing and warehousing facilities, this maturity in technology use and efficiency gave it a competitive advantage against the other sectors, with a picking rate around 900 picks per hour. Pharmaceutical demand can reach 10 million tablets per day, in most cases it can be 100% fulfilled by the automated solutions. Robots in these facilities can execute 75% of the picking orders without any manual intervention needed. A regional pharmaceutical distributor located in Branson Missouri in the United States, adapted fast-movers and slow-movers which led it to reach 2200 orders per hour (Meller, 2015).

On the other hand, the fashion industry is getting more involved in adopting logistic solutions and increasing automations in their fulfilment centres, ASOS for example announced its planes to make its orders worldwide eligible by implementing a worldwide network of centres and partnerships with third party distributers lowering the geography barrier. Thanks to its change in strategy to include automation in the core of its approach and its attempts to offer better service to its customers in the 2010s, the performance of its picking activities jumped from 55 to 120, and now it is more than 160 units picked per hour (Trimmer, 2021). We can mention also the German fashion retailer Zalando, it is taking an expanding approach by opening new fulfilment facilities closer to the end customer and identifying new opportunities in new locations, thanks to the high automation rate, it can process up to 2200 orders per hour in its facility located in Lahr, Germany (MMH, 2020).

Table 25:Benchmarking analysis

Name	Industry	Location	Estimated number of operators	Orders picked (orders/hour) (estimation)
Zalando	E-commerce company	Lahr, Germany, Zalando's fulfilment centre	1000	2200
Anon start-up	Textile, media and entertainment	N.A.	10	20
Amazon	E-commerce & distribution	Amazon fulfilment centre	1100	90
Amazon	E-commerce & distribution	Amazon fulfilment centre	1100	250
Amazon	E-commerce & distribution	Amazon fulfilment canter	1100	800
Regional Pharmaceutical Distributor	Pharmaceutical	Branson, Missouri, USA	350	2400
Ocado	online grocery solutions and logistics business	Erith, London, UK	150	650
Ocado	online grocery solutions and logistics business	Erith, London, UK	150	330

Tesco	groceries and general merchandise retailer	Welwyn Garden City, England	500	180
ASOS	online fashion and cosmetic retailer	UK	700	160

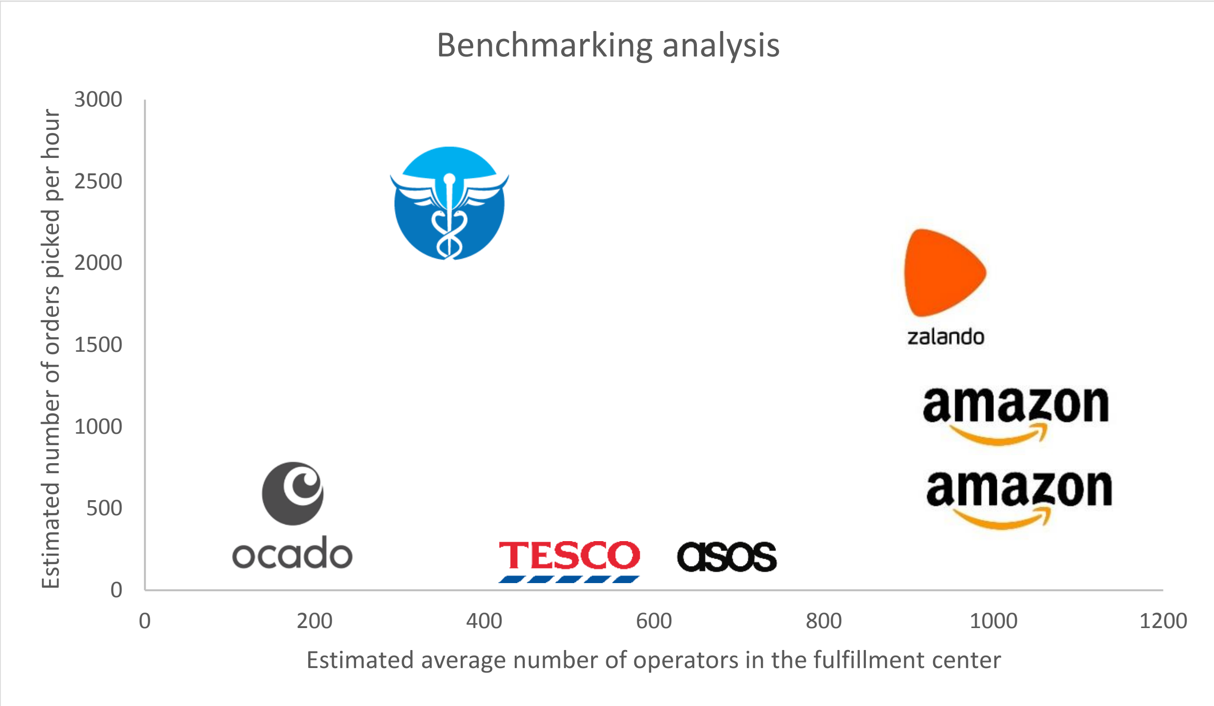

Figure 27:Benchmarking analysis

After estimating the performance of already established e-commerce professionals, we can use their performance values as benchmarks to evaluate our performance and make comparisons. It is true that these companies have the experience, knowledge, maturity and the resources to achieve such high productivities, their facilities are giant and equipped with more powerful automated solutions that work simultaneously, with hundreds of highly skilled operators. On the other hand, our automated warehouse has limited surface and resources, the objective was to identify the throughput of how many orders can be executed per hour. This value is estimated to be around 45 to 75 orders per hours, by only using 2 picking operators, 2 kitting operators and 2 handling operators, and selling mainly 10 different products.

Conclusion

In this chapter, we analysed the performance of the automated warehouse and we benchmarked it. The next step, we discuss the performance and its implications in our context and on e-commerce.

6. Discussions of results

In the next section, we try to identify the implications on our case and then we discuss the different sectors that are more suitable and adaptable to our warehouse, from the pharmaceuticals, retail and apparel industry, to the electronics and groceries sectors, then we suggest future research.

6.1. Implications on practice and e-commerce

In today's world of ever-changing technologies, it will become imperative for companies to invest in automation, it will have a major impact on the way they conduct their day-to-day operations. Automation saves time, frees up resources, lowers operating costs and improve operational efficiency. These are a few major areas where we expected to see the main change as we implemented the automated warehouse.

One of the first observations that we noticed, is the marked increase in productivity compared to non-automation productivity. One of the benefits of automating the picking and kitting process is that employees will waste less time on manual workflows that take up a large part of their daily to-do list. By implementing an automated retrieval system and keeping employee intervention to a minimum, operators don’t have to go from one rack to the other in the storage areas, they don’t have to search for the required products, instead products will arrive to them, pickers will spend less time picking from one customer order to the other. They will also be able to concentrate on producing better quality work will less error margins.

Automating workflows and adapting a WMS reduced dramatically the time operators spend on manual tasks. Tasks, like tracking approvals, updating, sending order confirmations and order notifications that normally eat up a lot of energy and focus on the operator, are then simplified. Who says less human intervention also says less human error. Once these repetitive and quickly boring tasks are handed over to machines, operators will be able to focus on the remaining tasks with less error margins. On what concerns document management, today, professionals spend half their time looking for information and take an average of 18 minutes to find the right document. With the digital switch-over to the warehouse management system, it makes sense that automation made managing documents easier. Tasks related to documents, customer orders, list of orders and records related to the list of missions executed in the station can all be performed electronically with automation; this improved the efficiency of these processes and workflows. Thanks to the high-quality reports and the data recorded, we were able to extract interesting insights and key trends related to the performance of the machine. The clear and detailed reports told us about the durations of processes and as discussed in the previous chapter, we were able to identify the weaknesses and improvement opportunities in our system. This key information can also help the finance department make informed decisions.

We can resume by saying that the benefits of automating the business process are significant. These factors combined has led to two main changes: saving more time and money. The hours gained can then be reallocated to other, more important tasks. All of the underlying and repetitive processes can be configured to run on their own, saving costs without having to do anything, reducing human error and increasing productivity and efficiency.

6.2. Compatibility with other sectors

In this part, we try to identify the adequate sectors that are most fit with the automated warehouse of our case.

The pharmaceutical and Parapharmaceutical sector

The warehousing and logistics of pharmaceutical and parapharmaceutical products have acquired an important role. In Italy, for example, online pharmacies or pharmacies operating as intermediary distributors cannot use third-party suppliers or wholesalers to ship products purchased by the customer and, therefore, can only ship what is physically present in their warehouse. Many companies in the pharmaceutical and parapharmaceutical industry have therefore turned to warehouse logistics solutions that facilitate the management of their goods, especially those of the e-commerce sales and distribution channel.

Automatic warehouses in the pharmaceutical and parapharmaceutical sector must respond to several criteria, they must assure a quick and ergonomic accessibility of items by all operators, optimization of picking time for order preparation, reduction of floor space, which makes it possible to exploit the storage density by a maximum use of the available storage space, while guaranteeing the good conservation of the products. The automatic warehouses must guarantee to operate in a temperature range between 2° C and 25° C (±1° C), with control of the relative humidity ≥ 5%. As well as the cleanness of the storage system in accordance with ISO 14644 standards which ensures that the racks are not compromised, thus preventing contamination of the material stored there. Even though the capacity of the warehouse can manage easily the small dimensions of the pharma products, the warehouse was installed in the DIGEP lab and it cannot comply to the safety criteria, because it is not isolated or protected, it has a high risk of contamination that can be caused by the other laboratories that are installed in the same building and the researchers who are currently operating in this facility. It does not have also temperature controlling system that can keep the temperature low for some medical products.

The retail and apparel industry

To say that fashion goes fast is an understatement. Time to market is fundamental in the retail and clothing industry. Product lifecycles are short, so logistics solutions must be flexible, modular and scalable to meet consumer and industry demands. The retail and apparel industries are transforming daily, not only because of trends, but also because consumer behaviours are constantly changing. Store traffic is declining and online orders are increasing. This has implications for shipping, replenishment, and reverse logistics, hence the need to optimize the on-site operations. The storage and order picking systems for consumer goods, enable rapid processing and replenishment, while the WMS gives visibility and the business intelligence capacity needed to make the necessary changes based on peak season volume. Speed to market and customer satisfaction have a big impact on the success of a retail and apparel business. These challenges can be for sure solved by our warehouse that has a fast order fulfilment, flexible throughput that can be adjusted to be aligned with peak and low seasons as well as the high volume storage capability.

Groceries sector

When we talk about online shopping, we often mean non-food material goods, such as high tech, electronics, music and cosmetics. However, besides these types of goods, there is another sector that has evolved rapidly, gaining more and more ground in recent months and becoming part of the shopping habits of many online users: online grocery shopping, from fresh and dry food products to household products. The Covid-19 pandemic has brought about a sudden transformation in consumer shopping habits. In order to continue to be effective, the retail network has expressed the need for solutions capable of adapting to the many transformations underway.

Micro-fulfilment Centres are the answer, they are small centres with a maximum size of 550 square meters, located in cities, closer to customers, specializing in the preparation and fulfilment of online grocery orders. These centres were created to meet the need for even faster management of deliveries, which can also take place on the same day. They are flexible, both in terms of size and functionality, with fast and efficient management of order preparation, adaptable to different operators depending on the volume of orders and demand peaks. Providing an optimal management of fresh and dry food products, with temperature-controlled stores maintained between 2° C and 25° C that allow the conservation of fresh and dry products, while keeping them protected from light, dust and sources of heat. Once the picking order is launched, products leave this area and are retrieved to the operator who doesn't have to work in a climate controlled environment. Same as the pharmaceutical sector, our automated warehouse will face some challenges in adapting to this sector.

The electronics market

In the electronics industry, storage and warehouse management play an essential role. This is because electronic components require rapid and correct management of the various phases of replenishment as well as a compliance with certain controlled environmental conditions (required by standards and protocols) to avoid degradation or risk to operators. In a highly technological and competitive sector such as electronics, having a 4.0 automatic warehouse therefore represents a clear competitive advantage because it speeds up operations and makes logistics more flexible.

There are mainly two main problems related to the storage of electronic components: operational management and security. With regard to the operational management of the warehouse, the problems arise from the fact that the electronic components are heterogeneous and often small in size, and therefore require special storage systems that make access and retrieval easy and immediate. The consequence would otherwise be an excessive slowdown in the efficiency of the entire supply chain. Managing a large number of articles and SKUs also means an increasing demand for storage space. On the other hand, in the field of security, it is the storage environment that plays an important role: it must be controlled to avoid the deterioration of electronic components. In particular, sensitive aspects must be taken into account, such as: humidity levels, temperature levels and presence of dust. These have a significant impact on the integrity of electronic equipment. The warehouse therefore must be equipped with refrigerated automatic stores that can keep the temperature stable, with a maximum humidity of 50%. In the case of electronic components sensitive to dust, it is necessary to work in clean rooms to avoid contamination from the external environment. When working with moisture-sensitive materials, it is necessary to ensure ambient humidity below a certain range in order not to risk irreparable damage to stored items. It must be guaranteed a relative humidity of less than 5%. the automated warehouse can easily be adapted to these constraints thanks to its ability to manage a high number of items that have small size and its storage capacity.

Even if we are not interested in e-commerce, the warehouse can still be adapted with other industries that are not mainly operating online. One of the strengths of this warehouse is that it is located in the industrial city of Turin, where hundreds of factories are scattered around the industrial areas, therefore, this warehouse could be integrated with these factories, as a spare parts warehouse, a handling centre that can prepare kitting orders of components that are going to be assembles together in a latter process or even a temporary inventory facility that has a high automation levels. Possible temporary partnerships with start-ups is also possible, in which the warehouse can be a micro fulfilment centre that handles the preparation of orders for small businesses. It could be also a research facility for students and researchers who are interested with automations in logistics and production optimization.

We can summarize the compatibility study of our warehouse by the analysis of the opportunities, threats, strengths and weaknesses of the automated warehouse with the SWOT analysis in table 26.

Table 26: SWOT analysis

Strength	Weaknesses
– High level of warehouse automation; – Reduce space and increase storage capacity; – High flexibility and productivity of picking and kitting processes; – High Efficiency in handling small size products; – Low man labour; – The warehouse is located in an urban area, in the heart of the city centre and it is near the end-customer;	– Low resources; – Costly investment and high priced technology; – Maintenance and upgrade costs; – Costs of software updates – back office – Machine errors; – Small catalogue of products; – AS/RS is newly installed: require knowledge, skills and experience; – Not equipped with temperature, humidity and dust control systems; – Product contamination risks;
Opportunities	**Threats**
– Growth of e-commerce sector and increase in online orders; – Shoppers are becoming more used and trusting of online shopping; – Technological advancement in the market;	– High market competitively; – High variability of demand; – Seasonality: periods with peak and low demand;

6.3. Limitations and future research

This thesis helped to identify the actual performance of an automated warehouse by taking measurements and by calculating key performance indicators of several operations that are performed before the delivery of the package to the customer.

The main limitation of this thesis is the absence of real products, we were not able the measure the actual performance of the warehouse with real products. If we had real items stored in the warehouse and loaded in storage keeping units, these units will have certain weight that can affect the performance of the stacker crane in particular, and the automated system in general, also it can change the duration of the manual picking process achieved by the operator, it is true that while taking measurements in the picking and kitting, we tried to simulate as much as possible how would a real picking operator act in this environment, by mimicking the movement of picking of an invisible product, but still, we won't be 100% authentic to a real case scenario, in which picking a book from a keeping unit on the rack is totally different from picking a small lipstick package from the next rack. Added to that, once a picking or a kitting operation is finished, the operator must discharge the racks and load the keeping units in the system again through the input conveyors. While taking the measurements, it was a sample task, we just pick the keeping unites that supposedly contain different quantities of products. In the real scenario, this keeping unit would be full of real products, thus including an extra weigh in these boxes, therefore the discharging operation from the racks will take more time and energy to execute by the operator.

We assumed that we have 10 products in the system, we did not define which products we had, we just named them product 0001 to product 0010. We suggest including real products from different sectors. For example, products that have expiry dates, this type of products can add a constraint to the algorithm of the system, products that have closer dates to their expiry must be retrieved before the ones that have further expiration. We can also include fresh products and add constraints to them such as a maximum storage duration of 3 days, if it is passed, then they have to be removed due to spoilage or decrease of quality.

In our study, we did not include the different batches and lots of some products, we just considered that each product has only one lot, which is not the case in a real warehouse environment. If a keeping unit, has more than one lot of the same product, it will not be retrieved to the kitting and picking flow racks, it will be delivered instead to the output conveyor of the warehouse. The machine does this, to make sure that the box is outside the warehouse, thus the operator knows that this box has different batches. The management software will notify him that he has to pick a specific lot of this product and it will display the number of batch and will ask for the operator to confirm that he did indeed select the batch in question. Therefore, the operator will pay extra attention to select the correct batch of the product. As we can see, by including the different batches in the product catalogue of the system, some changes will take place in the process of kitting. We suggest in future research to include this element and study the possible change of performance.

In the initiation phase of the warehouse, we assumed that each keeping unit will contain only one type of product. For future research, we suggest the use of multi product keeping units. This assumption will also change the behaviour of the machine, as a result the multi-product keeping units will be delivered to the output conveyer in the kitting station.

When we measured the put away and outbound productivity of the automated guided vehicles, we noticed that the cycle time is composed of a fixed time and a variable time. The fixed time included the processing, docking with the automated warehouse and the calculation of the path; the variable time includes the transportation time and the waiting to pass over an obstacle that was intercepted by the vehicle. we did not study how a change in the distance of the path, can result in a change of performance. We recommend testing this hypothesis. We recommend also the study of 2 scenarios, the first one measure the performance of 2 MIRs working simultaneously and the second scenario measure the performance of operating a single MIR.

The choice of the storage strategy for products in an AS/RS was not taken into account in this thesis, but it is still very important because it can influence the minimization of several parameters such as: the time of removal from storage, the cycle time of the S/R machine, the storage space… We suggest to address the problem of optimal storage allocation using the three methodologies: random storage, dedicated storage, and class-based turnover storage. In the dedicated storage strategy, the storage space is divided into blocks and the product has its own storage area defined in advance. In the open random storage approach, any product can be stored in any locker. And in the random storage by class: products which remain stored for a short time are placed near the delivery station and products which remain longer are placed far from the station, it subdivides the lockers into classes in relation to their distances from the point of delivery. The closest lockers form the first class; the farther ones form the last class.

And as a final suggestion, we can study the performance of the warehouse as a whole, while executing the put away, picking, kitting and outbound processes simultaneously. This is the closest we can get to a real case warehouse environment. Because measuring this scenario was too complicated and we had limited resources in term of labour and time, we decided to start as simple as possible, by measuring processes independently and to postpone this study for the future. This study will help us to analyse how these operations affect each other's, the picker crane will be performing multiple operation for the two stations, the conveyors also will be processing a high number of loading units. It will require the use of multiple operators and resources in the same time.

General conclusion

Our interest was focused on automated storage systems. These systems are a very popular technological solution in the industry, and their added value in the competitiveness of companies that use them is undeniable. In this thesis we have chosen to work on the unit load automated warehousing system, that is the type of AR/RS that specializes in the storage and processing of product pallets and keeping units. it is made up of several aisles, each placed between two adjoining racks and served by an S/R machine and it is mostly found in high volume distribution and production environments. This machine is linked with two functioning automated guided vehicles who took care of loading the warehouse of items and delivering the orders to the outbound station. The detailed study of the AS/RS has highlighted their importance and confirmed their effective performance in our context and in other sectors of application.

In this work we are precisely interested in the performance measurement of the automated system by proposing a set of key performance indicators that are best coherent with our context. Added to that, several tests were carried out in order to be able to find the best combination of settings and assumptions. In the measurement phase, we measure the average travel time of the automated warehouse, stocking and destocking operations that are executed by the AGV, we estimate also the productivity of the kitting and picking operations and we calculate the customer order throughput. Then we have focused particularly on the possible industrial field that can be adapted by our automated warehouse.

The results of our work have enabled us to determine an overall performance estimation for a system that was just installed and is not yet active. After analysing the outcome of our measurement experiments, we were able to identify interesting aspects related to the warehouse. For instance, the least productive processes in the warehouse are the kitting and picking operations and their efficiency can give us a picture of the general warehouse management performance. The throughput of these processes is less than the throughput of the following operation, which may result is slowing down the total throughput of the warehouse and losing a possible potential that would be useful to take advantage of. By analysing the data that was extracted from the WMS, we were able to identify the processes with high variabilities, we investigated their sources and we identified that some errors can cause delays that can affect all the activities that are carried out in the warehouse.

In summary, the other contributions provided by this thesis includes as well the clarification of the concepts of ecommerce warehouses and their constraints, performance indicators and the definition of their borders, the definition of a structure which classifies automated warehouses and performance indicators according to their size and activity; and the development of a benchmarking and a compatibility analysis of the warehouse with several sectors.

We can conclude that even with the presence of some difficulties and limitations in our study, the warehouse has a strong potential and our study can represent a good starting point of this potential that can be exploited in the future to the fullest. This study can be considered as the benchmark application from which others can draw inspiration and modify it according to the needs of the studied system and future perspectives.

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Annexes and attachments

Attachment 1: Full list of KPIs

KPI	Brief description	Related variables	Field of application	References
Time Indicators				
Receiving Time Rec t	Unloading time	$Rec\ t = \frac{\sum \Delta t\ (Rec)}{Pal\ Unlo}$ (hour/pallet) Δt (Rec)= Time between the supply arrival and the instant when product is unloaded (hour) Pal Unlo: number of pallets unloaded (nb/month)		(Gu, et al., 2007)
Put away time Pu t	Lead time since a product has been unloaded to when it is stored in its assigned place	$Pu\ t = \frac{\sum \Delta t\ (Sto)}{Pal\ Sto}$ (hour/pallet) Δt (Sto)= Time between the instant when product is unloaded until its storage (hour) Pal Sto: number of pallets stored (nb/month)		(Mentzer & Konrad, 1991)
Dock to sock time DS t	Lead time from the arrival of the supply until it is ready for pickup	$DS\ t = \frac{\sum \Delta t\ (DS)}{Pal\ Unlo}$ (hour/pallet) Δt (DS)= Time between the supply arrival up to product availability for picking (hour) Pal Unlo= number of pallets unloaded (nb/month)		(Ramaa.A, et al., 2012)
Replenishment time Rep t	Lead time to take products from reserve storage area to pick area	$Rep\ t = \frac{\sum \Delta t\ (Rep)}{Pal\ Moved}$ (hour/pallet) Δt (Rep)= Time between the transfer of products from reserve storage area to forward picking area (hour) Pal Moved = number of pallets moved during replenishment operation (nb/month)	Automated	(Mascolo, et al., 2014)
Order picking time Pick t	Lead time to pick an order line	$Pick\ t = \frac{\sum \Delta t\ (Pick)}{OrderLi\ Pick}$ (hour/order line) Δt (Pick)= Time between the instants when operator starts to pick an order and when the picking finishes (hour) OrdLi Pick= number of order lines picked (nb/month)	Automated	(Mentzer & Konrad, 1991)
Shipping time Ship t	Lead time to load a truck per total orders loaded	$Ship\ t = \frac{\sum \Delta t\ (Ship)}{Order\ Del}$ (hour/order) Δt (Ship)= Time between the instants when the order picking finishes and when the truck loading is complete (hour) Ord Del= number of orders delivered (nb/month)		(Campos, et al., 2004)
Delivery lead time Del t	Total time of distribution per total orders distributed	$Del\ t = \frac{\sum \Delta t\ (Del)}{Ord\ Del}$ (hour/order) Δt (Del)= Time between the truck loading and the customer acceptance of the product (hour) Ord Del= number of orders delivered (nb/month)		(Campos, et al., 2004)
Order lead time OrdLT t	Lead time from customer order to customer acceptance	$OrdLT\ t = \frac{\sum \Delta t\ (Ord)}{Ord\ Del}$ (hour/order) Δt (Ord)= Time between the customer ordering and the customer acceptance of the product (hour) Ord Del= number of orders delivered (nb/month)		(Mentzer & Konrad, 1991)
Productivity Indicators				

Labour productivity Lab p	Total number of items managed by the amount of item-handling working hours	$Lab\ p = \frac{item\ proc}{WH}$ (items/labour hour) Item Proc = number of items managed by the warehouse (inbound and outbound) (nb/month) WH = number of item-handling working hours (hour/month)		(DeMarco & Mangano, 2011)
Labour efficiency LE p	Standard time defined by engineering divided by actual time	$LE\ p = \frac{Theor\ H}{WH}$ (%) TheorH = theoretical time that the operator should take to accomplish a task (hour/month) WH = number of item-handling		(GOOMAS, 2011)
Receiving productivity Rec p	Number of vehicles unloaded per labour hour	$Rec\ p = \frac{Pal\ Unlo}{WH\ Rec}$ (pallets/labour hour) Pal Unlo = number of pallets unloaded (nb/month) WH Rec = sum of employee labour hours working in receiving activity (hour/month)		(Mentzer & Konrad, 1991)
Storage productivity Sto p	Number of products stored per labour hours in storage activity	$Sot\ p = \frac{Pal\ Sto}{WH\ Sto}$ (pallets/labour hour) Pal Sto = number of pallets stored (nb/month) WH Sto = sum of employee labour hours working in storage activity (hour/month)		(Mascolo, et al., 2014)
Average Stock S	The average quantity of products sored in the warehouse during a certain amount of time	$S = \frac{\sum s(i)}{N}$ N= the number of observed days S(i)= the stock measured the i-th day, expressed as a number of products or total weight	Automated	(Colla & Nastasi, 2010)
Receptivity Saturation Coefficient RSC	Express how much the warehouse has been exploited in a certain period of time	$RSC = \frac{S}{R}$ S= the average stock R= the receptivity, approximately equal to the maximum quantity of items that has been recorded	Automated	(Colla & Nastasi, 2010)
Replenishment productivity Rep p	Number of pallets moved by labour hour in replenishment activity	$Rep\ p = \frac{Pal\ Moved}{WH\ rep}$ (pallets/labour hours) Pal Moved = number of pallets moved during replenishment operation (nb/month) WH Rep = sum of employee labour hours working in replenishment activity (hour/month)		(Mascolo, et al., 2014)
Picking productivity Pick p	Number of products picked per labour hours in picking activity	$Pick\ p = \frac{OrdLi\ Pick}{WH\ Pick}$ (order line/Labour hour) OrdLi Pick = number of order lines picked (nb/month) WH Pick = sum of employee labour hours working in picking activity (hour/month)	Automated	(Kiefer & Novack, 1999)
Shipping productivity Ship p	Total number of products shipped per time period	$Ship\ p = \frac{OrdLi\ Ship}{WH\ Ship}$ (order line/Labour hour) OrdLi Ship = number of order lines shipped (nb/month) WH Ship = sum of employee labour hours working in shipping activity (hour/month)		(Mentzer & Konrad, 1991)

Delivery productivity Del p	Total number of orders delivered per labour hours in delivery activity	$DEl\ p = \frac{Ord\ Del}{WH\ Del}$ (order/Labour hour) Ord Del = number of orders delivered (nb/month) WH Del = sum of employee labour hours working in delivery activity (hour/month)		(Mascolo, et al., 2014)
Inventory utilisation InvUt p	Ratio of space occupied by storage	$InvUt\ p = \frac{Inv\ CapUsed}{Inv\ Cap}$ (%) Inv CapUsed = average space occupied by inventory (m^3) Inv Cap = total warehouse inventory capacity (m^3)	Automated	(Ramaa.A, et al., 2012)
Turnover TO p	Ration between the cost of goods sold and the average inventory	$TO\ p = \frac{CGoods}{Ave\ Inv}$ (times/month) $CGoods = \sum[(\text{number of items sold})i * (\text{cost})i]$ (\$/month) $\text{Ave Inv} = \sum[(\text{average number of items in inventory})i * (\text{cost})i]$ (\$/month)		(Johnson & McGinnis, 2011)
Transport utilization TrUt p	Vehicle fill rate	$TrUt\ p = \frac{Ton\ Tr}{Ton\ Avail}$ (%) Ton Tr = total of tons transported (ton/month) $\text{Ton Avail} = \sum(\text{ton capacity of each truck})$ (ton)		(Bourlakis & Matopoulos, 2010)
Warehouse utilization WarUt p	Warehouse capacity used	$WarUt\ p = \frac{War\ CapUsed}{War\ Cap}$ (%) War CapUsed = average space occupied in the warehouse (m^3) War Cap = total warehouse capacity (m^3)		(Bowersox, et al., 2002)
Equipment downtime EqD p	Percentage of hours that the equipment is not used	$EqD\ p = \frac{\sum HEq\ Stop}{\sum HEq\ avail}$ (%) HEq Stop = total number of hours during which equipment are stopped (hour/month) HEq Avail = total number of hours during which equipment are available to work (hour/month)		(Bowersox, et al., 2002)
Throughput Th p	Ratio between items and hours leaving the warehouse	$$Th\ p = \frac{Ord\ ship}{War\ WH}$$ Ord Ship = number of order shipped (nb/month) War WH = total number of hours during which the warehouse works (hour/month)		(Mentzer & Konrad, 1991)
In/out throughput	The measure of the number of items that enter or exit during a time unit (hour, shift, day)	$$T\ in = \frac{I\ in}{\Delta t}$$ $$T\ out = \frac{I\ out}{\Delta t}$$ I= number of inbound or outbound items	Automated	(Colla & Nastasi, 2010)
Cost Indicators				
Inventory costs Inv c	Holding cost and the stock out penalty	$Inv\ c = InvC + LostC$ (\$) InvC = financial cost to maintain warehouse inventory (\$) LostC = penalty measured by company as a cost when the customer makes an order and the product is not available (\$)		(li et al. 2009)
Transportation cost Tr c	Cost spent per order delivered	$Tr\ c = \frac{TrC}{Ord\ Del}$ (\$/order)		(Bowersox, et al., 2002)

		TrC= transportation cost, which is the sum of assets, oil, maintenance and labour costs ($/month) Ord Del = number of orders delivered (nb/month)		
Order processing cost OrdProcC c	Processing cost of all orders per number of orders	$OrdProc\ c = \frac{Ord\ ProcC}{Cust\ Ord}$ ($/order) Ord ProcC = sum of office and employee costs to process orders ($) Cust Ord = number of customer orders (nb/month)		(Campos, et al., 2004)
Cost as a % of sales CS c	Warehousing cost as a percentage of the total sales	$CS = \frac{WarC}{Sales}$ (%) WarC = sum of all activity costs that the warehouse has in charge ($) Sales= total of revenues from sales ($)		(Bowersox, et al., 2002)
Labour cost Lab c	Cost of operators responsible for warehouse operations	$Lab\ c = Salary + charges + others$ ($/month) Salary = salaries of all warehouse employees ($) Charges = charges paid for all employees ($) Others = other costs ($/month)		(Cagliano, et al., 2011)
Maintenance cost Maint c	Total maintenance cost of equipment and building	$\mathrm{Maint\ c} = \mathrm{BuildC} + \mathrm{EqMaintC} + \mathrm{Others}$ ($/monthe) BuildC = cost to maintain warehouse building ($/month) EqMaintC = equipment maintenance costs ($/month) Others = other costs ($/month)		(DeMarco & Mangano, 2011)
Quality Indicators				
Receiving accuracy Rec q	Number of pallets leaded without incidents	$Rec\ q = \frac{Cor\ Unlo}{Pal\ Unlo}$ (%) Cor Unlo = number of unloading pallets occurred without incidents (nb/month) Pal Unlo = number of pallets unloaded (nb/month)		(Mascolo, et al., 2014)
Storage accuracy Sto q	Storing products in proper location	$Sto\ q = \frac{Cor\ Sto}{Pal\ Sto}$ (%) Cor Sto = number of pallets stored in proper location (nb/month) Pal Sto = number of pallets stored (nb/month)		(Voss, et al., 2005)
Replenishment accuracy Rep q	Correct movement of products from storage area to picking area	$Rep\ q = \frac{Cor\ Rep}{Pal\ Moved}$ (%) Cor Rep = number of pallets moved to forward storage area correctly (nb/month) Pal Moved = number of pallets moved during replenishment operation (nb/month)	Automated	(Mascolo, et al., 2014)
Physical inventory accuracy Inv q	The physical counts of inventory agree with the inventory status reported in the database	$Inv\ q = \frac{(Unlo+Sto+Moved\ Pal)-Prob\ data}{Unlo+Sto+Moved\ Pal}$ (%) Pal Unlo = number of pallets unloaded (nb/month) Pal Sto = number of pallets stored (nb/month) Pal Moved = number of pallets moved during replenishment operation (nb/month) Prob data = number of pallets with inaccuracies between the physical inventory and the system (nb/month)	Automated	(Bowersox, et al., 2002)
Picking accuracy Pick q	Number of orders picked	$Pick\ q = \frac{Cor\ ordLi\ Pick}{OrdLi\ Pick}$ (%) Cor OrdLi Pick = number of order lines picked correctly (nb/month)	Automated	(Bowersox, et al., 2002)

	correctly per orders picked	OrdLi Pick = number of order lines picked (nb/month)		
Orders shipped accuracy Ship q	Number of errors free orders shipped	$Ship\ q = \frac{Cor\ OrdLi\ Ship}{OrdLi\ Ship}$ (%) Cor OrdLi Ship = number of order lines shipped correctly (nb/month) OrdLi Ship = number of order lines shipped (nb/month)		(De Koster & Warffemius, 2005)
Delivery accuracy Del q	Number of orders distributed without incidents	$Del\ q = \frac{Cor\ Del}{Ord\ Del}$ (%) Cor Del = number of orders delivered correctly (nb/month) Ord Del = number of orders delivered (nb/month)		(Campos, et al., 2004)
On time delivery OTDel q	Number of orders received on or before committed date	$OTDel\ q = \frac{Ord\ Del\ OT}{Ord\ Del}$ (%) Ord Del OT = number of orders received by customer on or before deadline (nb/month) Ord Del = number of orders delivered (nb/month)		(Voss, et al., 2005)
Orders shipped on time OTShip q	Number of orders shipped on time per total orders shipped	$OTShip\ q = \frac{Ship\ OT}{Ord\ Ship}$ (%) Ship OT= number of orders shipped on or before the deadline (nb/month) Ord Ship = number of order shipped (nb/month)		(Kiefer & Novack, 1999)
Order fill rate OrdF q	Number of orders filled completely on the first shipment	$OrdF\ q = \frac{Complet\ 1st\ Ship}{Ord\ Ship}$ (%) Complet 1st Ship = number of orders delivered complete on first shipment (nb/month) Ord Ship = number of order shipped (nb/month)		(Ramaa.A, et al., 2012)
Perfect order PerfOrd q	Number of orders delivered on time, without damage and with accurate documentation	$PerfOrd\ q = \frac{(Ord\ OT, ND, CD)}{Ord\ Del}$ (%) Ord OT, ND, CD = number of orders received by customer on time (OT), with no damages (ND) and correct documentation (CD) (nb/month) Ord Del = number of orders delivered (nb/month)		(Kiefer & Novack, 1999)
Customer satisfaction CustSat q	Number of customer complaints per number of orders	$CustSat\ q = \frac{Cust\ Complain}{Ord\ Del}$ (complains/order) Cust Complain= number of customer complaints regarding on logistics aspects (nb/month) Ord Del = number of orders delivered (nb/month)		(Voss, et al., 2005) (S.I., et al., 2011)
Stock out rate StockOut q	Number of stock products out of order	$StockOut = \frac{Item\ noAvail}{Item\ Out}$ (%) Item noAvail= number of products that are not available in stock when the customer makes an order (nb/month) Item Out = sum of the items processed by the warehouse with items in process in picking and shipping activities (nb/month)		(S.I., et al., 2011)