TÉCNICO LISBOA

Impacts of Implementing a High-Density Automated Storage System in a Warehouse

Worten Case Study

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Thesis to obtain the Master of Science Degree in

Industrial Engineering and Management

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November 2023

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgments

Gostaria de agradecer, em primeiro lugar, aos meus orientadores. À Professora Susana Relvas por todo o acompanhamento que me deu e ao Eng. Ricardo Cardão, em representação da Worten, por toda a disponibilidade e apoio no desenvolvimento do trabalho.

À minha família agradeço o apoio que sempre me deram. Aos meus pais, por terem tornado este percurso possível. Ao meu irmão, pelos fins de semana que passou a reler esta tese e à minha cunhada que me cedeu o seu lugar no escritório nos últimos meses. Ao Marcelo agradeço pela companhia nos dias de teletrabalho. Aos meus avós, e tios. Em especial aos meus padrinhos sempre presentes e à minha tia Fá, que foi quem acompanhou mais de perto este percurso. Obrigado pela motivação que me deu e pela paciência que teve comigo desde o primeiro dia.

Agradeço aos meus amigos por terem tornada esta jornada de 5 anos muito mais divertida. Em especial, a todos os que acompanharam de perto o desenvolvimento desta tese, nos gabinetes do Tagus.

Abstract

The retail industry has undergone significant changes in recent years, primarily due to the e-commerce continuous evolution. As a result, consumers are becoming more demanding and expect deliveries to be fast and efficient. In this sense, businesses have globally begun to implement automation in warehouses to increase storage density, throughput, and service level. The current thesis examines the impacts of implementing automated systems in the Worten warehouse, specifically in the area designated for storing low-volume products, which corresponds to 37% of the company's total storage area. Based on the use of a decision support framework already publicly available, the current situation of the company was examined, and the critical issues were identified: lack of space, lack of flexibility in space allocation, low storage density, and picking productivity. Subsequently, an analysis of scenarios with different automated solutions was conducted, followed by a comparison across various key performance indicators (KPIs). The most suitable scenario considered the implementation of a robot-based compact storage and retrieval system. The results suggest that it could represent a 52% reduction in the required space for 2025 and an increase of 9.4% in storage efficiency. Additionally, it would allow for a forecasted 10% increase in the company's service level during the most demanding periods in terms of sales and a 36% reduction in pallet time processing.

Key Words: E-Commerce, Warehouse, Automated Systems, Storage Density, Key Performance Indicators.

Resumo

Nos últimos anos, a indústria de retalho tem experienciado grandes mudanças, principalmente devido à evolução contínua do *e-commerce*. Em consequência, os consumidores estão cada vez mais exigentes e esperam entregas rápidas e eficientes. Assim, as empresas têm vindo a apostar na implementação de automação nos armazéns, um pouco por todo o mundo, como forma de aumentar a densidade de armazenamento dos produtos, o *throughput*, e o nível de serviço.

A presente dissertação visa estudar os impactos da implementação de sistemas automatizados no armazém da Worten, especificamente na área de armazenamento de produtos de pequena dimensão, que corresponde a 37% da área total de armazenamento da empresa. Partindo da aplicação de um mapa conceptual de apoio à decisão disponível publicamente, a situação atual da empresa foi analisada e os pontos críticos foram identificados: falta de espaço, falta de flexibilidade na alocação de espaço, baixa densidade de armazenamento e reduzida produtividade de *picking*. Seguiu-se a análise de cenários distintos com diferentes soluções automatizadas e posterior comparação entre eles, em diferentes indicadores de performance. O cenário mais adequado consistia na implementação de um *robot-based compact storage and retrieval system*. Os resultados sugerem que este representaria uma redução de 52% no espaço necessário até 2025 e um aumento de 9.4% na eficiência de armazenamento. Permitiria ainda um aumento previsto em 10% no nível de serviço da empresa durante os períodos de procura elevada e uma redução de 36% no tempo necessário para processar uma palete de artigos.

Palavras-chave: *E-Commerce*, Armazém, Sistemas Automatizados, Densidade de Armazenamento, Indicadores de Performance.

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List of Abbreviations and Acronyms

3PL	Third-Party Logistics
APR	Adjustable Pallet Racking
AGV	Automated Guided Vehicle
ASN	Advanced Shipping Notice
AS/RS	Automated Storage and Retrieval System
ASS	Automated Storage System
B2B	Business-to-Business
B2C	Business-to-Consumer
COI	Cube per Order Index
DIN	Drive-in
EO	Express Operator
FTE	Full Time Equivalent
GRA	Big (“Grande”)
HD	Home Delivery
iLPN	Inbound License Plate Number
IMG	Image
IO	Internal Operator
I/O	Input/Output
KPI	Key Performance Indicator
LAV	High-Value Logistics (“Logística de Alto Valor”)
LT	Long-Tail
LIFO	Last In, First Out
MED	Medium (“Médio”)
MF	Supplier Brand (“Marca Fornecedora”)
MP	Own Brand (“Marca Própria”)
oLPN	Outbound License Plate Number
ONL	Online
OPW	Order Picker Walkie
PBL	Pick By Line
PBLS	Pick By Line to Store
PBS	Pick By Store
PDT	Portable Digital Terminal
PEQ	Small (“Pequeno”)
PMS	Performance Measurement System
PTL	Put To Light
PTS	Put To Store
PTW	Put To Wall
PTZ	Put To Zone
PUIS	Pick Up In Store

RCSRS Robot-based Compact Storage and Retrieval System

RFID Radio Frequency Identification

RMFS Robot Mobile Fulfillment System

SBS/RS Shuttle-Based Storage and Retrieval System

SC Supply Chain

SCED Complementary Service of Home Deliveries (“Serviço Complementar de Entregas ao Domicílio”)

SKU Stock-keeping Unit

SM Slow Mover

UN Business Unit (“Unidade de Negócio”)

WMS Warehouse Management System

Chapter 1 – Introduction

This first chapter is an introduction that aims to provide an overview of this master's dissertation. Firstly, the problem that inspired this study is explained. Then, the main objectives of the dissertation are presented and, to conclude the chapter, the document structure is described.

1.1 Problem Background

All around the world, the retail industry is facing several changes in consumption trends, and the Iberian market is no exception. E-commerce had already been growing for a few years when the COVID-19 pandemic, and consequent lockdown, pushed consumers to make more purchases online. This factor further accelerated the growth of e-commerce, and this is a trend that is expected to continue in the future (Ecommerce News, 2023). This growth has forced changes in supply chains, leading many companies to embrace an omnichannel strategy.

This dissertation will explore the case study of Worten, which is a Portuguese retail company, leader in the sector of home appliances, consumer electronics, and entertainment. Worten owns the biggest e-commerce site in the country and is expanding the variety of products sold, entering new product categories (Worten, 2023). This led to an increase in sales, namely on its marketplace platform (Moreira, 2018).

The rise in sales is naturally reflected in the increased quantity of stocked products. It is important to emphasize the significance of the warehouse in the supply chain since, in addition to serving the fundamental purpose of storage, it must also provide an effective response to the new market challenges. To meet the customers' expectations, which are continually rising, some performance indicators must be met. There are new issues that need to be handled, namely in space management, considering the increase in the quantity and diversification of stocked products. There is the necessity to increase the productivity of the system, reduce lead times, and ensure an answer to demand fluctuations, flexible enough to guarantee a good service level.

To meet the need for greater storage capacity and quick response, the company's strategy involves implementing automated solutions. Therefore, given the growth in the storage of small items, there is a clear need to analyze the possible impacts in the warehouse of implementing an automated solution to store these small products. In this sense, this dissertation was developed. The present work also intends to fill the gap regarding the lack of real cases of automation explored in the literature and mainly its impacts on the warehouse in a holistic way.

1.2 Objectives

The main objective of this master's dissertation is to analyze the impacts of implementing a high-density automated storage system in Worten's warehouse. It is intended to reach a feasible solution that can be adopted by the company, considering its current need for an improvement in space usage. To that end, the following specific objectives were defined:

- Characterize the problem to be solved and the context of the case study.

- Carry out a scientific literature review, in order to develop a theoretical base for the topic under study.
- Implement a methodology that leads to achieving the dissertation's main objective.
- Collect and interpret relevant data to create different scenarios and evaluate automated solutions.
- Recommend the adoption of the system that constitute the most suitable scenario and analyze its impacts throughout the warehouse's different operations.

1.3 Dissertation's Structure

This master's dissertation is structured into seven chapters, that are briefly described below.

- **Chapter 1 – Introduction:** The purpose of this chapter is to present the problem that led to the thesis development, followed by its objectives. Next, the dissertation structure is briefly explained.
- **Chapter 2 – Case Study:** The second chapter contextualizes the developed work. It consists of the presentation of the company with which the dissertation was developed, and it further discusses the problem under analysis.
- **Chapter 3 – Literature Review:** In this chapter, a review of the scientific literature, related to the research area of this work, is presented.
- **Chapter 4 - Frameworks Presentation:** This chapter explores different methodologies found in the literature related to the objectives of the dissertation. A framework is proposed to be followed during the work.
- **Chapter 5 – Framework Application:** In this fifth chapter, the previously proposed framework is applied to the small-sized products' storage area of Worten's warehouse.
- **Chapter 6 – Results Discussion:** In this chapter, different developed scenarios are analyzed, based on the previously established metrics.
- **Chapter 7 – Conclusions and Future Work:** The last chapter presents the main conclusions that were obtained and suggests future research topics related to the developed work.

Chapter 2 – Case Study

This chapter aims to contextualize the problem that will be studied in this dissertation. Firstly, a global approach to the issue and the company in analysis is presented. Then, a more thorough contextualization of the current warehouse activities will be carried out.

The chapter is structured into five sections. The first one refers to Sonae and the second one is regarding Worten. These 2 sections are more general. Then, Worten Supply Chain and Worten Warehouse are covered in sections 3 and 4, respectively. There are three subsections under the major topic "Worten Warehouse": Layout, Flows, and Operations. Finally, it is presented the Problem Definition, in section 5. The problem is contextualized and stated in this last section and the objectives are explained.

The information present in this chapter was gathered through regular visits to the Worten warehouse, access to corporate documents, and meetings with members of the Supply Chain Team.

2.1 Sonae

Sonae is a multinational company, founded in 1959 in Portugal by the banker Afonso Pinto de Magalhães. Originally named “Sonae - Sociedade Nacional de Estratificados”, the company focused on producing wood-based panels. Over time, Sonae expanded through several acquisitions, such as NOVOPAN in 1971 and Agloma in 1984. In 1983, Sonae formed a joint venture with the French company Promodès, to renew their distribution and retail business. That same year, Sonae created the holding Sonae SGPS, SA, and entered the capital market. Sonae opened the first Portuguese supermarket (Continente Matosinhos) in 1985 and, nowadays, Sonae is the leader in Portuguese food retail (Machado, 2009).

Throughout the nineties, the group created various specialized retail brands such as Modalfa, Maxmat, SportZone and Worten. With a strong presence in Portugal and Spain, Sonae opened “Centro Comercial Colombo”, the largest mall in the Iberian Peninsula, in 1997. Besides retail, some other sectors where Sonae is present are Telecommunications and Entertainment (with NOS), Sports (with JD, Sports Zone, Size? and Sprinter), and Health (with Wells and Dr. Wells) (Sonae, 2023).

The latest available Annual Report states that Sonae owns 1 342 stores, with more than 37 000 workers and generates €5.4 thousand million in sales volume. Sonae is also committed to social and environmental responsibility. In 2020, the company signed a manifest supporting the Portuguese Ecological Pact, which promotes a new growth model based on a circular economy, renewable energies, and low-carbon industries. Sonae has pledged to avoid deforestation until 2030, demonstrating its commitment to sustainability. The Sonae Portfolio is organized with Sonae MC in food retail, Sonae Sierra in the real estate market, Worten in electronic retail, Zeitreel in fashion, Universo in financial services, Bright Pixel in tech investment, NOS in telecommunications and ISRG in sports retail.

This dissertation will focus on a case study related to one of Sonae’s companies - Worten - that will be further described in detail.

2.2 Worten

As previously mentioned, Worten is the electronics retail brand of Sonae. Worten was founded in 1996 and the first store was opened that year in Chaves. Worten has as its mission to "bring the best of technology (and not only) to all consumers, without exception" (Worten, 2023).

In 2004, Worten Mobile was launched. Worten Mobile Stores are dedicated to the commercialization of consumer electronics goods and telecommunications services. Another important milestone was the entrance into the Spanish Market, which occurred in 2009. In 2013, the Worten Resolve Card was launched (Worten Resolve is an umbrella brand of Worten Services in the repair area). Thus, Worten is a single company that comprises three different Sonae brands: Worten, Worten Mobile and Worten Resolve. Besides electronic devices and home appliances, Worten is expanding its offer in several different categories. Recently, the company started selling products like toys, beauty products, or micro-waves.

Nowadays, this retail brand is a Leader in the sector of home appliances, consumer electronics and entertainment, offering more than six million products in physical or online stores. Worten owns the biggest e-commerce site in Portugal and detains more than 240 stores in the Iberian Peninsula. According to the 2021 Integrated Report of Sonae, the increase in sales during the pandemic (2020) and the restructuring process in Spain (2021), lead to an increase in EBITDA to €78m, in 2021. During this year, online sales were the main driver of growth, registering an extraordinary progress of more than €200m. Worten has also made progress in its marketplace, with the entry into new product categories. The Marketplace is a digital platform, launched in 2018, where Worten's selected partner companies sell their own products on Worten's website (Moreira, 2018). The company has also been investing in an omnichannel strategy. This strategy consists in a fully integrated shopping experience that connects between the physical world - of stores and warehouses - with the digital channels. Customers are nowadays more demanding and well-informed about the product they intend to buy, and there is the need to correspond to expectations, fulfilling the orders in a short period of time.

The omnichannel strategy ensures a high level of customer satisfaction once the customer can order a product from the website and pick it up in a store or receive it directly at home, for example. Thus, some products are sold directly from the warehouse to customers' houses without even passing by a store.

2.3 Worten Supply Chain (SC)

Worten's supply chain has been changing over the years. Initially, it was a linear chain, where the products flowed unidirectionally from suppliers to the Worten warehouse, and then from the warehouse to the stores. Customers had to pick the product in stores. Nowadays, the supply chain is much more complex and dynamic. With the appearance and growth of the online channel, the expansion of the company to Spain, and the impact of the pandemic on customers' habits of consumption, Worten has been adopting the omnichannel strategy, investing in the interconnectivity between physical stores and online channels. It allows the creation of a personalized experience for customers, regardless of how they interact with the company. In the current supply chain, it is possible to see a diverse number of flows that include reverse logistics for returned products, cross-docking operations, or marketplace platform. The current Supply Chain is represented in Figure (Appendix). Customers now have different ways to place their orders and receive the desired products:

- Traditional process of purchasing in-store.
- Home Delivery (HD) - ordering online and receiving the goods at home.
- Pick Up In Store (PUIS) - ordering online and picking up the goods in a chosen store.

2.4 Warehouse

Worten has one main warehouse in Azambuja, with an area of around 50 000 square meters and 10.5 meters in height. This warehouse is open 18 hours a day, six days a week, the operation being split into two shifts, the first one from 8 a.m. to 5 p.m. and the second one from 5 p.m. until 2 a.m.

All the Worten products, that are distributed in Portugal and Spain, pass through this warehouse, totalizing more than 26 000 different stock-keeping units (SKUs). There is a wide range of products stored in this space, from heavy fridges or large TVs to small light pens or pencils. These differences in products' characteristics, such as size, weight, and value, need to be carefully taken into consideration when every product is stored, prepared, and shipped.

There are two main different types of products stored in the Worten warehouse: big-sized products, which are classified as 701, and small or medium-sized products, classified as 708. Usually, the 701 section is composed of large home appliances, such as fridges and washing machines, while the space dedicated to the storage of 708 products is usually occupied by books, fans, etc.

In this section, the warehouse will be further described, considering the main aspects regarding the warehouse layout, flows and operations.

2.4.1 Warehouse Layout

The warehouse layout can be divided into two main areas: the storage area (storage of 701 products, 708 products, and the mezzanine) and the preparation area (inbound and outbound areas; operations area). The warehouse is organized with a drive-thru Layout, meaning that the inbound area and the outbound area are located on opposite sides, which turns the flow of products easier. Figure 1 represents the current layout of the warehouse. Each one of the areas will be described, as well as the storage methods adopted by Worten.

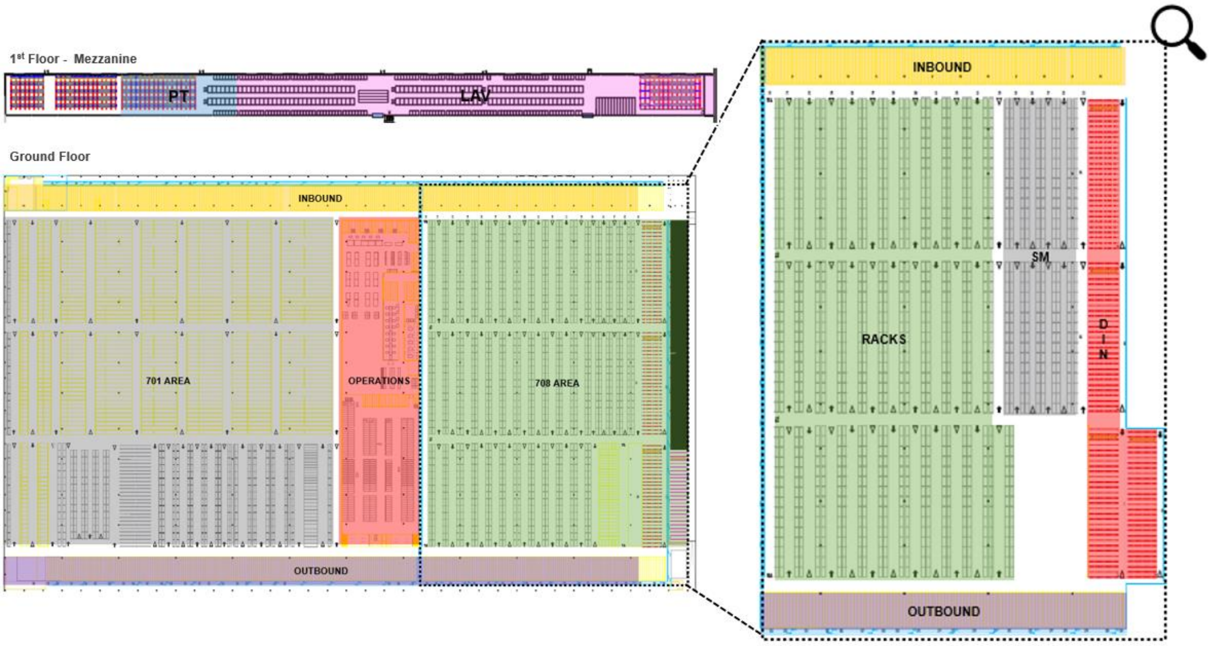

Figure 1 Layout of Worten's Warehouse, 2023

Inbound Area

Consists of a set of docks where the products are delivered by Worten suppliers. Docks that are allocated to 701 products are in front of the 701 storage area, and the same happens for 708 docks to facilitate the flows in the warehouse. Two 708 docks are specifically allocated to receive own-brand products. After the delivery, small products are labelled and kept in pallets until a worker is available to pick them up and store them in the appropriate location. Every time a new product enters the warehouse, it passes through the Cubiscan. In the Cubiscan, an operator manually registers products' methodologic characteristics (height, length, width, weight, stacking height, and TiHi), and designates the Pick Location Assignment Type (PLAT) to each SKU. PLAT indicates the zone of the warehouse where the item is supposed to be stored.

701 Area: This area encloses three different storage systems for products with different characteristics.

1) **Solo 701: Block Stacking**

Block Stacking is a high-density method viable for robust products with high stowability, like washing machines or dishwashers. On the one hand, it is an inexpensive storage system (de Koster et al., 2017). On the other hand, one disadvantage of this method is that access to the products is limited. The operator must remove the items at the top to reach the bottom ones.

This type of storage occupies the majority of 701 storage area, and the locations where the products are stored are progressively bigger and in lower quantity. At the corner of the warehouse are mostly stored SKUs provided by suppliers (small quantities of several SKUs, placed in small locations), and near the central area of the warehouse are stored own-brand products (larger quantities of a few SKUs).

2) Racks + *Imagem* (IMG): Single-deep Racking Storage

This versatile storage system allows the storage of different SKUs. It is where the remaining big-sized products are stored, which are usually more fragile and require more care to be handled and stored. Another advantage is the fact that every product is always accessible.

There are racks exclusively used to store products in Europallets and others (with three pillars) that can be either used for Europallets or pallets with more than 1.20 m in length (useful for larger TVs, for example). This zone is composed of high and medium pallets. Leaning against the wall are stored 701 outlet products in high pallets.

3) Drive-in (DIN) 701: Gravity Flow (Live Storage System)

The Gravity Flow system is used to store TVs in the “Image Zone”. It is appropriate for fast-moving products and allows the adoption of a first-in-first-out policy. Operators resort to this system when there are many TVs to be stored at the same time. In the same tunnel, different SKUs can be stored in different tiers. This system is useful to increase the occupancy of the storage space.

708 Area: The 708 area is dedicated to the storage of small appliances. At a micro-layout level, it is composed of four types of storage.

1) DIN: Drive-in Racking

Allows higher space usage efficiency since there are no aisles. It is used for own-brand products that have larger lead times (around three months), coming from countries such as China or Vietnam. The level of confidence in the suppliers of these products is low, and the uncertainty associated with each order is high. Therefore, Worten keeps stock of these products. It is used to store large quantities of a reduced number of SKUs. DIN is placed in one corner of the warehouse since many of its products are stored for long periods, and there are other places in the warehouse where it is possible to find some units of them. A DIN system is considered a high-density methodology of storage because the volumetric efficiency is high, and to access some items, it is necessary to remove the ones stored in front of them.

2) Racks: Wide Aisle Single-Deep Racking

It is the most versatile racking system, with every product always accessible. However, it demands a considerable ground area for accessibility. It is composed of Active Locations in the lower level, where products are easily picked, and Reserve Locations, used to stock products in the higher levels of the racks. It is important to note that products stored in racks are placed according to their volumes and weights in four different sectors. On one side of the warehouse, far from the central zone of operations, are stored the biggest and heaviest products. Near the central zone are stored smaller items. Thus, during the batch picking process, the picker starts building the pallets with bigger items and continues to pick gradually smaller ones until it is completely full.

In racks, each location is filled with single SKUs (Single SKU location approach). It is possible to find different types of storage: high pallet (with 190 cm of height), medium pallet (half of the high pallets' height), low pallet (one-third of high pallets' height), shelves (35 cm of height), large alveoli and small alveoli.

3) Narrow Aisle Single-Deep Racking

Used to store slow movers (SM), i.e., products that are not frequently required. Slow movers may be outlet products, single articles, products of new collections with low demand, etc. Thus, the quantity of stored product is low, but the number of SKUs is high. The aisles are shorter in comparison with conventional racks, which results in space savings and more compact storage of the items. On the other hand, both provisioning and picking have lower productivity rates.

These racks are located far from the operations area because the number of slow movers demanded is low. In the SM racks, it is possible to find three types of storage: high pallet, medium pallet, and shelves.

4) Mezzanine

Besides the Ground Floor, there is also the mezzanine where some 708 products are stored. The mezzanine is used for LAV (from the Portuguese *Logistica de Alto Valor* – High-Value Logistics) and for Fulfillment Products. LAV products stored in this area are the ones with both the higher value and smaller volume, like smartphones, considered more prone to be steeled. For that reason, the mezzanine is a restricted access zone, and employees must be inspected every time they leave this area. Fulfillment products are the ones sold by other companies through the Worten website (in the Marketplace). In the mezzanine, there are different areas to store products with different characteristics.

Mezzanine Racks – LAV: The smaller products are stored in the mezzanine racks (which have a lower capacity than the racks of the 708 area). There are two floors of racks. Floor 0 is used to store Pick-by-Store (PBS) products. The first floor is used to store Pick-by-Line (PBL) products in racks and Outlet Products in alveoli. These types of products will be described in section 2.4.2 Warehouse Flows.

Central Zone: The larger and medium-sized items are kept in high pallets in the center of the warehouse, separated from each other with cardboard panels. Each pallet is composed of one SKU. The picking of these products is performed following a circuit, as happens in the 708 area's racks. Moreover, roll-cages enable the storage of two separate SKUs, each in its own layer.

Mezzanine Racks – Fulfillment: One side of the mezzanine is used to store other companies' products that are willing to pay for that service. Worten provides the possibility of delivering these items during the following business day. It is composed of racks and alveoli. Part of this zone is dedicated to Worten Resolve products, known as Telecom parts.

Operations Area

Located in the central zone of the warehouse, the operations area is not used to store products but to process orders instead. It contains the online (ONL) flow for both Pick Up In Store products (PUIS) and home delivery products (HD). Products that are to be sent to stores are also processed in this central zone.

Outbound Area

Consists of a set of docks where the orders are shipped, either to stores or to customers' homes. There are three different companies in charge of delivering the products that will be further detailed in the Warehouse Flows section.

2.4.2 Warehouse Flows

Warehouse flows can be divided into two main types: inbound and outbound flows (Figure 2).

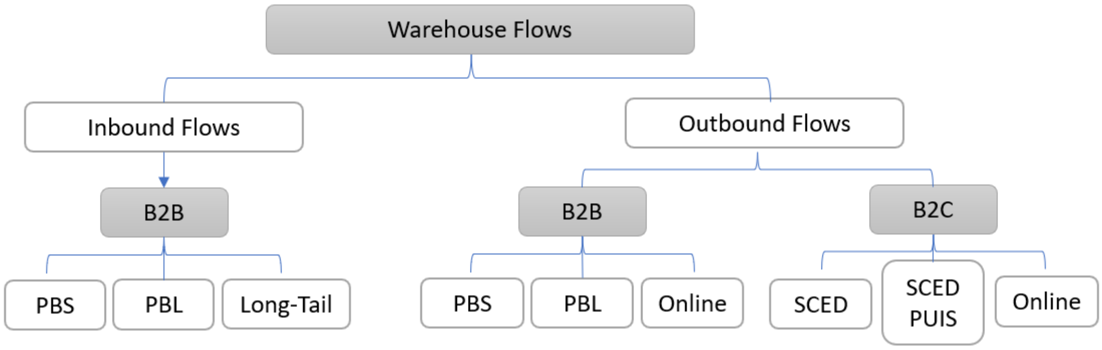

Figure 2 Warehouse Flows, 2023

Inbound flows are always considered business-to-business (B2B). In this section, there are different possible merchandising flows inside the warehouse: Pick by Store, Pick by Line and Long-Tail (LT).

Pick by Store: Products that came to stock. It may be a 701 product (large home appliances are always to stock) or a 708 product stored in high pallets. These products are required with no associated order. To distinguish the items that are supposed to follow this flow, it is used the white label, during receiving process, prior to provisioning items to stock storage areas.

Pick by Line: In contrast to PBS Flow, in PBL, there is the necessity of having a specific order for one product for it to be required by Worten to the supplier. Worten adopts a cross-docking strategy to deal with these items. Cross-docking is used when the stock is not held in the warehouse but in the supplier's facilities to save space and reduce costs. Although cross docking allows for a reduction in stock and space usage, storage is important to gain market share and fulfill the demand in a quick way.

When a PBL order arrives, it is supposed to be delivered within the following 24 hours. PBL products are signed with a yellow label, differing from the white label for PBS products. In PBL flow, the picker moves with the SKU and leaves the necessary quantity for each order. In this process, each picker satisfies several orders. To facilitate the PBL process, operators are assisted by a Pick by Voice system. With this system, employees are guided by voice throughout the picking process, confirming the correct picking or correcting the quantity through acoustic messages. This not only improves quality but also speeds up order picking. There is no need to keep the PBL items in stock, once the suppliers are considered to have a high service level, responding to the orders with the desired quantity of product with low lead times associated. Nonetheless, sometimes there are some exceptions when a PBL product must be stored – Pick by Line to Store (PBLS). It happens in exceptional circumstances, for example when an order is cancelled and the product is not distributed, remaining in the warehouse. Besides that, there are some items that Worten keeps in stock to efficiently fulfill the less predictable online orders. The racks where the PBLS products are stored are located near the conveyor of the online area. It is a way of speeding up their picking, since travel time from online area to storage location is reduced, and these products are usually held for short periods.

Long-Tail: LT flow deals with unpopular products that have unpredictable demand and are supposed to be kept neither in the warehouse nor in stores. These products are only sold through online channels. As with the PBL flow, there is the necessity of having a specific order for one product for it to be required by Worten to the supplier. Worten has access to information about the supplier's inventory and respective delivery times, which is used to manage the product information provided to customers. These are the pink-labelled products. These types of products are either stored on shelves, pallets, or alveoli. Usually, when one LT product is not sold for any reason, as a cancelation of the order, the product is changed to the slow-movers area.

Besides the three flows already mentioned, there is another one composed of “orange-labelled” products. This is a B2B flow for the direct sale to the customer company (for example, other retail companies that buy Worten’s own-brand products). It is a special case, not frequent, therefore it will not be further deepened in this dissertation.

Outbound Flow: The different picking methods used, as well as the processes of packaging, consolidating, and shipping, will be covered in the outbound flow.

Pick by Waves: An order-picking method called wave picking is used to increase picking productivity and efficiency. The management releases different waves accordingly with the distributor that will deliver the orders, i.e., there are different waves for products that will be delivered by different carriers. Teams can become more productive by cutting down on (or even eliminating) picker idle time. After the release of a wave, Worten adopts two main strategies of picking for the products that correspond to the PBS flow: bulk picking and batch picking. As previously explained, PBL products are processed with a cross-docking strategy. The picking method used for these products is bulk picking.

Bulk Picking: With bulk picking, one SKU is picked for all the stores it was requested. This method is mostly used for large items stored on shelves. The SKU is stored in its picking location and the picker moves with a forklift and an order with all the units needed for that SKU for all the stores. The separation of products by store only occurs later in the process, in the distribution zone of the Put to Store (PTS).

Batch Picking: Batch picking is the method carried out to pick 708 products, stored in the lower level of the racks - active picking locations. It requires an operator that uses an electric pallet truck with two pallets. Each pallet corresponds to a specific store and the operator follows a previously defined track, loading the pallets with the ordered items. Some products have permanent active picking locations because of the batch picking organization by volumetry. This organization, from the heaviest and biggest products to smaller and lighter ones, facilitates the process of building the pallet, increasing batch productivity. The pallets are then sent to the wrapping zone before moving on to the outbound docks.

Wrapping: Products from all the flows - PBS, PBL, Online & Complementary Service of Home Deliveries (SCED) - are prepared and wrapped in a wrapping zone close to the outbound docks. Pallets containing large-size products are usually wrapped with transparent film. Pallets with smaller products are wrapped in black film, so the products cannot be identified, for security reasons. The wrapping activity is mostly performed by machines.

After the wrapping process, there are two main points of control performed with Radio Frequency Identification (RFID) technology, before the shipping of orders:

1) Scan the boxes in each pallet- to ensure the boxes that must go to the same store are correctly placed together in the same pallets.
2) Scan the barcode of pallets - to check if they were placed in the right dock.

Distribution

Products that leave the warehouse may have different destinations, including Worten stores (B2B - both PBS and PBL flows) and final customers (B2C), through the HD service or Pick Up In Store process. Worten relies on third-party logistic companies to distribute its products.

There are three companies in charge of products delivery:

- Luís Simões – Is the Internal Operator (IO) responsible for distributing products to Worten stores with a delivery window the following day.
- CTT – Express Operator (EO1) that has an everyday route defined for HD products.
- DPD – As not all stores receive merchandise every day, DPD is the express distributor used to ship products to stores that do not have a delivery window the following day. It is an Express Operator (EO2).

There are also SCED and SCED PUIS Flows, which deal with big-sized home appliances that usually require installation services, such as fridges and washing machines. Totalmédia is the company in charge of SCED. SCED is used for HD products. SCED PUIS is used for products to be picked in-store, being performed by the Internal Operator, Luís Simões.

Products are positioned at the corresponding outbound dock in accordance with the distributor. An assigned vehicle will deliver the goods from each outbound dock, traveling along a predetermined route.

To cut down on transportation expenses, it is examined whether it is possible to combine the contents of different pallets into just one pallet when there are two or more pallets to be delivered to the same location. This process is called consolidation.

2.4.3 Warehouse Operations

Most of the operations take place in the central zone of the warehouse. There are four different zones that can be considered regarding the type of operation that occurs in each one of them: Put to Zone (PTZ), Put to Light (PTL), ONLINE and Put to Store (PTS). These operations and their organization in the warehouse central zone can be seen in Figure 3.

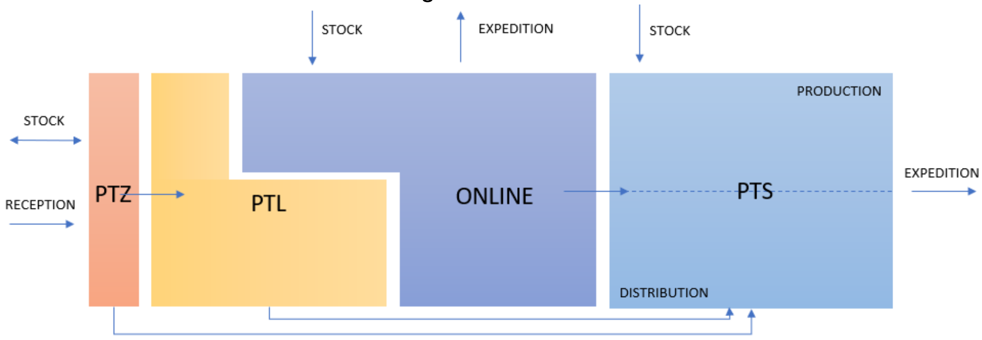

Figure 3 Main Warehouse Operations

PTZ: Firstly, products are separated accordingly to their volumes. Among the products <6L, there are three possible classifications: small products (PEQ), medium size products (MED) and big products (GRA). The ones with more than 6L advance directly to the distribution zone of the PTS. A manual pre-sorting of the 708 items classified as GRA occurs in the Put to Zone, while MED and PEQ products go to the PTL section. In this pre-sorting activity, products are allocated to one of six different totes, each one corresponding to a zone (and not a specific store). The PTZ allows making the preparation of orders in a more efficient way, contributing to reducing the travel times of the workers. Once the GRA products are sorted by zones, they go to PTL.

PTL: It is the system used to allocate the products to the store where they are supposed to be delivered. The operator receives the products and distributes them by boxes using light indicator modules integrated into shelves. The modules indicate whether the product should be placed to be distributed to that store or not, and in the affirmative case, the number of units required. The operator places the items accordingly and proceeds until the box is full. After this stage, the boxes are placed in the PTS zone.

PTS: The PTS area is where the boxes (having a physical store as destination) of the Online and Retail channels will be consolidated. It is divided into two zones: production and distribution. In the production zone are usually placed the 708 products that come from stock throw the bulk picking method. Here, it takes place the separation of these SKUs by stores. Products with a volume higher than 6L are also received in the production zone. In the distribution zone are the 708 products collected from the mezzanine, PTL Retail and PTL ONL. It is where the pallets are consolidated (if possible). Both the products that go to the store to be sold there and the ones that were already sold online and will be collected in-store (PUIS) are joined to be delivered in the same trucks.

Put to Wall (PTW): PTW is the strategy adopted to deal with multi-orders (orders composed of more than 1 product). When the first item of the order is picked, the operator leaves it in a "wall" until the remaining products of the same order are picked. Then, all the products are consolidated. Therefore, the order is only shipped once all the products are brought together.

Operations: Online Sector

There are three main aspects to consider regarding the orders processed in the online flow:

1) Order Type (mono-order or multi-order): when the order is composed of more than one product, Worten adopts the PTW order process.
2) Product size: 708 products are stored in either the 708 area or in the mezzanine, while 701 products may be coming from storage (in the 701 area) or may be received and distributed on the same day.
3) Carrier: HD orders are separated to be shipped either by CTT or DPD. PUIS orders are delivered by Luís Simões. For products to be delivered in-store, it must be considered the delivery windows of each store.

Figure (Appendix) represents the operations that happen in the online area. When an order is picked, it needs to be prepared. It is firstly packed in the packing stations near the conveyor. Both HD products and products to be picked in the store are labeled before going to the conveyor. HD products are packed in plastic bags which will arrive at customers' homes. Then, the operators put them on the conveyor. At the end of the conveyor, products are maintained on a rotating table until a worker sorts them in different totes, according to their destinations.

Currently, the totes near the accumulation table are allocated as follows:

- Four totes for different PTL sectors: each PTL sector contains several boxes representing a store to which the order must be sent. PUIS orders are delivered via Luís Simões.
- Three totes to receive the PUIS orders of stores that do not have a place in the PTL sector.
- Two totes to receive HD orders, delivered via CTT.
- One tote to receive HD orders, delivered via DPD.

This separation in totes allows optimizing the following process, which will take place in the PTL Online. There, PUIS orders are processed with the help of a PTL system. After being prepared and consolidated in a box in the Online PTL, the PUIS orders are sorted into one of four PTS sectors according to the location of the correspondent store in the PTS. HD orders go through a case association operation, where a pack is manually associated with a box that will be put on a pallet to be later shipped.

2.5 Problem Definition

Worten has been facing logistical challenges in its warehouse due to the increasing demand for its products, which has been driven by a rise in Spanish sales, online demand during the pandemic, and growth in marketplace sales. Additionally, Worten's strategy of expanding its range of products and services has resulted in a diverse inventory with different characteristics such as size, volume, stowability, and weight. Thus, the company’s stock has increased both in quantity of products and in terms of references stored. In Figure 4, blue bars depict product quantities, while the red line illustrates the progression of SKUs stored from January 2021 to June 2023. There is a rising trend in both cases. The highest quantity peak was observed in May 2023, and the maximum number of references was recorded in November 2022, during the Black Friday.

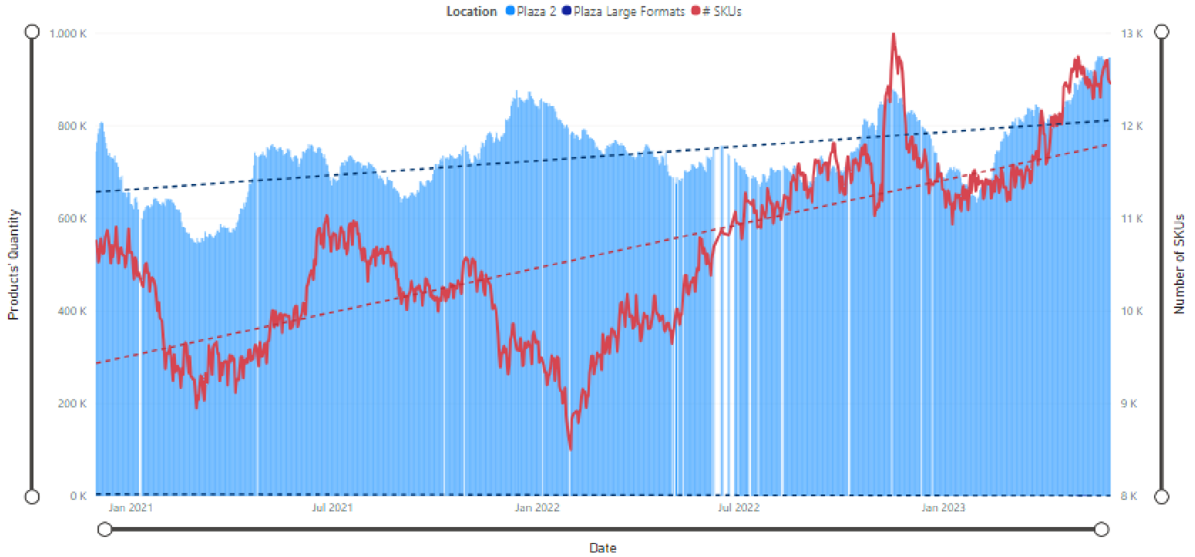

Figure 4 Evolution in the Number of 708 SKUs and Quantity of Products Stored (01/21 - 06/23)

The limited space in the warehouse has made it difficult to accommodate these products. Therefore, Worten aims to increase efficiency in the storage of products without investing in expanding the warehouse space. To address this issue, Worten plans to implement an automated storage solution that can increase the storage density (ratio of available storage area to total warehouse space) of 708 products. The main goal of this project is to assess the impact that the implementation of an automated storage solution would have in the warehouse.

The project aims to contribute to solving Worten's space management issue by studying different automated solutions that may increase the storage density and optimize the space utilization of the warehouse. It is intended to identify the products or families of products (according to their dimensions and weight) that are suitable for the proposed storage system. The project will also assess Worten's needs and business requirements for the proposed solution in order to analyze the feasibility of implementing such equipment. The main focus of the project is to analyze the impacts of the new system in the warehouse. It will be performed in different areas, such as space management, and systems' throughput. The most suitable solution for Worten’s reality will be proposed, and, finally, this solution will be compared with the expected scenario for 2025, regarding different key performance indicators (KPIs).

Chapter 3 – Literature Review

This chapter is divided into three subsections. The first subchapter regards broader concepts related to warehouses. For material collection, the keywords utilized in this subsection were warehouse, storage, design, put-away (and other possible designations for the same process as physical supply and inbound logistics), as well as different combinations of these terms. The second subchapter deepens the theme of warehouse operations. At the storage level, different storage systems that may be adopted are identified. As keywords, they were utilized: high-density storage, automated storage systems, and the names of each storage system studied. The last subchapter summarizes the main gaps found in the literature review, that this study intends to fulfill. For the entire literature review, the search procedure was managed in the Web of Science database, Google Scholar, and Ebsco.

3.1 Warehousing

Warehousing is traditionally defined as the intermediate storage of goods between two successive stages of a supply chain (Bartholdi & Hackman, 2016). A warehouse is a vital component of any supply chain (Custodio & Machado, 2020). Warehouses act as a node, linking product flows between suppliers and customers (Ramaa et al., 2012). In other words, warehousing makes it possible to decouple supply from demand, allowing the grouping of flows and products, and reducing transport costs (Zaerpour et al., 2017). Some of the basic functions of a warehouse are: receiving, storage, order picking, and shipping (Gu et al., 2007). Nowadays, warehouses are much more than a place to store products, as they may serve different functions such as consolidation, cross-docking, transshipment, product-fulfillment, reverse logistics for returned goods; or serve as centers for repairs and factory-outlet (Baker & Halim, 2007).

In terms of costs, they represent approximately 20% of total logistics costs (European Logistics Association & Kearney, 2004). Regarding service level, warehouses play a key role in achieving high customer service levels (Frazelle, 2016) because, besides the functions previously mentioned, a warehouse may be the final point in the supply chain for order assembly and value-added services (Baker & Halim, 2007; Ramaa et al., 2012). Some of these value-added services are: pricing, labelling, customization and kitting (Gu et al., 2007). Creating manufacturing postponement options also contributes to reducing inventory costs (Zaerpour et al., 2017).

With increased trade, the number of warehouses and the space used for warehousing has grown rapidly (Zaerpour et al., 2017). The main downside associated with warehouses is that they occupy much land and infrastructure. The land has become increasingly scarce, especially in cities, where most of the customers are located. The following subchapters develop different areas within this topic: warehouse design layout, operations, management, and performance measurement.

3.1.1 Warehouse Design Layout

Focusing on decision-making regarding design layout, three levels of decisions may be considered: strategical, tactical, and operational. The strategic level considers decisions that usually concern large investments, that have a long-term impact (5 years ahead). Main decisions at this level are the design of the process flow and the ones regarding the selection of the warehousing systems. On the tactical level, medium-term decisions are made, and influenced by strategic decisions. They typically concern the dimensions of resources and the determination of a layout design. Operational decisions are constrained by both the strategic and tactical decisions previously made. At this level, decisions regard the organization's policies (Rouwenhorst et al., 2000).

There are five major steps to consider when designing a warehouse: determining the warehouse structure; sizing and dimensioning the warehouse and its departments; determining the detailed layout of each department; choosing the equipment; selecting operational strategies (Gu et al., 2010). Table 12 (Appendix) summarizes different decisions to be performed at each level of decision for the different processes of a warehouse. These five design decisions are strongly interdependent. They are defined by Gu et al. (2010) as follows:

- Warehouse structure has a significant impact on the material flows, the functional department's specifications, and the flow relationships between departments. These process flow decisions are of a strategic nature.
- Sizing and dimensioning influence the overall size of the warehouse and the distribution of space across different departments.
- Department Layout refers to its detailed configuration.
- The choice of equipment problem addresses the type of storage and material handling systems to select and the degree of automation to be implemented.
- The operation strategy specifies how the warehouse will function, especially in terms of storage and order picking.

When deciding about the layout of a warehouse, it is important to keep in mind the type of warehouse that is being studied. Two types can be distinguished: the distribution warehouse and the production warehouse (Rouwenhorst et al., 2000). A distribution warehouse holds goods and completes orders from external customers, which are typically made up of numerous order lines. A quantity of one specific product is specified for each order line. Typically, there are many products and few products per order line (Rouwenhorst et al., 2000). On the other hand, a production warehouse has as main function to store raw materials, work-in-process, and finished products for a manufacturing and/or assembly process.

As this project is focused on a distribution warehouse, it is important to mention that this type is often optimized for cost-efficient order picking. Thus, it is aimed to maximize throughput, to be reached at minimum investment and operational costs.

3.1.2 Warehouse Operations

Between all the operations that can take place in a warehouse it is possible to highlight four: receiving, storage, order picking, and shipping (Rouwenhorst et al., 2000). Receiving is the first process to be executed. When products arrive, they are unloaded from the transport carrier, the inventory record is updated and the products may be inspected to check for quality and quantity (de Koster et al., 2007). Sometimes repacking activities also occur at this stage (Kamali, 2019).

The storage operation consists in placing the products in their respective storage location. Usually, two parts can be considered in the storage area. The reserve area, where products are usually bulk stored (most economical way), and the forward area where products are easily available to be picked, being stored in smaller quantities (Kamali, 2019; Rouwenhorst et al., 2000). The transfer of products from the reserve storage to the forward storage, when the pick storage drop to certain amounts, is called replenishment (Kamali, 2019; Rouwenhorst et al., 2000). Storage is a topic to be further developed in section 3.2.2 Inbound Operation's Impacts.

Order picking refers to the retrieval of products from their storage locations. It can be performed manually or automated (Rouwenhorst et al., 2000). If the product is transported to the picker, it is called a part-to-picker system. Otherwise, the picker has to travel to the storage location, in picker-to-part systems (Gu et al., 2010).

The last operation is shipping. At this point orders are checked, packed, consolidated and loaded to be distributed (Kamali, 2019). Orders and trucks are allocated to docks by a dock assignment policy (Rouwenhorst et al., 2000).

Besides the four operations mentioned, one also considers put-away, sorting and cross-docking. Put-away is the process of moving the incoming products from the unloading dock to the storage area (Kamali, 2019). Following the pick process, sorting takes place when chosen items need to be sorted by client order. Cross-docking is performed when the products are not supposed to be stocked. Instead, they are directly transferred to the shipping docks (de Koster et al., 2007; Kamali, 2019).

3.1.3 Warehouse Management

Warehouse management is a key part within the supply chain (Kamali, 2019), playing a vital role for an organization to success in any type of industry (Lam et al., 2009). Warehouse planning can be crucial to assure a smooth daily workflow through the supply chain (Aviso, 2023). Organizations consider inventory management as a key to achieve excellent service levels (Gallmann & Belvedere, 2011).

A warehouse may be characterized according to three angles: processes, resources, and organization (Rouwenhorst et al., 2000). Processes are the steps that occur inside a warehouse. Resources are the equipment and personnel needed to perform the processes. Organization includes planning and control procedures adopted by the organization. Both popular and scientific literature are paying more attention to subjects like planning and control (Rouwenhorst et al., 2000). Operational control includes processes such as: zoning, batching, and routing activities (Custodio & Machado, 2020).

The operating procedures of warehouses have seen significant changes throughout the years, pushed by the increased customer service standards; greater number of SKUs stored; necessity to improve space utilization and warehouse operating efficiency. In consequence, new automated technologies like very high-density storage systems are continuously receiving more attention. Automated methods proved to be beneficial in order to meet rising consumer demands and improve operational efficiency (de Koster et al., 2017).

One of the key elements to improve performance in warehouses is efficient management, which helps to raise the effectiveness of operations (Accorsi et al., 2014; de Koster et al., 2017). Therefore, it is crucial to comprehend the various warehouse operations as well as how to measure and quantify the warehouse performance. The next subchapter regards warehouse performance and suggests several KPIs. On the other hand, warehouse operations were previously explained in the section 3.1.2 Warehouse Operations.

3.1.4 Warehouse Performance

It is important to understand the drivers of service level to correctly manage performance, which is becoming more relevant as it influences customer decisions (Gallmann & Belvedere, 2011). Different KPIs concerning warehouse operations were identified and aggregated in three main categories: Order Fulfillment, Inventory Management and Warehouse Productivity (Ramaa et al., 2012).Order fulfillment includes measures as: on time delivery, order fill rate, order accuracy, etc. Inventory management encloses inventory accuracy and storage utilization. Warehouse productivity includes orders/lines/items processed per hour. Table 13 (Appendix) details all the measures of the three categories, as well as their definitions.

Most recently, the most popular operations performance indicators were distinguished in two categories: hard metrics (direct), and soft metrics (indirect) (Staudt et al., 2015). The first ones are quantitative measures provided by straightforward mathematical equations (as order cycle time) and the others are qualitative measures and compel complex formulation (as the perception of customer satisfaction). Indirect indicators consist, in many cases, of a concept measure, so direct indicators continue to be the basis for warehouse performance measurement (Staudt et al., 2015). Hard metrics include four dimensions of performance indicators: time related, quality related, cost related, and productivity related (Baruffaldi et al., 2020). In Table 1 are presented the different indicators that may be considered in each category.

Other classifications were found in the literature. Kusrini et al. (2018) classified the indicators into five groups: financial, productivity, utilization, quality, and cycle time. Nantee and Sureeyatanapas (2021) consider only three classifications, according to the three pillars of sustainability: social, environmental, and economical (Table 14-Appendix). In the same way, other indicators were employed for the evaluation in this same study, such as error rate, productivity, efficiency, and simplicity of the work processes.

Table 1 Performance Indicators According the Four Dimensions | Adapted from: Baruffaldi et al. (2015)

Dimensions	Indicator name
Time	Order lead time; Receiving time; Order picking time; Delivery lead time; Queuing time; Put-away time; Shipping time; Dock-to-stock time; Equipment downtime
Quality	On-time delivery; Customer satisfaction; Order fill rate; Physical inventory accuracy; Stockout rate; Storage accuracy; Picking accuracy; Shipping accuracy; Delivery accuracy; Perfect orders; Scrap rate; Orders shipped on time; Cargo damage rate
Cost	Inventory cost; Order processing cost; Cost as % of sales; Labor cost; Distribution cost; Maintenance cost
Productivity	Labor productivity; Throughput; Shipping productivity; Transport utilization; Picking productivity; Inventory space utilization; Outbound space utilization; Receiving productivity; Turnover

As this project focuses on the impacts observed in the warehouse, it is important to analyze Table 15 (Appendix), that establishes the relation between indicators and activities (Staudt et al., 2015). The category "Inventory" is considered by the author as the point in between inbound processes (receiving and storage) and outbound logistics (picking, shipping, and delivery). Kusrini et al. (2018) concluded that the most important KPI for receiving and shipping is productivity, for put away and picking is the cycle time, and for storage is utilization (location and cube percentage occupied). These metrics will be approached in section 6.2 Scenario 0 Vs Proposed Scenario.

Most articles concentrate on the performance evaluation of relatively clean, isolated systems, instead of focusing into an overall design model (Rouwenhorst et al. 2000). Recent studies mention this gap, emphasizing the value of considering practical and holistic models composed of picking workstations, conveyors, and storage systems rather than only addressing the element in isolation (Azadeh et al., 2019; Boysen et al., 2019). It would enable a more thorough study by allowing for a cohesive view of the entire warehouse process. For instance, shuttle's related articles primarily focus on storage systems without considering downstream pick performance, while the literature on RMF systems primarily focuses on design issues rather than operational policies that integrate the various processes (Azadeh et al., 2019). The authors add that to account for variations in the receiving and picking throughput needs, which change over time, it is essential to consider interactions between upstream and downstream processes. Table 15 (Appendix) shows that outbound logistics is more explored in the literature, which is reflected in the higher number of KPIs presented. The empty spaces mean that none of the analyzed papers by Staudt et al. (2015) has reported an indicator related to the respective activities. This confirms the previous statement of Gu et al. (2007) that "the research on receiving is limited".

3.2 Automation in Warehouses

Nowadays, in a rapidly changing world, industries' operations are exceedingly complex (Lam et al., 2009). Market conditions have been changing over the years. Just-in-time philosophy promoted a change from high volumes of few SKUs to small orders of a wide range of products. Warehouse Managers are realizing that the manual resources have reached the limits of their productivity levels. The literature indicates that automation allows to achieve the necessary throughput at high levels of speed and accuracy, whilst maintaining costs at an acceptable level (Baker & Halim, 2007). Therefore, to conserve profit margins and increase quality requirements, automated systems have been adopted (Custodio & Machado, 2020; Yamazaki et al., 2017). Moreover, the increase of e-commerce, mass customization, and omnichannel distribution are other factors pointed out as the main drivers to automate the warehouses (Custodio & Machado, 2020). The global need for automation systems in such market conditions is reinforced in several other papers (Custodio & Machado, 2020; Yamazaki et al., 2017).

An important concept related to the automation of warehouses is "Industry 4.0". It emerged in 2011 and refers to the fourth industrial revolution (Edouard et al., 2022). Recent investigations have been conducted on the application of Industry 4.0 in warehouses and automation is one of the nine technological groups in which this application is studied (Edouard et al., 2022). The biggest difference between automatized warehouses and the traditional ones is the fact that in an automized warehouse the manual intervention is reduced as much as possible, to improve processes' efficiency (Kamali, 2019; Zaerpour et al., 2017). In an automated warehouse, a number of programmed instructions converts manual processes in automatic ones (Custodio & Machado, 2020).

The disadvantages associated with traditional warehouses were identified in a study where a traditional warehouse was compared to an automated one (Kamali, 2019). Some of the mentioned disadvantages were over-handling material, that represents a cost of employee time and, consequently, companies' money; damaged materials due to human accidents; inefficient materials handling equipment; inefficient space management, with only around 30% of storage space being used to effectively store products. On the other hand, automated systems allow to reduce the storage space, which is important due to the increasingly limited availability of land (Deng et al., 2023). New smart technologies can work 24/7, and efficiency can be up to four times higher than manual work (GEEK+, 2018). There are several new innovations in automated warehousing systems and technologies that allow to achieve an increase in throughput rates, contributing for the operations to become cost-effective (de Koster et al., 2017; Ramaa et al., 2012). The effects of adopting these technologies are reflected in higher customer service levels and reduced lead times (Ramaa et al., 2012). The need to accommodate growth was identified as the main reason for companies to adopt automated systems (Baker & Halim, 2007).

The lack of flexibility and the high initial investment are the most common reasons of resilience when it comes to implement automated systems (Custodio & Machado, 2020). Nevertheless, its implementation continues to rise, even considering that the demand is becoming increasingly volatile (Baker & Halim, 2007). Despite the initial investment, new technologies could lead to a reduction of up to 30% in the operations costs in just a few years. Losses in inventories can be reduced up to 75%, and the operations become more agile and efficient (Kamali, 2019). The market size of Automated storage systems (ASS) is growing, and it is projected to reach around US$ 13000 million by 2027 (Korad & Rake, 2020).

To conclude, automation level is increasing in warehouses to satisfy market conditions and automated warehouses are evolving into more flexible storage systems to respond to market alterations (Custodio & Machado, 2020). Therefore, several organizations, such as Amazon, have been on the forefront of smart warehouses adoption (Kamali, 2019). In the following subsections, different types of automation will be discussed, as well as their respective impacts on different warehouses' processes.

3.2.1 Storage

Storage is the process of moving products from the offloading area to the storage area (Sangsane & Vanichchinchai, 2021). It is concerned with the organization of products kept in the warehouse to achieve high-space utilization and facilitate efficient material handling (Gu et al., 2007). Every warehouse adopts one or more storage assignment methods. A storage assignment method is a "set of rules which can be used to assign products to storage locations" (de Koster et al., 2007). There are three main storage policies: random storage, dedicated storage and class-based storage (Gu et al., 2007). In the random storage policy, products are randomly assigned to the warehouse available spaces. The decision is left to the operator (Rouwenhorst et al., 2000). This strategy has as its main advantage the low aisle congestion and the higher space utilization (Petersen, 1999). However, it is naturally harder to locate an SKU during the picking operation (Sangsane & Vanichchinchai, 2021). On the opposite side, a dedicated storage method allows for faster picking of a product, by assigning a specific storage location to each SKU (Bektas & Korkmaz, 2015; de Koster et al., 2007). Compared with the random storage policy, the space utilization is lower, due to the impossibility to store different products in a certain dedicated area. The third method, the class-based storage, can be considered a combination between the other two, storing products considering their classes (Wang, 2020).

There are different ways to classify products in classes. Two widely used methods are the ABC analysis and cube per order index (COI). In ABC analysis, products are divided according to their turnover rate, or popularity, for example (Rouwenhorst et al., 2000). In this analysis, "A" is used for fast-moving products, "C" for slow-movers and "B" for the products in between. COI consists of a ratio between the products' storage space requirement and its popularity-defined as the number of storage/retrieval operations per unit time period (Frazelle, 2016). Products with lower COI (smaller products with higher popularity) are stored in the most accessible locations (Gu et al., 2007; Malmborg & Bhaskaran, 1990). The COI policy has been extensively studied in the literature and is considered the most effective policy, from the three mentioned ones. Goods are assigned to storage locations within a department or zone, and the storage location assignment significantly affects storage capacity, inventory tracking, and order picking (Gu et al., 2007). Three main questions that should be addressed regarding storage are distinguish by Gu et al. (2007):

1) How much inventory for each SKU should be held in the warehouse?
2) How often and at what time it should be replenished?
3) Where should the SKU be stored and moved among the different storage areas?

When discussing storage solutions, it essential to address the notion of high-density storage. High-density storage systems are defined by the occasional need to move interfering items to reach the desired ones. The primary benefit of these systems lies in their high space utilization efficiency. However, it may take longer to retrieve the desired products (Gue, 2006).

3.2.1.1 Traditional Methods of Storage: As-Is System

In this subsection, the methods currently used in Worten's warehouse will be described. Its respective images can be consulted in Figure -38 (Appendix).

Drive-In Racks

With this type of system, pallets are stored on rail beams, one after the other, with no space between them. Thus, drive-in racks require less floor space than traditional racks (Gilbert & Rasmussen, 2011).

It is a dense storage system, suitable for product lines with high stock levels (Rushton et al., 2014). With the increasing price of land, drive-in racks are often a more economical solution than traditional racks when storing the same goods (Gilbert & Rasmussen, 2011). DIN are generally built up to about 11 meters in height and to about six pallets deep, although they can be deeper, resulting in a complex slender structure (Rushton et al., 2014).

The forklift truck drives into the rack and carry the pallets at the height at which they will be held. Pallets can be stored on the floor or on the metal flanges with last in, first out (LIFO) principle. The main drawbacks of this systems are that the travel speed within the racks tends to be slow and it suffers from low utilization of the pallet positions - only about 70% (Rushton et al., 2014).

Adjustable Pallet Racking System (APR)

The most popular type of racking, APR, is broadly utilized in warehouses. These steel constructions are made up of vertical elements (uprights), horizontal (rear beams), and sloping (diagonals). The rack structure is referred as "adjustable" because it is possible to connect the shelves to different heights of the supporting members. Pallets are stacked single-deep onto the horizontal beams. Beams are fixed to vertical frames. The uprights of the frames are bolted to the ground (Rushton et al., 2014).

APR are typically set up with one rack against the wall and then double racks accessed from aisles on each side. Typically, three Europallets (80x120 centimeter dimension) are stored in a single bay, between the uprights (Rushton et al., 2014).

The main advantage of single-deep APR is that the pallets can be accessed directly. It is suitable to store few pallets per SKU. Individual access also helps to prevent the honeycombing effect, making it simple to reach pallet location utilizations of 90 to 95% (Rushton et al., 2014). Honeycombing occurs when there are empty locations that cannot be used, resulting in a waste of space. Manual pallet racks are considered the cheapest systems when the storage capacity and throughput are low (Zaerpour et al., 2017). However, when compared to denser storage systems (like DIN), floor usage is poor. The racking is versatile and can be adaptable to accommodate various types of loads (Rushton et al., 2014).

Narrow-Aisle Racking System

Consists of a racking system with narrower aisles than those needed for reach truck operations, used in a traditional racking system. Therefore, aisles must be supplied by specialized trucks, so they can reach a reduced length of 1.8 meters or less. There is no need to turn in the aisle because the forks on these trucks are extendable from the side. Pallets may be removed from either side of the aisle. Narrow-aisle trucks can have a lift height of about 14 meters, nevertheless, are more expensive when compared to reach trucks. A wire-guidance system, which consists of a wire embedded in the floor and sensors within the vehicle, directs the trucks through the aisles (Rushton et al., 2014). The larger height of storage and the denser footprint obtained with the narrow aisles, allow for a higher storage occupation than the one obtained with regular racks (Rushton et al., 2014).

Mezzanine

Warehouse mezzanine systems are elevated platforms constructed between the industrial facility's ceiling and floor. They feature staircases that lead to different floors or to the top of the mezzanine (O'Neill, 2023). A mezzanine can be customized to meet the exact needs and space demands of each warehouse (Parisi, 2023).

A warehouse mezzanine system allows storing items at the floor level as well as above, optimizing the vertical dead space, by roughly doubling the storage capacity of the available floor space. As a result, it is a cost-effective way to increase the available storage space in facilities with high ceilings (O'Neill, 2023).

Some other advantages of this flexible solution are the fact that it does not require to redesign the existing warehouse area, it allows for a better inventory control, and is a smart way to assure accessible inventory while also maintaining literal oversight (O'Neill, 2023). The fact that a mezzanine can be complemented with other storage solutions is another benefit (Alphalogic Industries Limited, 2023).For instance, some mezzanine systems also use shelving or racking systems (Parisi, 2023).

3.2.1.2 Automated Storage Options

The Literature Review on the automated storage options available was primarily based on the paper "Robotized and automated warehouse systems" (Azadeh et al., 2019), where several automated systems are explored, as demonstrated in Figure (Appendix).

From these systems, only the high-density storage ones that could be suitable for the case study were selected to be further discussed. The truth is that automated storage systems have become the basis of warehouse logistics. They are key components of automated warehouses due to the high throughput and storage capacity (Lewczuk, 2021).

Thus, some high-density automated storage systems will be presented and analyzed. The study will be focused on automated storage and retrieval systems (AS/RS), where they are included AS/RS with forklifts/cranes; shuttle systems (both Aisle-based and Grid-based), and Robotic Mobile Fulfillment Systems (RMFS).

AS/RS are nowadays considered as a solution from Industry 4.0 (Edouard et al., 2022). AS/RS are "a combination of equipment and controls which automatically handle, store and retrieve materials with great speed and accuracy" (Manzini et al., 2006). It is intended to determine the potential of different types of AS/RS to meet the warehouses' challenges. Their ability to optimize available surfaces by densifying stocks in limited spaces is documented in the literature (Edouard et al., 2022) and is particularly important in the present project.

In a general way, Automated Storage Systems (ASS) bring many advantages as the reduction in human involvement in storage and retrieval processes, the possibility to lower labor costs, increase safety and productivity and speed up processes (de Koster et al., 2007; Hu & Chang, 2010). McKinsey Global Institute estimates that the transportation-and-warehousing industry has the third-highest automation potential of any sector (Dekhne et al., n.d.).

The bibliographic sources utilized to evaluate the various systems are listed and detailed in Table 2.

Automated Storage and Retrieval Systems with Cranes or Forklifts

AS/RS with cranes/forklifts (Figure 5) are parts-to-picker systems, introduced in the 1960s. They have already been extensively studied in the literature. AS/RS is defined as a system that performs storage and retrieval operations with speed and accuracy based on automated equipment (Manzini et al. 2006).

Figure 5 AS/RS with Automated Forklifts | Source: https://adaptecsolutions.com/automation/asrs-cranes/

This system can sort, sequence, buffer, and store a wide range of items with high accuracy and efficiency (Yu et al., 2017). AS/RS reduces labor requirements and avoid capital expansion by exploiting unused vertical space (Custodio & Machado, 2020).

A conventional AS/RS is composed of storage racks erected along aisles with cell conveyors, input/output (I/O) stations for receiving and shipping items, and storage/retrieval machines to transport products between I/O stations and storage cells (Custodio & Machado, 2020). The storage/retrieval machine may be a stacker crane or a forklift. It is installed in the picking aisle for reaching the storage cells. The stacker crane/forklift can travel simultaneously in the vertical and horizontal directions to store and retrieve products. Conveyor systems are another key component of AS/RS, supplying and receiving units from it (Hu & Chang, 2010; Lewczuk, 2021).

To perform a storage operation, a crane picks up a load from the conveyor, and stores it in the racks. A rack may reach up to 40 meters high (Azadeh et al., 2019). The retrieving process occurs in the reverse way. It is suitable for a scenario of low variety of loads and high throughput requirement (Custodio & Machado, 2020; Hu & Chang, 2010).

There are three classes of AS/RS, according to the weight and size handling characteristics of the loads: (i) Unit-Load AS/RS - stores pallets, (ii) Miniload AS/RS - stores totes, and (iii) Carousel AS/RS (Shivanand et al., 2006). Carousels are AS/RS in which shelves are linked together and rotate (horizontally or vertically) in a closed loop (Azadeh et al., 2019). This type will not be further explored. Literature mentions as main drawbacks the fact that the throughput capacity of AS/RS is constrained because only one crane/forklift is responsible for handling loads at all vertical levels within a given storage aisle (Azadeh et al., 2019).

Regarding Miniload AS/RS, they are used for totes' manipulation. Miniload AS/RS systems have several advantages, as a good utilization of warehouse space, reduced number of damaged and lost items, good storage and retrieval control, and reduced labor costs (Lerher et al., 2021).

Shuttle-Based Storage and Retrieval System (SBS/RS)

SBS/RS (Figure 6) was first introduced in 1990s by Savoye Logistics (Azadeh et al., 2019), and it is characterized by using shuttles to operate in X and Y directions (horizontal movements) on any level in the aisle, and lifts to operate the vertical movements (Z direction). Lifts move products/totes/pallets between different levels (Azadeh et al., 2019; Fukunari & Malmborg, 2009; Zaerpour et al., 2017). Although diagonal shuttles already exist, their use in modern warehouses is still scarce. In addition, this system has limited research in the literature. Therefore, they will not be considered in this project.

This system stores products in multitier storage racks. These racks are separated by orthogonal aisles where the lifts operate, moving the products between tiers. The horizontal moves occur within the tiers. To retrieve a product, the shuttle moves to its storage location, picks it, and moves it to the lift. Then, the lift moves to the lower level and leaves the product in a conveyor to be transported to the pick station. There are two different types of SBS/RS Systems:

- Tier-captive System: if each shuttle is allocated to a specific tier and is not transported by the lift.
- Tier-to-tier System: if the lifts carry both products and shuttles, allowing the same shuttle to move between different tiers. It allows for a reduction in the necessary number of shuttles.

Despite operational flexibility, if one shuttle breaks down in the tier-captive system, no SKUs of that tier can be stored or retrieved. In the tier-to-tier SBS/RS this does not happen, since each shuttle can reach any tier of the storage rack (Zhao et al., 2020).

As in conventional AS/RS, there are Unit-Load shuttles - for pallets - and Miniload shuttles – for totes. They can also be classified as single-deep, double deep or multi-deep.

Figure 6 SBS/RS Miniload | Source: https://www.conveyco.com/blog/automated-storage-and-retrieval-types/

Their required investment is similar to that of AS/RS with cranes/forklifts, but they offer a higher retrieval capacity. Another benefit, when compared to conventional AS/RS is its flexibility. It allows to change the number of shuttles being utilized, to change the capacity of the system. Thus, the vehicle fleet size can be adapted in response to variations in the demand, for example (Edouard et al., 2022). On the other hand, while SBS/RS systems are more adaptable in terms of throughput capacity, travel patterns in traditional AS/RS are generally more efficient within storage racks (Fukunari & Malmborg, 2009).

Grid-Based Shuttle Systems: Live-Cube Compact System and Robot Based Compact Storage and Retrieval System (RCSRS)

This system is a variant of the SBS/RS in which shuttles move on a grid. Grid-based systems may be dynamic (puzzle-based) or static. This project will focus on two dynamic systems: RCSRS (Figure 7), and Live-Cube Compact System (Figure 8).

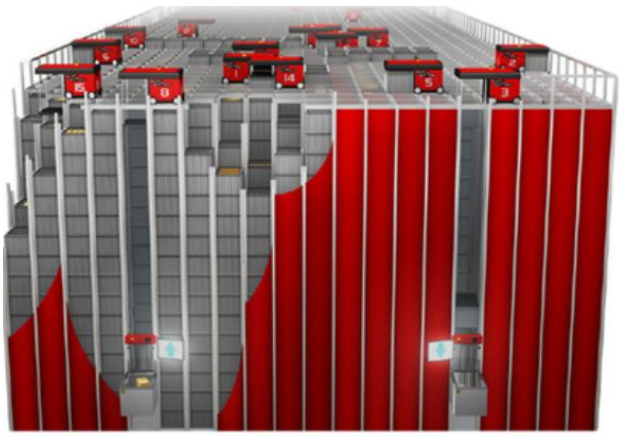

Figure 7 RCSR System | Adapted From: Zou et al. (n.d.)

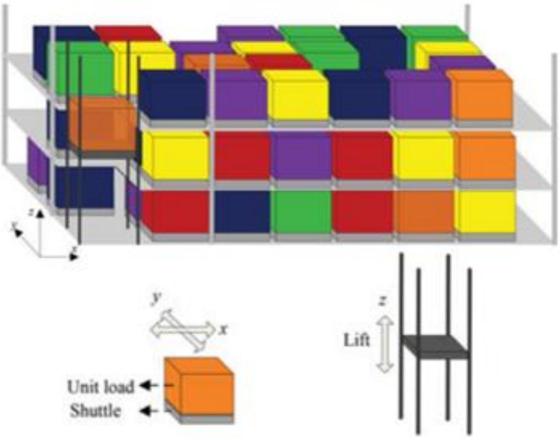

Figure 8 Live-Cube Compact System | Adapted From: Zaerpour et al. (2017)

Live-Cube Compact Systems consist of a multilevel puzzle-based storage method that enables to store product up to the height of the warehouse (Azadeh et al., 2019). In this system, a lift transports the shuttles between different levels of grids, until they reach a depot (Azadeh et al., 2019; Zaerpour et al., 2017). In each grid, the process can be described as follows: products are stored in a grid with at least one open location. To retrieve an item, an open location is first moved next to the requested product, through a set of movements between full locations. Then, an open location is used to move the item to the I/O point. To store a product, the procedure occurs backward. When multiple empty locations are available on a level, shuttles can cooperate to create a virtual aisle for a faster retrieval. This system allows for a high efficiency of occupation, as the height is used to the fullest. It does not require travel aisles as a conventional AS/RS, for example (Zaerpour et al., 2017). Usually, there are enough empty spaces to set up a virtual aisle for moving a required load to the lift without interfering with other loads, which reduces the retrieval time while not prohibit a potentially high utilization of the system. If the movement path is straight, block movement - moving many loads at once - is feasible (Zaerpour et al., 2017). The major drawback is that the physical layout cannot be changed easily. It is not a flexible solution, which may be problematic in case of high variations in demand or increase in sales volume, in the long-term. Besides, all storage locations are standard and must have the same size.

Another type of grid-based system is the RCSRS. It is a most recent technology that was firstly explored in 2016 (Zou et al., 2016). It is an order-picking system, where robots transport and store products, that are kept in a grid-topped, dense storage stack. Plastic totes that contain the items are placed on top of each other, forming the storage stacks. The workstations are located at the lowest level next to the storage stacks (Azadeh et al., 2019). Each cell of the grid corresponds to the entrance of a storage stack. The lifting-capable robots roam on the grid and extract totes from the storage frames. Totes are then transported to the workstations (Zou et al., 2016). The robot must reshuffle the stack to collect a tote that is not at the top. A tote, on the other hand, is always placed on top of a storage stack (Zou et al., 2016). It is a system suitable for small and light products (Edouard et al., 2022). An advantage, when compared with the Live-Cube Compact System, is that its layout is easily changed. This system has outstanding throughput capacity and have seen many implementations in recent years, particularly in e-commerce retailers (Zou et al., 2016).

Robotic Mobile Fulfillment Systems

This system is composed by autonomous guided vehicles (AGV) capable of following prescribed paths (Custodio & Machado, 2020). RMFS (Figure 9) are automated, parts-to-picker storage systems that were developed in 2003, and nowadays are a wholly owned subsidiary of Amazon. Recently, it has been an increasing in the utilization of AGVs in warehouses (Wurman et al., 2014). They are composed by three main parts:

- Robotic drive units: robots that transport inventory pods to the workstation.
- Inventory pods: movable shelf racks utilized to store the products.
- Workstations: areas where operators realize pod replenishment, picking and packing activities.

RMFS make use of robots (drive units) to lift and carry movable shelves to retrieve the storage pods from the storage area and transport them to the pick stations. When an order is placed, it is assigned to a workstation and then the product is assigned to a pod and a robot. The robot moves, without load, towards the pod to retrieve it. Empty robots can move underneath the pods standing in between the right one. Once the robot lifts the right pod, it must be transported using the travel aisles. The robot brings the pod and enters a workstation buffer and queues for its turn. Then, the robot stores the pod back in the order pick area. Each workstation has one worker that picks products from the pod and then adds them to the order totes (Azadeh et al., 2019).

After the picking, the robot returns the pod to a storage location and drives to the next pod. Once all the products of an order are retrieved, that order leaves the system and another one can be assigned to that workstation (Azadeh et al., 2019; Lamballais et al., 2017; Nigam & Roy, 2014). This system is gaining interest over the years for e-commerce fulfillment (Nigam & Roy, 2014), because online retailers usually have large assortments of small products, with strong demand fluctuations (Lamballais et al., 2017). Their demand consists of multiline small quantity orders.

Figure 9 Amazon's Autonomous Mobile Robot | Source: https://www.zdnet.com/article/amazon-builds-its-first-fully-autonomous-mobile-robot-for-warehouses/

Some authors pointed out AGVs as the ideal technology to use in a warehouse due to its flexibility (Custodio & Machado, 2020). AGVs can be quickly reprogrammed to change their tasks or the path of operation, eliminating the need for expensive physical equipment installation and enabling changes to respond to demand variations (Azadeh et al., 2019). It is flexible in throughput capacity as well since the layout is not static. It can be adjusted by adding more pods, storage locations, robots and workers (Lamballais et al., 2017). Other advantages of using an AGV, highlighted by Custodio and Machado (2020), are their efficiency, precision and safety.

The main disadvantages mentioned in the literature are the possibility for delays at aisle intersections to occur due to either battery recharges or robot downtime, as well as the robot congestion or blocking in aisles that may occur for more complex systems (Lamballais et al., 2017). Moreover, sometimes the storage area does not contain a single pod with sufficient units of a product to satisfy the incoming order line. When it happens, it is necessary to utilize more than one robot to retrieve more than one pod to fulfil the order, which is an inefficient process. Lastly, acquiring a RMFS typically requires a multi-million-dollar investment, most of which is used to buy the robots (Lamballais et al., 2017).

3.2.2 Inbound Operations' Impacts

First, it is crucial to define the concepts of inbound and outbound logistics. Inbound logistics encloses the operations that concern both the transportation of materials and their storage, whereas outbound logistics includes the activities related to outbound warehousing tasks, transportation, and distribution. As a result, receiving and storage activities are considered part of the inbound processes, whereas picking, shipping, and delivery activities are covered by outbound logistics (Staudt et al., 2015).

Beyond space optimization, by densifying product storage, ASS are known to influence other warehouse's areas. They provide employees with more ergonomic workstations, faster processing times, and flow traceability (Edouard et al., 2022). Most studies found it relevant to concentrate on order picking and storage. ASS has been recognized as a viable option to address both processes, among the various technological solutions available in the market. The studies found in the literature, both related to inbound and outbound logistics, will now be presented.

Nantee and Sureeyatanapas (2021) discuss the advantages of inbound logistics, citing the elimination of manual lifting during put-away and picking. Put-away is a key activity that significantly affects warehouse performance (Lam et al., 2009). It entails the process of matching the storage item's and storage location's properties (Custodio & Machado, 2020; Lam et al., 2009). To reduce material handling costs, product damage, and order cycle, personnel in a traditional warehouse must be proficient in the characteristics of incoming products and storage position (Lam et al., 2009). With an automated storage solution, the product is stored in the proper spot on its own.

Automation technologies appear to have a highly positive influence on the implementers' financial health. Thus, empirical evidence supports the logistics 4.0 literature's praise of ASS and WMS for their advantages in terms of productivity, resource utilization, operational accuracy, responsiveness, and financial outcomes. WMS is a software that helps to efficiently manage and control warehouse operations. By increasing process effectiveness, operating costs can be decreased (Nantee & Sureeyatanapas, 2021).

Lewczuk (2021) was one of the few studies founded that explored the impacts in the inbound logistics (namely put-away time), as most of the studies focus on outbound processes. It studied the impacts of the variation in the number of cranes (2, 5, 7, 10) and conveyors (1-2) of a traditional AS/RS in different parameters: average put-away time, average retrieval time, number of units handled in a given time and number of delayed units. According to the study's findings, the number of cranes that are used in the system has a direct impact on the average put-away time. Due to the lack of a crane in the corridor and the necessity of moving it between corridors, unit put-away periods when two cranes are used range from 20 to 25 minutes. Conveyor system congestion results from this. The access time is decreased by increasing the number of stacker cranes (to 5, 7, and 10 respectively), placing it between 1.5 and 3 minutes. For five cranes, the congestion is not visible. The put-away time is decreased by using two conveyors when there are only a few stacker cranes, but not considerably when there are five or more cranes. The same study concludes that efficient resources assigned to AS/RS will increase plausibility of immediate put-away and retrieval – dependability but cost more. Inbound processes will affect the execution time of outbound processes. The next section focuses on this second type of processes.

3.2.3 Outbound Operations' Impacts

An AS/RS is frequently a crucial component of the picking system, which has an impact on how outbound procedures are organized. It establishes the warehouse's buffer capacity (Lewczuk, 2021). This method decreases the need for labor (Custodio & Machado, 2020), which will free up workers to conduct jobs that add value but still need for judgment and expertise from individuals (Nantee & Sureeyatanapas, 2021; Yamazaki et al., 2017). It can efficiently and accurately sort, sequence, buffer, and store a variety of products (Ying et al. 2017).

Numerous studies have shown the effects of implementing automated storage systems in outbound logistics. For instance, a recent study on AS/RS (Nantee & Sureeyatanapas, 2021) found that the system's implementation in two different warehouses, in conjunction with a WMS, sped up and simplified both inbound and outbound processes, mentioning in particular the picking and storing processes. Additionally, it made product tracking easier and decreased human error, increasing warehouse productivity. The number of accidents decreased, as did the number of work-related accidents and occupational illnesses in the warehouses. The systems also increased the efficiency of space and equipment utilization. In terms of space usage, AS/RS allowed for a more effective use of vertical space and eliminated the need for wide aisles, for forklifts, and sorting areas. According to one manager, it had the potential to increase space utilization by up to 30% (Nantee & Sureeyatanapas, 2021). The same study shows that picking and storage accuracy have improved, while product damage and loss have decreased. Since a storage and retrieval machine's handling equipment could be modified both horizontally and vertically to accommodate different product and package sizes, using one as opposed to forklifts also minimized product damage and loss (Nantee & Sureeyatanapas, 2021). Because AS/RS required less time to pick and store products, both warehouses reported a reduction in the order cycle. The ability to change its movement speed as well as the function of partial picking reduced the amount of unnecessary work procedures (Nantee & Sureeyatanapas, 2021).

AS/RS supply the dynamic order picking system with required products. Additionally, it is utilized to buffer homogeneous units directly from delivery and releases units outgoing directly to customers. The remaining parts of the warehousing process will therefore be impacted by delays in put-away (inbound logistics) or retrieval of units by AS/RS (outbound logistics) (Lewczuk, 2021). AS/RS are the automatic solutions around which the warehouse process is built-in or which directly feed high-efficient order-picking or production systems (Lewczuk, 2021). Picking efficiency in AS/RS is impacted by the proper storage assignment (Lewczuk, 2021).

Regarding the parts-to-picker systems, it was proved that bringing the inventory to the picker instead of the picker traveling to the inventory can double the picker productivity (Wurman et al., 2014). Due to its tendency to be either exceedingly labor - or capital-intensive, order picking is acknowledged as the most expensive process (Gu et al., 2007). Order pick costs can account for up to 55% of operating expenses (de Koster et al., 2007).

After researching AGV technology, Nigam and Roy (2014) concluded that the system enhances worker pick conditions and lowers order pick inaccuracies because picker travel is reduced. In manual picking systems, much nonvalue added time is needed by the pickers to travel along the aisles (Azadeh et al., 2019). A great benefit of the AGVs system regarding the picking operation, for instance, is its “dynamic layout reorganization”. Regarding the sorting operation, ASS can also increase its efficiency. Sorting is required when multiple orders are picked together. It can be performed either during the picking process (sort-while-pick) or after the picking process (sort-after-pick) (Gu et al., 2007). It is not mandatory for a pod to remain in one spot during the day. The system may autonomously sort inventory during operations and adjust to fluctuating demand in the near term by shifting the placements of the pods (Lamballais et al., 2017). Even during times of strong demand variation, the often-requested pods are gradually moved closer to the workers. On the other hand, the ones that are less requested are gradually pushed farther from the picking stations, toward the back of the aisles (Nigam & Roy, 2014). It helps shorten the picking time and effort.

3.2.4 Summary of Automations References

Table 2 contains the articles consulted to collect the information regarding the automated systems and operations’ impacts approached in the previous sub-section 3.2.1.2 Automated Storage Options.

The articles are organized by year of publication. Being a recent topic, most of the articles have been published since 2019. The earliest articles (those published before 2016) were mainly utilized to describe each technology and its origin, while the most recent ones (those published after 2017) revealed the most recent advancements in each field of study. The column “Case-Study” is filled with “YES” when a real case study is explored in the respective article, and “NO” otherwise. The table also shows the systems explored in each article, as well as the main research issues, KPIs analyzed and impacts (either upstream or downstream ones).

Table 2 Consulted Articles Characterization

Title	Authors	Year	Case Study	Storage Solution	Methodology	Research Issue	KPIs Analyzed	Impacts
"Design and control of an AS/RS"	Manzini et al.	2006	NO	AS/RS with cranes	Dynamic multi-factorial analysis	Impact of alternative design and operating configurations on the expected performance. Identify critical factors affecting the response of the system.	Throughput capacity; operating costs; position of I/O area	Storage; Picking
"A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems"	Fukunari and Malmborg	2009	NO	SBS/RS	Network queuing approach	Introduce a new analytical modelling approach for estimation of SBS/RS system performance based on the design variables driving most of the initial system cost.	Expected resource (vehicle and lifts) utilization; cost; space requirements; expected cycle times	Storage
"An innovative automated storage and retrieval system for B2C e-commerce logistics"	Hu and Chang	2010	NO	AS/RS with cranes	Meta-heuristic algorithm (ACV)	Effects of three-dimensional velocity and rack shape. Compare a typical S/R system with the AS/RS and make recommendations for practical applications.	Setup costs; risk of goods damage; system complexity	Sorting
"Analysis of class-based storage strategies for the mobile shelf-based order pick system"	Nigam and Roy	2014	NO	RMFS	Multi-class closed-queueing network	Evaluate the MSOP system with class-based storage with two pod storage policies within the zone: "random open location storage" and "closest open location storage".	Robot utilization; service times; cycle time for order-picking; queue lengths; throughput	Picking; Sorting
"Evaluating dedicated and shared storage policies in robot-based compact storage and retrieval systems"	Zou et al.	2016	YES	RCSRS	Semi-open queueing networks	Estimate the performance and evaluate storage policies of RCSRS, considering dedicated and shared storage policies coupled with random and zoned storage stacks.	Cost, space utilization; racks' filling degree; throughput, waiting times, utilization of resources	Storage
"Estimating performance in a RMFS"	Lamballais et al.	2017	NO	RMFS	Queuing network models	Performance and robot utilization, with different system parameters, warehouse layouts, and control policies.	Maximum order throughput; order cycle time; robot utilization	Picking; Sorting
"Small is beautiful: a framework for evaluating and optimizing live-cube compact storage systems"	Zaerpour et al.	2017	YES	Live-cube compact storage	Closed-form solution	Optimize systems' dimensions.	Retrieval time; maximum response time; cost	Storage
"Automated or manual storage systems: do throughput and storage capacity matter?"	Zaerpour et al.	2019	NO	Miniload AS/RS; Mobile racking,	Microsoft Excel	Provide insights to select the suitable system, minimizing the investment and operational costs.	Storage capacity; throughput; costs	Storage

Table 2 Consulted Articles Characterization | Continuation

"Robotized and automated warehouse systems: review and recent developments"	Azadeh et al.	2019	NO	AS/RS with cranes; SBS/RS; Live-cube compact; RMFS; RCSRS	Literature review	Operations research modelling methodology adopted to analyze the problems for each system.	Throughput flexibility; retrieval capacity; system capacity; vehicle utilization; cycle time; space efficiency; throughput	Storage; Picking; Sorting
"Warehousing in the e-commerce era: a survey"	Boysen et al.	2019	NO	AGV; Mixed-shelves; Shelf-moving robots	Literature review	Study automated warehousing systems especially suited for e-commerce retailers. Survey the relevant literature and define future research needs.	Retrieval time; cost; space utilization	Storage; Picking; Sorting; Put-away; Batching
"Integrated storage-order picking systems: technology, performance models, and design insights"	Tappia et al.	2019	NO	AS/RS; SBS/RS	Semi-open queuing networks; discrete-event simulation	Study the interactions between upstream storage and downstream picking systems in integrated storage and order picking systems.	Order throughput; picking performance and waiting time; investment costs: total throughput time	Storage; Picking
"Analysis of the shuttle-based storage and retrieval system"	Zhao et al.	2020	YES	SBS/RS	Semi-open queuing network; simulation	Identify the optimal number of shuttles and guide the design of an SBS/RS system.	Resources utilization; task cycle time	Storage
"Throughput performance analysis of SBS/RS with multiple-tier shuttle vehicles"	Lerher et al.	2021	NO	SBS/RS	Simulation	Compute the cycle times and throughput performance of SBS/RS.	Cycle time; throughput capacity; resources utilization	Storage
"The study on the automated storage and retrieval system dependability"	Lewczuk	2021	NO	AS/RS with cranes	Simulation	Test the influence of AS/RS configuration and assigned resources on the dependability of the warehouse.	Put-away and retrieval time; units handled and delayed	Picking; Put-away
"Automated storage and retrieval systems: an attractive solution for an urban warehouse's sustainable development"	Edouard et al.	2022	YES	AS/RS for pallets, Miniload, SBS/RS, RCSRS, AGV	Christine Bauer and Anind K. Dey methodology	Study AS/RS to determine its potential to meet the challenges of urban warehouses. Analyze AS/RS ability to optimize available surfaces by densifying stocks in limited spaces.	Speed; Flow rate; Density of storage; Costs; system's Flexibility; Picking Accuracy	Storage; Picking

3.3 Literature Gap

Throughout the development of the current literature review, the need for a holistic analysis of warehouse operations became apparent. This gap has been highlighted by several writers, encouraging further research in this direction.

The lack of research regarding inbound logistics was also mentioned in this chapter. Thus, this dissertation also aims to fill this gap, evaluating performance indicators for inbound processes, namely, put-away. As referred, the number of outbound indicators is much higher than the number of inbound indicators. This is due to the fact that warehouse activities are getting progressively more customer oriented (Staudt et al., 2015). However, the outbound performance is largely influenced by the inbound processes. In conclusion, inbound performance is as important as the outbound performance and effects the global results of the warehouse (Staudt et al., 2015).

Another identified gap was the little direct evidence of collaboration of the academic research community with industry. There is a significant gap between scientific literature and warehouse design and management practices. Some authors have identified this weakness (Gu et al. 2007; Rouwenhorst et al. 2000; Zaerpour et al. 2019). Many research findings are not effectively shared with businesses to have a substantial influence on how warehouse operations are carried out. Increased communication on both sides may make it easier to recognize the actual problems that warehouse operations face, to recognize the improvements that can be made, and to take advantage of these improvements through close collaboration between researchers and practitioners (Gu et al., 2007). More industrial case studies are required, in order to help the warehouse research community to better understand the actual problems with warehouse design (Gu et al., 2007). This project aims to have a real impact in the company, supporting the choice of an ASS. Scientific literature reveals a need for more studies to confirm the advantages of automated systems through a case study, using both qualitative and quantitative data (Edouard et al., 2022), which corroborates the interest of this Dissertation.

Chapter 4 – Frameworks Presentation

It is important to follow a framework, not only to apply an automated solution in a currently non-automated warehouse but also to measure its impacts. Some frameworks were already well described in the literature. This chapter aims to explore these frameworks, proposing one of them to be adopted during the following section. Firstly, general frameworks are presented, secondly, a framework regarding the choice of a suitable ASS for the warehouse is presented. In the third subsection, a tailored framework, that will serve as the basis for the one adopted, is explored. Lastly, after some adaptations, the final version of the adopted framework is proposed.

4.1 General Frameworks for Warehouse Automation

There were two general frameworks examined. The first was presented in the paper "An exploration of warehouse automation implementations: Cost, service, and flexibility issues", published in 2007; The second, was presented in the paper titled: "Facilitating automation development in internal logistics systems", published in 2014.

The first framework analyzed (Baker & Halim, 2007) provided the generic steps that should be followed in a warehouse automation project. These steps are aggregated in three sequential phases: pre-project phase, implementation phase, and post-project phase, as represented in Table 3.

Table 3 Typical Warehouse Automation Project Steps | Adapted from: Baker & Halim, (2007)

PRE-PROJECT PHASE	IMPLEMENTATION PHASE	POST-PROJECT PHASE
Business Requirement	Project Set-Up	Build-Up and Snagging
Analysis of Automated and Conventional Options	Equipment/Supplier Selection	Final Acceptance
Definition of Automation Scope	Equipment and Software Construction	Follow-Up Evaluation
Top Management Commitment	Installation, Testing, Commissioning and Training	-
Operational Specification	"Go-Live" and Client Sign-Off	-
Board Approval	-	-

The pre-project phase begins with the collection of the business requirements, followed by the analysis of automated and conventional options, and ends with the presentation of a high-level design of the implementation to the Board of Directors for approval, so the project may proceed. The company's mission, vision, strategy, and prerequisites should be the foundation from which the goals should be derived. This is because the automation strategy cannot be developed in isolation, independent of the corporate objectives, capabilities, and competitive necessity in the business operations it is meant to support. The implementation phase begins with the creation of the project team and involves steps such as: selecting a supplier for the equipment purchase (procurement process); developing and installing the software; testing, and commissioning. It comes to an end at the "going live" point when the equipment is used. The final phase includes the build-up of throughput to full capacity and the elimination of the faults, conducting to the final acceptance by the customer. Subsequently, a follow-up evaluation is conducted to ensure the equipment is still properly working and to identify any adjustments that may be required compared to what was previously defined.

A more recent methodology found in literature was presented by Granlung (2014). The study is focused on developing a framework to facilitate automation development in internal logistics systems. It is separated into three models. The first one is for internal logistics strategy, the second one for automation strategy and the last one is a process model for automation development. The model for internal logistics is focused on the analysis of company's strategic goals and pre-requisites defined by customers and internal logistic system, as shown in Figure (Appendix). Once again, the significance of aligning and supporting the automation process with the strategic goals is highlighted (Granlund, 2014). The second model, for the automation strategy, encloses four areas of action: organization, technology, process, and economy. There are subheadings inside each category, each with different factors to consider. Figure (Appendix) contains a list of these concerns.

The process model for automation development in internal logistics systems is presented in Figure (Appendix). This model integrates both models previously mentioned, throughout all the steps. It may be analyzed in three parts. Starting with the initiation of the project, the first part ends at the first decision gate, that consists in choosing on what to automate. After deciding on automating part of the system, the second stage starts with the "planning for automation", where the potential solutions are designed. This culminates in the second decision gate, where the company must choose the best solution that matches the pre-defined requirements. Finally, the implementation phase has as first deliverable the "detailed solution design". From that point on, the framework is out of scope of the present project with the implementation and follow-up phases.

Despite constituting a valid starting point for studying the implementation of automated solutions in warehouses, the truth is that both methodologies presented are generic. They do not mention in detail each of the steps that must be taken in each phase. In addition, the focus of these frameworks is not on the impacts that the proposed solutions will have on the warehouse at an operational level, or in terms of space dimensioning (which is the main topic of this project). Instead, they have different main purposes. For instance, the first presented framework contains a "Post-Project Phase" (out of the scope of this Thesis). Finally, it would be useful to resort to a tried and tested methodology, previously implemented in a real case, to validate its effectiveness. Therefore, instead of these general frameworks, the one covered in the section 4.3 will be used. This framework lists well-defined and detailed tasks aggregated in sequential phases. A new phase only starts when the previous one is fully completed. Moreover, it has already been applied to real cases.

4.2 Framework for the Selection of an Automated Storage System

It can be challenging for many companies to select the best ASS, yet there are not many articles regarding this topic in the literature. The most recent research on this subject was presented in the article "Selection process for an automated storage system: a unison framework approach" (Darmawan et al., 2022). The authors begin by emphasizing the value of using a framework to make a valid decision. For warehouses with automation, at least 40% of the costs are made up by ASS machines (Lerher et al., 2021). As a result, "the selection of the right ASS system needs to be carefully considered to avoid investment mistakes." (Darmawan et al., 2022). Their research attempted to utilize the UNISON framework to give a thorough approach for choosing the best ASS. It established two primary goals for the selection process: (1) selecting the best design for the ASS; and (2) selecting the best vendor to build and implement it. One will investigate the initial goal of selecting the best ASS since this dissertation is not focused on selecting the best vendor for the project execution. The fundamental goals were then divided into more specific ones. A research technique that used the UNISON decision analysis framework is suggested to comprehend the ASS selection procedure. It consists of six steps that are each illustrated in Figure (Appendix), and can be summarized as follows:

1. Understanding and defining problems: recognize the main reason for ASS implementation. Realize a deeper analysis to comprehend the internal capacity and capability, gathering data on the use of ASS, its advantages, difficulties, and cost.
2. Defining the niche for decision quality improvement: the ASS selection problem should accommodate stakeholder inputs, project objectives, and project hazards. In this phase, it is formed the team that will take the decision.
3. Structure the objective**:** it aids to frame goals and incorporate them effectively into their decision-making model. At this stage, the different solutions available in the market are identified.
4. Identifying and describing the expected outcomes: The attributes are generated from the fundamental and intermediate objectives. The evaluation of the available choices is influenced by attribute generation. The team assesses the attributes (both qualitative and quantitative), to aid the company in the selection process for the most suitable ASS.
5. Making overall judgements and value assessments: analysis of the qualified ASS that met the requirements. At this stage, the decision-maker compares the solutions pairwise. The project team discusses and evaluates those criteria and combines them into a single decision to represent the company’s choice.
6. Making trade-offs and decisions: the ASS selection framework’s final stage is to take the decision, selecting the most suitable solution.

The procedures described in this methodology are consistent with those exposed by Baruffaldi et al. (2020). Starting with a clear definition of the company's strategic perspective and the goals to be attained through the implementation of the ASS, finding the solutions that are available in the literature, and deciding which of the solutions best achieves the previously established objectives. The team's managers and consultants work closely together the entire time. This dissertation will compare the various solutions using a table where the attributes are listed for each solution (5.4.1 Systems Survey).

4.3 Tailored Framework for Third-Party Logistics (3PL)

The main goal of this framework, presented in the paper "Warehousing process performance improvement: a tailored framework for 3PL" (Baruffaldi et al., 2020), is to aid in the deployment of effective performance improvements, resulting from the knowledge of the observed warehouse. Although it was conceived for non-automated 3PL warehouses, it will be adapted for a retail warehouse in the present project. In the same way, this framework was not adopted to study the viability of the implementation of automated solutions, which will also require some adaptations to the original model.

During the different tasks proposed, different actors are involved, as the warehouse managers or operators, combined with sources of information, as the company WMS and the literature research. The systematic procedure that constitutes the framework is illustrated in Figure 10.

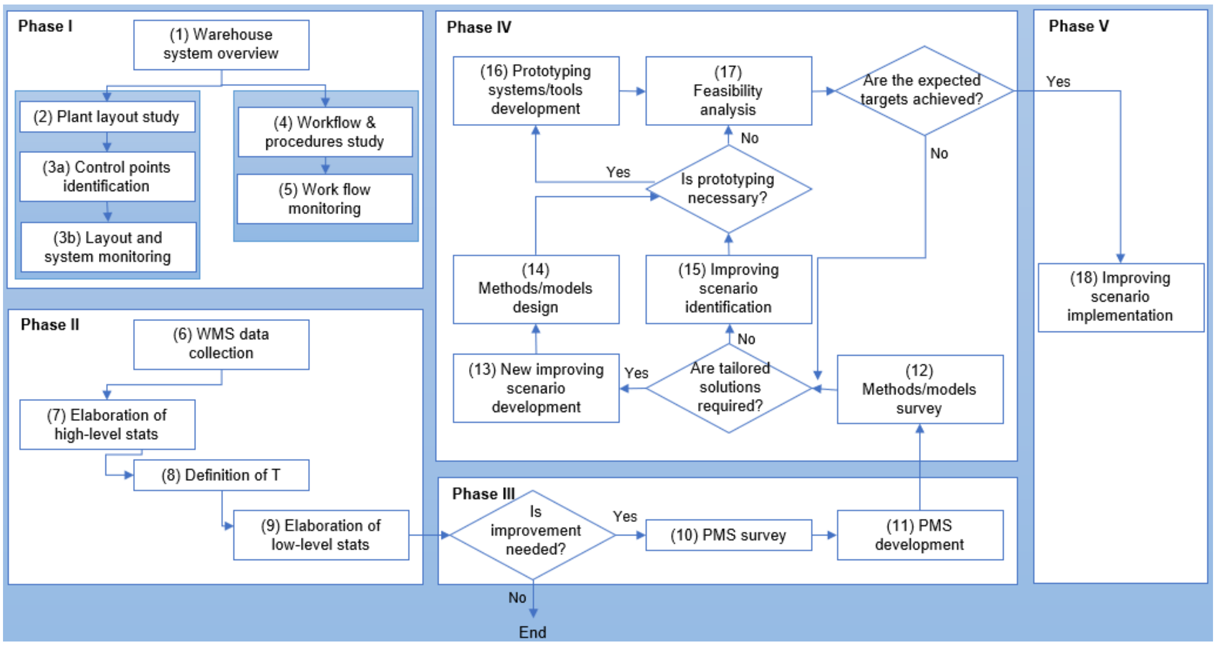

Figure 10 Decision Support Framework | Adapted from: Baruffaldi et al., (2020)

It is composed by five phases that can be described as follows:

Phase I - Warehouse Mapping: Has as major objective to obtain an overview of the current system. To achieve this, it is crucial to analyze both the warehouses' infrastructure as well as its operations. Different tasks are described for both areas of analysis. This phase entails an initial inspection of the warehouse with on-field observation of the storage system and the workflows.

1. Warehouse System Overview: general system presentation regarding the current company's infrastructure and layout. Identification of the type of products under study. Identification of company's storage assignment, routing and picking policies.
2. Plant Layout Study: general presentation of the plant of the research area.
3. A. Control Points Identification & 3. B. Layout and System Monitoring: control points (CP) and systems features (racks, aisles, etc.) identification in the plant.
4. Workflow & Procedures Study: processes flow charts presentation, containing the distinction between handling, pause, storing and control processes.
5. Workflow Monitoring: activities' time measurement. Activities' impact in the total time process and productivity measurements.

Phase II - Warehouse Diagnosis: Focuses on data gathering and analysis. Its major objective is to measure the flows previously defined in Phase I, over a defined period.

6. WMS data collection: data collection and treatment.

7. Elaboration of High-Level Stats: comprehension of the systems' main characteristics through the data analysis over a timeframe. These metrics seek to obtain general and average metrics (as the average level of inventory, or the number of SKUs held, for instance).
8. Definition of T: establishment of an adequate period that accurately represents the warehouse processes under study.
9. Elaboration of Low-Level Stats: explore the tendency of different metrics throughout the previously defined time horizon.

Phase III - Performance Measurement System (PMS) Development: Starts with the identification of room for performance improvement according to the analysis of the data collected in the previous phases. It is divided into two tasks:

10. PMS Survey: study the literature to search for existing PMS that have already been applied in the field of warehousing operations.
11. PMS Development: analyze the sources of inefficiency to establish the KPIs to increase the warehouse performance. The outcome of this phase is a tailored panel of performance metrics.

Phase IV - Improvement Scenario Design: Aims to design the improvement scenario that better addresses the panel of KPIs.

12. Methods/Models Survey: the literature is explored to find the existing approaches, to cope with the indicators identified in the PMS.
13. New Improving Scenario Development: in case it is decided to create new scenarios, instead of implementing existing ones.
14. Methods/Models Design: in case it is decided to design new methods/models instead of implementing the existing ones, identified in task 12.
15. Improving Scenario Identification: identification of the most suitable scenarios found in the literature.
16. Prototyping Systems/Tools Development: the prototypes of the different scenarios are created.
17. Feasibility Analysis: different scenarios are tested, through a technical-economic feasibility analysis, to choose the most suitable one.

Note that tasks 13 / 14 and task 15 are mutually exclusive. Either no tailored solution is required, and the improving scenario is immediately identified; or a new improving scenario must be developed, and the methods/models designed. In other words, one can decide to design new models or implement existing ones.

Phase V - Improving Scenario Implementation: This last phase entails one single task.

18. Improving Scenario Implementation: includes all the activities needed for the implementation of the best improvement scenario.

Despite the detailed tasks, this framework can be applied in general performance improvement projects. In fact, it has already been adopted in a few warehouses with different characteristics, operations management, and types of products stored. Examples include a biomedical warehouse, in which the traveling picking time was reduced by 12% and stock safety improved by 20%, through optimization and simulation. The storage assignment policy adjustment that made this improvement feasible is described in detail in (Accorsi et al., 2014). Another example is a beverage industry warehouse, where travel picking time was reduced by 47.6% utilizing simulation (Baruffaldi et al., 2020). The framework application to these specific warehouses had a favorable impact, however both focused KPIs related to outbound logistics, while the use of the framework for the measurement of impacts in inbound processes was also a matter of interest in this research.

4.4 Framework Proposal

After analyzing the presented frameworks, it was decided to implement the last one, with some adaptations, considering the Thesis's purpose. In Figure 11 is represented the framework followed, after the respective changes, as well as the primary analyses that will be presented in some of the steps.

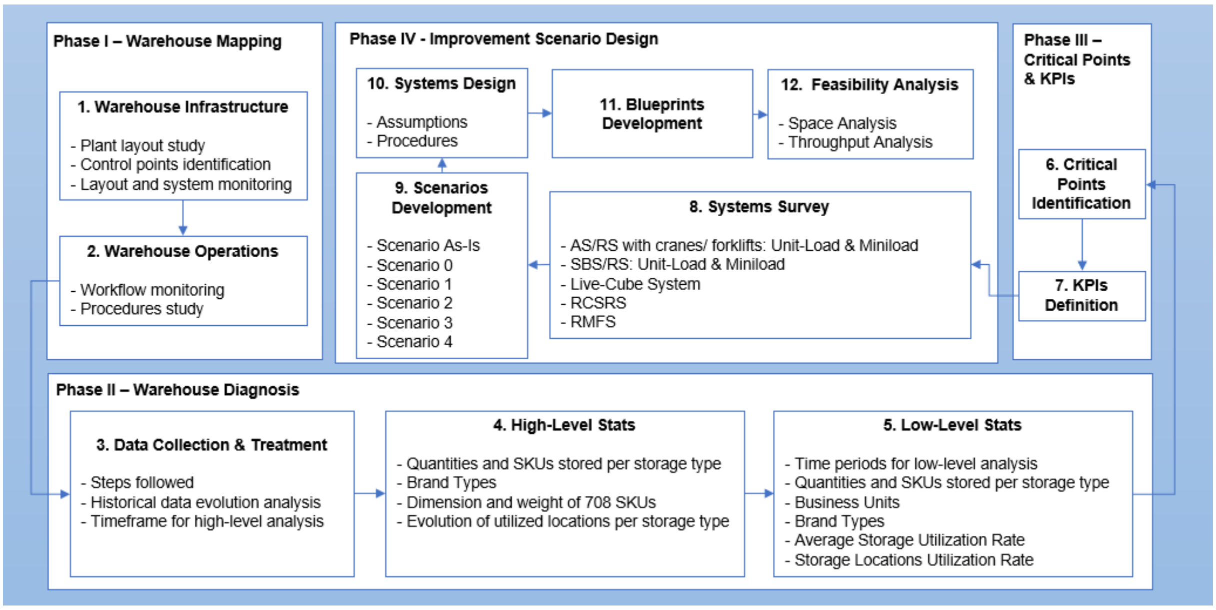

Figure 11 Proposed Framework | Adapted from: Baruffaldi et al., (2020)

The first phase had no adaptations. In phase II, there is a subsection dedicated to explain the data collection and treatment. Instead of picking a short time-period to perform the low-level stats, as suggested by the authors of the original framework, two specific moments were selected, to analyze a dataset representative of Worten's warehouse. At phase III, the original framework suggests developing a PMS. As elaborating a PMS is a complex and time-consuming activity, in this dissertation, one will just define the most relevant KPIs to be lately analyzed. In phase IV, instead of choosing standard systems, it was decided to study five systems (from which three were selected) to adapted for Worten storage needs. The modifications required will be to size the solutions in accordance with the dimensions and shape of the warehouse and, naturally, the quantity of products and number of SKUs to be stored. Therefore, stage 15 of the original framework will be skipped. Chapter 5 is fully dedicated to the implementation of the proposed framework. Nevertheless, the feasibility analysis step will be performed in Chapter 6, that is exclusively dedicated to that end. This analysis is performed based on space and throughput indicators. Finally, phase V will not be followed, as it is out of the Thesis' scope.

Chapter 5 – Framework Implementation

This chapter is divided into four sections that together make up the framework that will be applied to Worten's warehouse. The steps followed in each phase are listed, along with the main conclusions reached that will be discussed later in Chapter 6. As the current dissertation is focused on the storage of 708 products, the framework will be applied exclusively to the areas and processes related to this category.

5.1 Phase I: Warehouse Mapping

The first phase's objective is to better understand the current warehouse configuration, to identify possible improvement measures. Since Chapter 2 already discusses several topics concerning the current situation, here, the most important aspects are summarized, and some additional data is provided. From an initial inspection of the warehouse, it is possible to provide a brief overview of the systems. Some information such as the kind of products to be stored, the available storage resources (vehicles and workers), and the storage policies adopted by the company are presented in Table 4.

Table 4 Storage System Overview for 708 products

Type of products	708 – Small, light and not perishable items	
Number of products	950 000	
Number of SKUs	12 500	
Number of vehicles	25 Picking 4 OPW - Picking ONL	
Number of operators	Reception	15
	Put-away (Racks and SM)	17
	Pickers (Retail and Online)	33
	PTL (Retail and Online)	10
	Billing ONL	6
	PTS	9
	Shipping	15
Put-away Policy	Directed Put-away	
Storage Policy	By type and volumetry/weight	
Routing Policy	Batch Routing	
Picking Policies	Batch Picking and Bulk Picking	

The directed put-away strategy mentioned in Table 4 is a process where incoming products are placed into their designated storage locations based on an optimized plan, defined by the WMS. Instead of placing them randomly, the system directs the articles to specific locations based on factors such as their characteristics, or the storage capacity. It ensures optimized storage and accurate inventory tracking. However, in practice, sometimes this is not respected, and the workers perform "manual put-away", choosing themselves a free location where the item is stored. Ideally, it should not happen.

The storage is performed according to the product's classification (PBS, PBL, LT, e LAV). Each item has a storage system assigned to it based on its classification. The different systems and the characteristics of the corresponding stored products were described in section 2.4.1 Warehouse Layout. The procedure for organizing products onto racks according to their dimensions and weight was also described in the same section. Worten follows a strategy of fixed-picks, in which each SKU has a specific assigned location. This method facilitates replenishment since knowing the exact location of each product makes it easier to restock products as needed. It is also useful in the context of picking based on volume and weight, allowing for a more efficient organization of the warehouse. However, it is a rigid system, meaning it is not flexible to changes like the introduction of new products. This is because when a new SKU enters the warehouse, it is necessary to assign an available location to it.

As previously stated, Worten uses a wave-picking approach. This comprises the batch routing strategy, which focuses on minimizing travel time by optimizing the picking path, and the batch picking policy, which aims to improve picking efficiency by managing many orders at once. Batch picking is particularly helpful to deal with a high number of small orders. That is why it is used to pick the products that will be shipped to a reduced number of stores. When several stores order the same product, bulk picking is adopted. With bulk picking, the whole pallet is picked and later in the process, in the PTS-Production zone, the product is sorted to the different stores.

Another classification given to the stock is based on its Business Unit (UN). This classification is defined according to the features and functions of the products. Table 16 (Appendix) lists the 708 UN items that will be examined in the next phase.

5.1.1 Warehouse Infrastructure

This step consists of the presentation of the plant of the study area, regarding the processes applied to the 708 products. The different storage areas are identified with a color scheme, as well as their respective dimensions and areas (Figure 12 and Figure 13). The orange zone (PTS) is not part of the storage area, however, it is represented in the figure to explain one of the Control Points (CP) regarding 708 products. Despite not being utilized to store products, inbound and outbound areas are also included in the plant, to explicit the flows from the entrance to the exit of the warehouse. For the sake of simplicity, the dimensions shown exclude the measurement of the side aisles and the aisles separating different areas. Each feature dimensions can be consulted in Table 17 (Appendix). In the blueprints, the main control points are highlighted and can be described as follows:

1 Receiving and Checking: occurs in the inbound area and consists of rectifying the received products, through the identification of products, confirmation of the quantities received, and quality control process.

2A Put-Away Provisioning Check Digit: consists of scanning the inbound license plate number (iLPN), by the employees with the portable digital terminal (PDT), to insert the information regarding the product's storage location in the WMS. This must be stored in the previously defined location, by the directed put-away method.

2B LAVA Drop: for mezzanine products there is one extra CP. Products are checked at the entrance of the elevator (the iLPN is picked once again with the PDT). Then, the product is stored in its mezzanine location and the remaining processes are like the ones applied for the products outside the mezzanine.

3 Picking Check Digit: like the previous step, it consists of using the PDT to inform the WMS that a certain product was picked up from its location, according to the order list lines.

4 Outbound Checking: check the articles in the master pallet and confirm in the system that the pallet has the correct outbound license plate number (oLPN). This CP takes place in the PTS zone.

5 *Pica no Cais*: check if the pallets are in the right dock. It gives a visual signal if the worker is trying to allocate the pallets to the wrong dock.

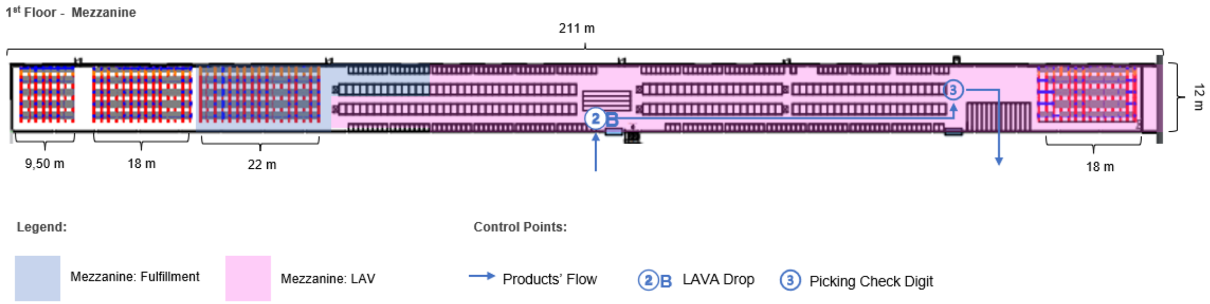

Figure 12 Mezzanine Layout

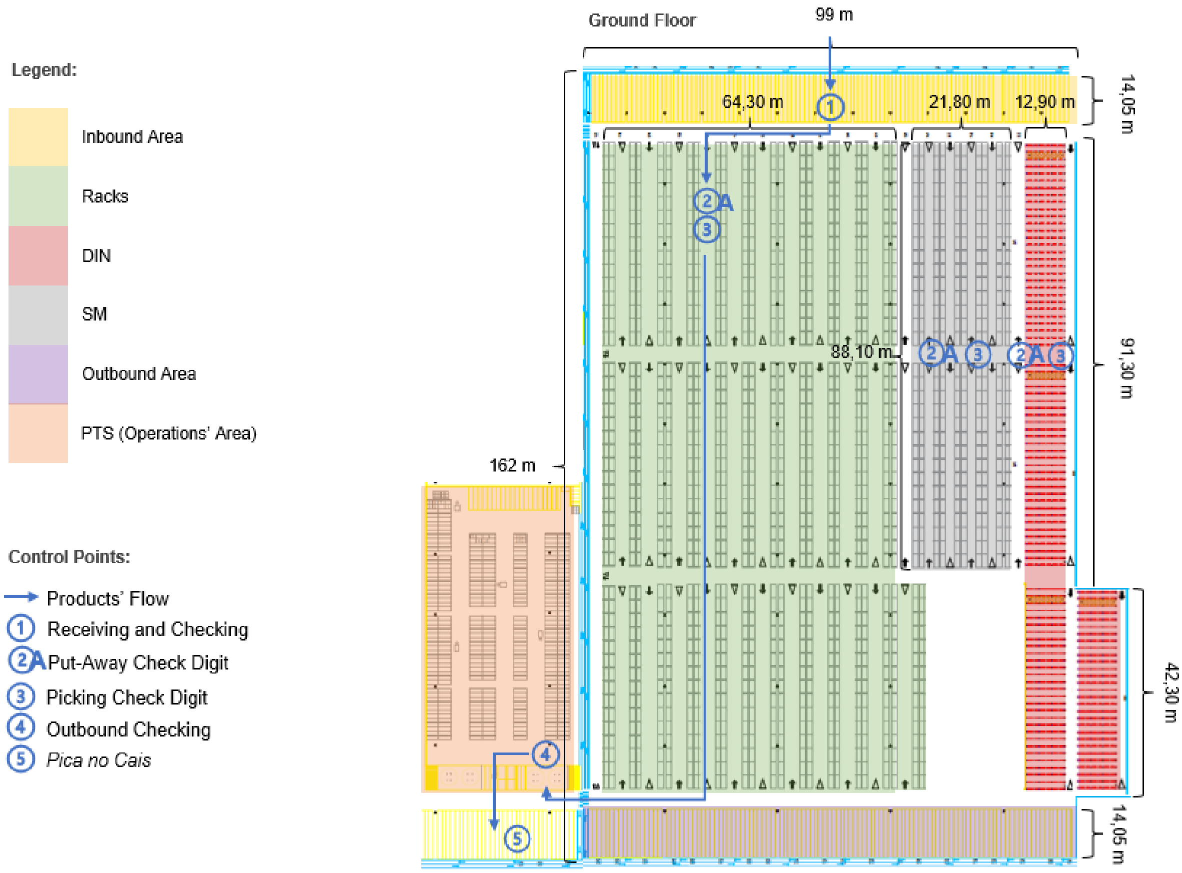

Figure 13 708 Storage Area Layout

This set of control points ensures that, when shipping, the products registered in the system are going out and that the WMS is in accordance with the reality of the warehouse. Regarding the system layout monitoring step of the methodology, it is possible to see the representation of regular racks, narrow-aisle racks, DIN, as well as their length and width. The remaining space is made up of aisles, inbound and outbound areas, etc.

5.1.2 Warehouse Operations

Regarding the workflow of 708 products, the directions of movement in the aisles are highlighted in Figure 12 and Figure 13, as well as illustrative examples of the products' routes, passing through all the control points. The flowcharts that describe the products' movements from the moment they enter the warehouse, until they are stored may be consulted in Figur-46 (Appendix). Each step is classified as: handling, pause, store or control point. At this point, some data was collected from on-field monitoring of the workflow to account for the time spent with each activity. The data regarding the productivity of the main activities are presented in Table 5.

Table 5 Productivity of the Main Activities

Activity	Productivity - 708 Racks	Productivity - Mezzanine
Receiving	0.6 min/pallet	
Checking	0.16 min/product	
Put-away	0.14 min/product	0.25 min/product
Replenishment	0.25 min/product	0.35 min/product
Picking	1.8 min/product	1.3 min/product
Shipping	0.8 min/pallet	

Based on the presented information, picking is the most time-consuming process. This current reality can be, most likely, changed with the implementation of a parts-to-picker system. Although the table only presents the time associated with the mezzanine and regular rack picking, it is known that picking in narrow aisles is less productive, taking more time than 1.8 minutes per product.

5.2 Phase II: Warehouse Diagnosis

At this stage, a set of high-level metrics are calculated to better comprehend the system's behavior. The data supplied by Worten, in PowerBI, contained representative information regarding the stock present in the warehouse from January 1st, 2021, to June 6th, 2023. The first step is to collect and treat the data that will be used.

5.2.1 Data Collection & Treatment

Even though this dissertation concerns products classified in category 708, Worten supplied information on all items. The dataset provided by the company is representative of the currently warehouse situation. It was verified from a preliminary review of these data that 708 products correspond to 71% of the total number held, or 76% in terms of SKUs. WMS data provided by the company will be handled in Excel and Power BI. Firstly, the data had to be curated and the outliers removed before the effective data analysis could begin. To do so, the following steps were applied to the original dataset:

1) Data removal regarding 701 category products:

Products classified as 701 were deleted from the dataset. From this point on, only 708 category articles will be considered.

2) Removal of some types of locations:

For simplification, they were only considered four main types of storage: regular racks, narrow aisle racks (SM), DIN, and mezzanine. All the other types were excluded from the dataset (virtual, sorting, staging, and LT products, for example).

3) Removal of locations with negative quantity values:

The parameter “quantity” is obtained considering the current value in storage plus the quantity already ordered but not yet received (Entering) minus the quantity sold but not yet shipped (Leaving):

$$Q = Q_{Stored} + Q_{Entering} - Q_{Leaving} \tag{1}$$

Hence, the value that is displayed may be negative. Negative quantity values were excluded from the sample since it is assumed in this dissertation that the quantity corresponds to the actual value that is present in the warehouse for simplicity's sake.

4) Removal of outliers regarding the stored quantities:

It was found that there were SKUs with enormous amounts (thousands) coming from products like stickers and envelopes. Although these values were accurate in these instances, it was decided to eliminate them so as not to distort the sample. It was established a maximum amount of 3 000 products per SKU.

5) Removal of the locations that contain products that had been inaccurately parametrized:

It was discovered that some of the products had been improperly parameterized in terms of dimensions and weight when the products were arranged in descending order of weight, length, height, and width. For a 708 product, the dimensions of a Europallet (120x80x175 cm) are taken as the upper limit for admissibility. However, as different workers may consider different faces of a product when measuring length and width, the maximum width considered is 120 cm instead of 80 cm. Additionally, some products were found with weights that were in the admissible values yet inconsistent with their descriptions (for example, laptops weighing dozens of kilograms). These were also eliminated.

After the data treatment, the historical evolution of the data was analyzed, using the same dataset, in order to select a representative period of the company's activity. As Worten’s demand is seasonal, the quantity of products stored in the warehouse varies throughout the year. The company defines three seasons according to the levels of demand :

- Low-demand season: from February to May, sales volume is typically low.
- Medium-demand season: from June to August, there is usually an increase in the number of stored products.
- High-demand season: between September and January, there are several high-demand events such as back to school, Black Friday, and Christmas.

In Figure (Appendix), it is possible to identify the different demand seasons. In general, the behavior of the number of products and SKUs stored corresponds to what is expected, except for the high-demand season of the year 2021.

Considering that the events in which the demand is higher are repeated annually, it will be considered an annual period for the analysis of high-level stats. Therefore, it will be used the most recent data for a whole year, outstanding in Figure (Appendix). The selected period ranges from January 1st, 2022, to December 31st, 2022.

5.2.2 Elaboration of High-Level Stats

The first analysis conducted concerns the number of products and SKUs stored per storage type. As mentioned, different types of products require different storage types. Figure 14 confirms that DIN stores

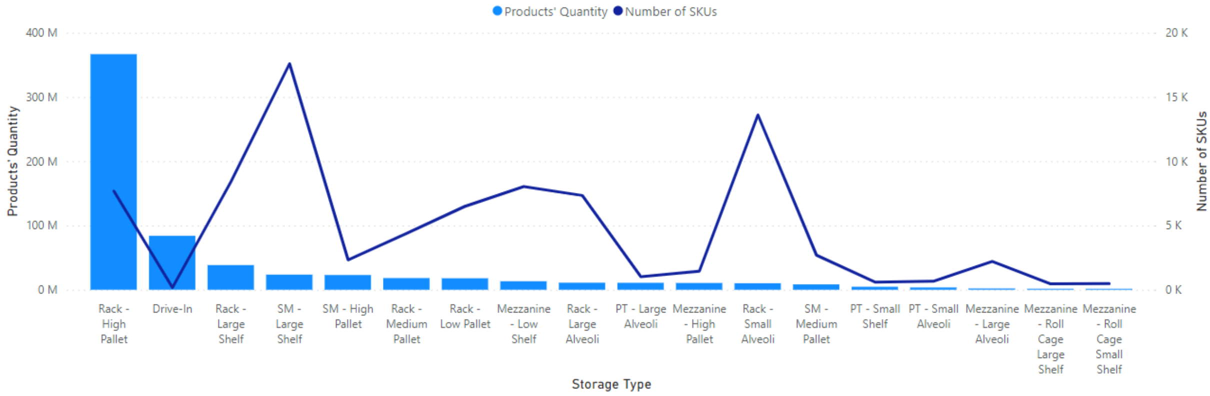

Figure 14 Product's Quantity and SKUs Stored per Storage Type

a low number of SKUs, but a considerable quantity of items. This happens because Worten's own brand products consist of a reduced number of references that come in large quantities. The same relation between SKUs and product quantity is observed for high pallet rack. On the opposite side, Slow Movers have a higher number of SKUs, each one stocked in reduced quantities. The same happens to alveoli and shelves. All of them store supplier brand, which is characterized by a high number of SKUs presented in small quantities. The analysis of the different storage types reveals that more than 139 M of products, in terms of SKUs (corresponding to 55.8%) are stored in high pallets.

The analysis regarding products' brand types shows that, as own brand (MP) products have a low number of SKUs that came with large quantities of products, the number of MP SKUs represents less than 5% of the products stored. On the other hand, it is equivalent to more than 55% in terms of quantity. This discrepancy is depicted in Figure (Appendix). In terms of locations, almost 64% are occupied by supplier brand (MF) products.

Given that Worten stocks a wide range of products, it is natural that there will be significant variations in its dimensions and weights. The boxplots in Figure -52 (Appendix) were constructed in order to quantify this disparity in weight and size. In these boxplots, the distribution of product weights and dimensions is displayed with the products being grouped in categories:

- Alveoli (Fulfillment, LAV and Racks)
- DIN
- Roll-cages, Medium and High pallet (LAV, Slow Movers and Racks)
- Shelves and Low Pallet (Racks, SM, LAV, Fulfillment)

The exposed differences will condition the choice of automated systems, which are limited to a maximum value in terms of both dimensions and weight.

Figures 52-56 (Appendix) were generated considering the number of locations utilized by each form of storage. Observing these figures, one can see that the values for LAV items and items stored in regular racks remain stable (showing a slight upward trend). It is evident that the overall increase seen in the warehouse is primarily due to an increase in slow mover locations and fulfillment items. The lines that stand out in the graphs with the highest number of locations correspond to types of storage for small products, such as alveoli or shelves. Worten's supply chain team validated these findings. The fulfillment area has been consistently growing and its mezzanine space tends to grow over time. Similarly, slow movers have also grown, since the large number of references kept increased as a direct result of the variety of products now offered. This constitutes one of the issues that Worten is facing in its warehouse. In addition to slow movers, the narrow aisle area is also being utilized to keep other products temporarily, namely items that are new to the market. The picking of these products is impaired by this space misuse, which, as aforementioned, is inefficient in this part of the warehouse.

5.2.3 Elaboration of Low-Level Stats

Previously to elaborate the low-level stats, it was necessary to identify the proper horizon of analysis, that better represented the performance of the warehouse, considering the time-driven behavior exposed in the previous step. Two representative moments were selected to proceed with the low-level metrics analysis, one day in April and another of November (day 20 of each month). As depicted in Figure 15, April was a regular month of low-demand season, having a lower number of products and SKUs stored, while November was the month with the highest level of storage. It was expected to capture the effect of the increase in the items stored depicted in Figure 15.

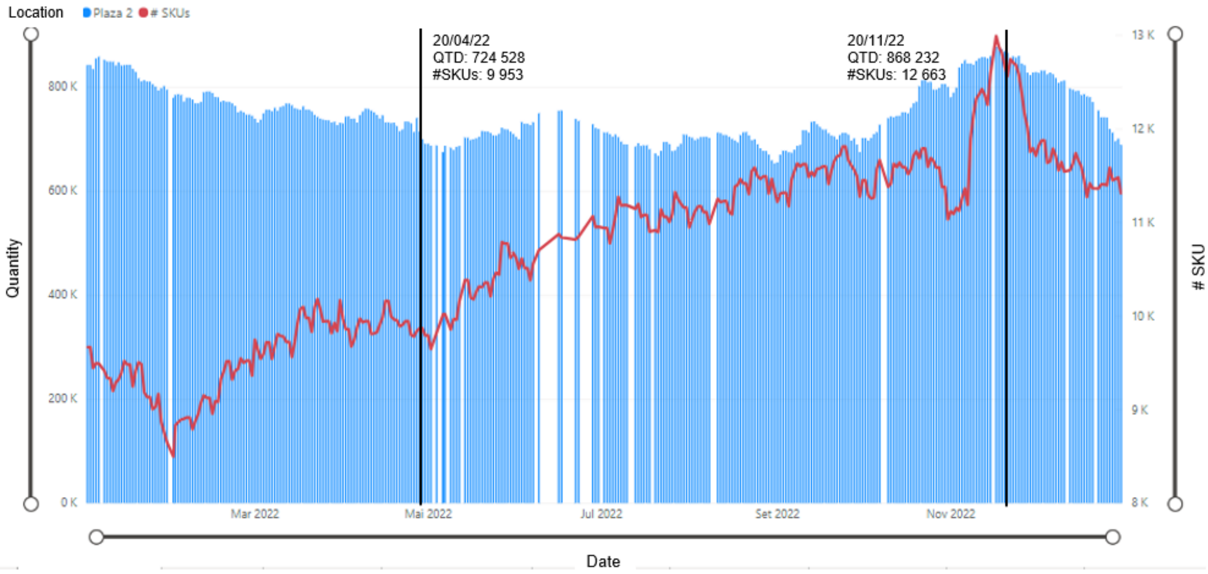

Figure 15 Units and SKUs Stored at 20/04/22 and 20/11/22

The data treatment to the Excel files that contain the information regarding the inventory in these two 2022 days (April and November 20th) was the same as the one applied in the PowerBI to the whole year, previously explained.

After the definition of the period to be analyzed, the dataset was examined in detail by quantifying low-level metrics, which enabled to study the trend of a metric through the selected time horizon. The distinction between different types of location was once again the first aspect to be analyzed, both in terms of SKUs and quantity of products (Figure 16). This time, the purpose was to compare the development of these metrics, between low and high-demand seasons.

Generally, November displayed higher values in terms of both SKUs and the quantity of products stored. Starting with the latter, high pallet rack stood out for storing more products. This system was the one where the difference between the two months is the most pronounced. In November, the quantity stored in this system consisted in 55% of the total 708 products. When it came to the number of SKUs stored, the difference was more noticeable in small rack alveoli. This storage type usually registers a higher increase in the number of references stored during Back Friday, while the variation in the quantity of each product stored is reduced.

The business units' analysis was then performed. It showed a predominance of UN 56 - Small appliances and UN 57 - IT accessories and multimedia. In both. months, the quantities' distribution was remarkably sparse. Approximately 40% of products were categorized as “Small Domestics”, and 17% as “IT and Multimedia Accessories”. Together, they comprised 57% of the 708 SKUs. As shown in Figure (Appendix), it is possible to verify a Pareto Distribution, with 23% of the business units (five UN) achieving 80% of the total amount of stocked products. In November, the quantity increased for almost all the business units, nevertheless, the most stored Business Units are nearly the same.

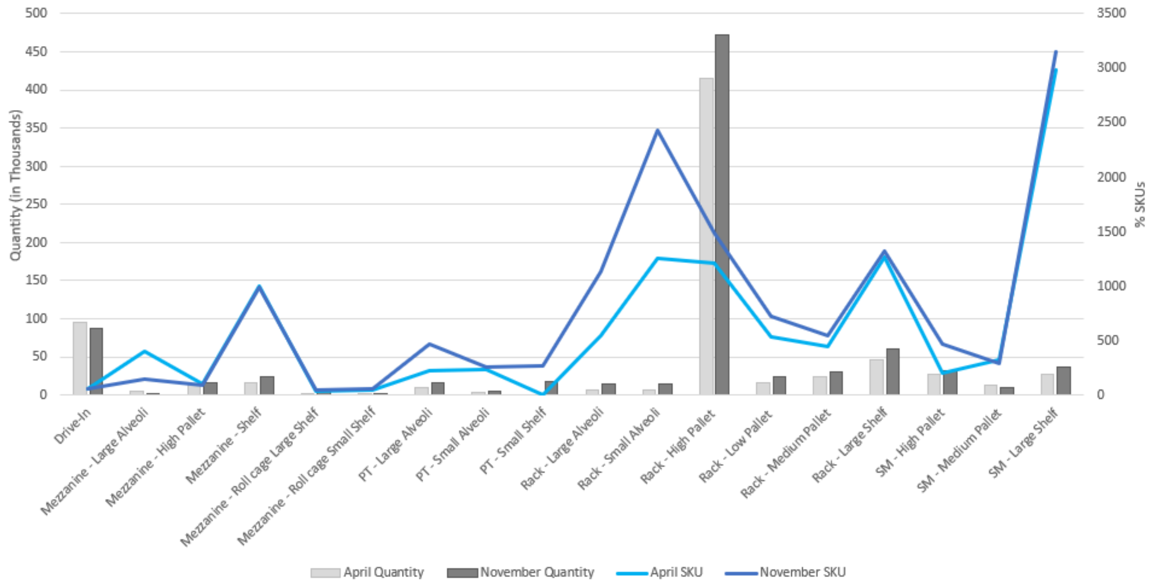

Figure 16 Product's Quantity and SKUs Stored per Storage Type in April and November

Regarding the product's brand types, the analysis to the SKUs revealed a reduced oscillation between MP and MF from April to November, as depicted in (Figure 17). MP varied from 5% to 7%, and MF ranged from 95% to 93%. Alternatively, in terms of stored quantity, the majority (59%) was own brand in April and shifted to supplier brand (51%) in November (Figure 18).

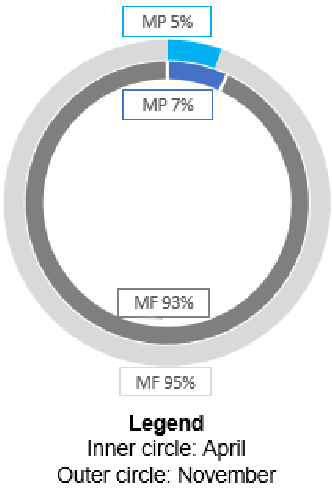

Figure 17 Variations in Products' Brand Type (SKUs)

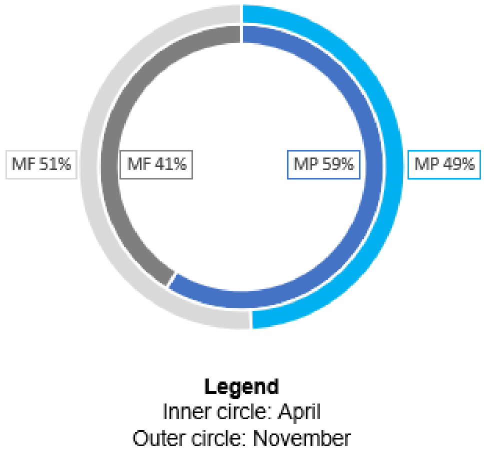

Figure 18 Variation in Products' Brand Type (Product Quantity)

The growth of supplier brand products was mostly due to Black Friday. During this period, a greater variety of items was sold, some of which do not sell during low-demand season. While MP items are sold in a generic manner throughout the year, there are highly specific MF products that experience higher demand during Black Friday. Thus, there was an increase in MF, not only in the number of references but also in the quantity of stored items (increasing 2% and 10% compared to April, respectively).

As mentioned in Chapter 3 Literature Review, the most important KPI for storage is utilization (Kusrini et al., 2018). Therefore, two rates will be examined: storage utilization rate and location utilization rate. Both were obtained for the two months in analysis. The storage utilization rate (Figure 19) is the ratio of the stock space (used storage space) to the total storage space of the location where they are kept:

$$Storage\ Utilization\ Rate = \frac{Used\ Storage\ Space}{Total\ Storage\ Capacity}\ x\ 100 \tag{2}$$

Every type of location is considered in this calculation. The Location Utilization Rate (Figure 20) is the average percentage of locations occupied, out of the total number of available locations:

$$Location\ Utilization\ Rate = \frac{Number\ of\ Locations\ in\ Use}{Total\ Number\ of\ locations}\ x\ 100 \tag{3}$$

For the two months under study, storage methodologies remained the same. Some types of storage were grouped to facilitate data analysis. This applies to both large and small alveoli as well as LAV and fulfillment products. In these cases, the average values were multiplied by the corresponding number of locations found in the warehouse in each month. The overall number of locations in the warehouse increased throughout the course of the months studied. This aspect was considered. However, since no data was available regarding the number of locations during the month of April, the values for August - the closest month for which storage data could be obtained - were used. The analysis of Figure 19 reveals that DIN have the highest average storage utilization rate. Given that it is a high-density type of storage, this is an expected outcome. When compared to the others, high pallet racks also have a higher rate. Both types of storage receive products in high pallets.

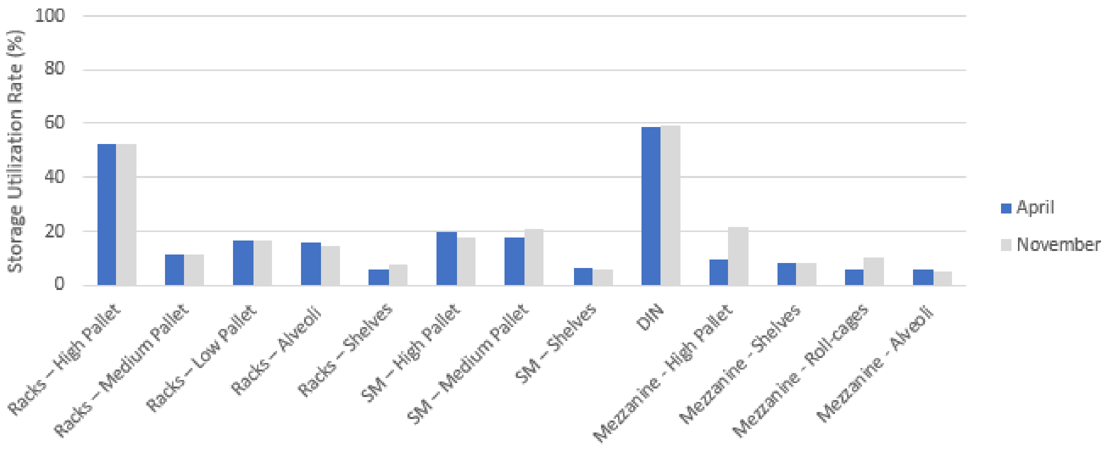

Figure 19 Average Storage Utilization Rate in April and November

Despite the increase in the amount of inventory held, the variation between April and November was low (apart from the mezzanine-high pallet). This suggests that the rise in products' quantity and SKUs stored is supported using more locations. That is to say, the locations are not filled in November; rather, more locations are added. In fact, along with an increase in the overall number of locations in the warehouse, the utilization rate is also higher, as shown in Figure 20. This is due to the fixed-picks system adopted by the company. When a new reference enters the warehouse (that happens mostly in November), a new location is assigned to it, even if the pre-existing locations have enough space to accommodate it – Honeycombing effect.

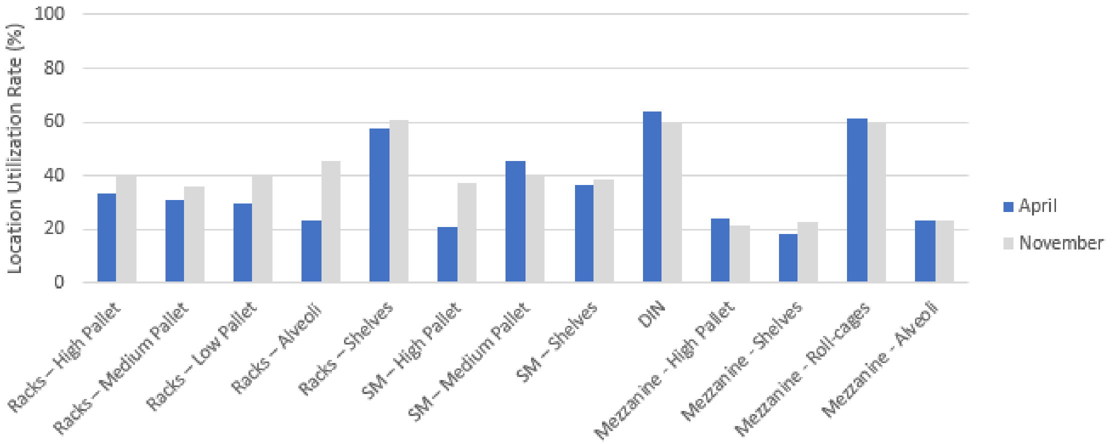

Figure 20 Location Utilization Rate in April and November

The main takeaway from the analysis of the two figures is that both values are low. In the first case (Figure 19), it frequently goes below 50% and never exceeded 60%, and in the second (Figure 20), the highest value was around 64%.

5.3 Phase III: Critical Points & KPIs

5.3.1 Critical Points Identification

After analyzing the warehouse and the available data, it is possible to summarize the critical points resulting from the currently adopted system, that may be improved in the future:

- **Lack of space:** The presented 708 storage area layout (Figure 13) suggests that almost all the space is being used. Knowing that the quantities to be stored and the number of references are increasing, it will most likely lead to a lack of space in the warehouse.
- **Manual put-away:** It is compromising the warehouse's organization.
- **Honeycombing effect:** As analyzed in phase II, through the location occupancy rate, several available locations are not being utilized. The fixed-picks system can be problematic due to the lack of flexibility in space allocation, especially in the scenario of rising demand and product diversification that Worten is facing. The same difficulty is encountered due to the demand seasonality. This method requires regular maintenance to ensure an effective space allocation according to the products stored in each season.
- **Mezzanine:** The need to store some products separately requires more space and different processes associated with the picking process. It comes with a decrease in the process productivity, since the travel time is higher, stock counts are more frequent, and there are a greater number of control points.
- **Picking productivity:** Namely the low picking productivity verified for Slow Movers.
- **Storage density**: Low density, mostly because of the aisles required for the current storage type.
- **Active and reserve locations:** Despite the advantage of easy ground-level picking, there are several disadvantages, such as the need for replenishment, a repetitive and time-consuming task. Some operators perform replenishment, almost exclusively, when they could be performing value-added tasks. Besides, there is the need to ensure sufficient ground-level locations for all SKUs.

5.3.2 KPIs Definition

Having identified these areas for improvement, the next step is to create the list of KPIs. The list has been developed based on the metrics currently used by Worten, some others mentioned in several references approached during the literature review, and others proposed by the author. KPIs that were specifically proposed based on the information collected during the literature review were subsequently validated by the company's Supply Chain Team. Table 6 presents the KPIs to be considered, as well as their respective definitions, and the dimensions they have an impact on. The dimensions considered were the ones utilized by Staudt et al. (2015) and Baruffaldi et al. (2015), excluding the cost related one, considering the scope of this work.

Table 6 KPIs and its Dimensions and Definitions

Dimension	KPI	Definition
Time	Put-Away Tyme	Average time spent directing the product to its location, from when it is received until it is stocked
	Order Picking Time	Average duration it takes for workers/systems to retrieve a product from the inventory to retrieve an order Systems' Retrieval Time
	Pallet's End-to-End Time	Total Time it takes for a pallet to be processed
	Required Full Time Equivalent (FTE)	Full Time Equivalent necessary to ensure the warehouse operations
Quality	Damaged Products	% of damaged products, comparing to the total number products stored
Productivity	Occupancy Rate	Ratio between the storage space (or systems total space) and the total 708 space (%)
	Effective Storage Space	% of the total 708 space that may effectively contain stock (does not include aisles or free spaces)
	Storage Efficiency	Ratio between Effective storage space and the storage space or systems total space)
	Storage Utilization Rate	Average percentage of the stock's volume, comparing with the storage locations volume
	Products Stored in Automated Systems	% of products stored in automated systems, out of the total number of products stored in the warehouse
	Throughput	Number of products that leave the warehouse over a timeframe (per hour, day, week, etc.)
	Automated Systems Location Utilization Rate	Average percentage of locations occupied, out of the total number of locations
	Number of Products per tote (or per pallet)	Self-explanatory

5.4 Phase IV: Improvement Scenario Design

This fourth phase aims to design the scenarios that will be evaluated in the next phase. By the end of the chapter, a proposal will be made to address the critical aspects identified in Worten's warehouse, particularly in terms of space management and system's throughput.

This phase is divided into four subchapters. Firstly, the literature is explored to find existing systems to cope with the indicators defined in the second phase. Then, according to the defined methods, different scenarios are developed. After that, the procedures adopted to obtain each systems' dimensions are explained. Finally, blueprints are drawn and analyzed.

5.4.1 Systems Survey

In the context of this dissertation, the selection of models to be applied in the methodology consists of choosing the high-density automated storage system(s) to be employed for Worten's reality. Thus, in this step, seven storage systems that had been previously selected on the literature review were further analyzed:

1) AS/RS with cranes/ forklifts: Unit-Load
2) AS/RS with cranes/ forklifts: Miniload
3) SBS/RS: Unit-Load
4) SBS/RS: Miniload
5) Live-Cube System
6) RCSRS
7) RMFS

To identify the most suitable systems for Worten, Table 7 was built, based on several information sources[1]. It summarizes the key characteristics of each system. To be noted that, at this stage, the systems (1) to (4) are grouped into only two main groups: AS/RS with cranes/ forklifts and SBS/RS.

From Table 7, it becomes easier to compare the systems. Conventional AS/RS and SBS/RS are similar ones. One of the most important differences is that the first has larger aisles, which results in a reduced use of space to effectively store products, and consequently lower storage density, compared to the second one. This does not invalidate that the AS/RS with forklifts/cranes has high storage density. When storing on pallets, it allows to reach a density up to eight times higher than a traditional storage system.

Table 7 Main Features of the Automated Systems

Storage System	AS/RS with cranes/ forklifts	SBS/RS	Grid-based		RMFS
			Live-Cube System	RCSRS	
Usage of Space	✓ Narrower aisles than traditional racks	✓ Narrower aisles than traditional AS/RS	✓ No aisle needed	✓ No aisle needed	✓
Flexibility Scalability	✗	✓ More flexible than traditional AS/RS	✗ Fixed Inventory	✓ Highly Scalable	✓ Highly flexible and scalable
Selectivity	✗	✓	✗	✗	✓
Storage Density	✓ Pallets: High Units: Medium	✓ Higher than AS/RS	✓ High	✓ High	✓ Medium
Adaptability	✗ Pallet: Very Low Units: Low	✗ Standardized loads	✓ Medium	✓ Medium	✓ Adaptable Layout
Throughput Capacity	✓ 1 crane for all vertical levels	✓ Higher than traditional AS/RS	-	✓ High	-
Stability	✓	✓	✓	✓	✓
Max. Supported Weights	Pallets: 1815 kg Units: 230 kg	Pallets: 1500 kg Units: 35 kg	30 kg	30 kg	460 kg -1350 kg
SKU Arrangement	✓ Mono or multi-SKU totes	✓ Mono or multi-SKU totes	✗ Only mono SKU per tote	✓ Mono or multi-SKU totes	✓ Several SKUs per POD
Maximum Height	✓ High	✓ High	✓ Medium	✓ Medium	✗ 2 meters
Type of Products	Pallets: Heavy and bulky Units: Small and medium	Pallets: Heavy and bulky Units: Small and medium weights	Small and light	Small and light	Small

[1]Azadeh et al., (2019); Edouard, (2022); Swisslog: https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-retrieval-systems/boxes-cartons-small-parts-items/cyclonecarrier-shuttle-system-logistics; Geek+ Robotics: https://blog.geekplus.com/company/news-center/geek-robotics-to-showcase-warehouse-automation-system-at-deliver-portugal-event

The shuttle system stands out in a positive way in terms of flexibility since it allows for the number of shuttles to be changed according to the warehouse needs. This has implications in the throughput capacity, which is higher as the number of shuttles in utilization increases. Furthermore, the SBS/RS has a lower retrieval time than AS/R with cranes/forklifts. For these reasons, it was decided to exclude the convention AS/RS and focus in SBS/RS. In the following steps the distinction between Unit-Load and Miniload SBS/RS will be detailed.

The third and fourth alternatives are also similar to each other, being both grid-based systems. The main difference is that the live-cube system has a fixed number of non-adaptive locations, contrary to RCSRS which allows the number of locations to be extended over time, in accordance with the storage needs. This increases the system's adaptability and suitability for a retail business with a variety of products in storage, whose future expansion is predicted. The live-cube system was discarded as a result.

The category in which RCSRS has the lowest rating is selectivity. Selectivity refers to the ease of accessing and retrieving products. Different storage systems offer varying levels of selectivity, and there is a trade-off between this factor and storage density. For that reason, RCSRS and Live-Cube have the highest storage densities and the lowest selectivity, while RMFS are in the opposite situation.

Concerning RMFS, these have the significant restriction of having a two-meter maximum height. Bearing in mind that the available height of the warehouse is 10.5 meters, the implementation of this type of system would result in a considerable waste of vertical space. The failure to take advantage of space in height leads to the classification of RMFS as a medium-density storage system. Nonetheless, in the future, it could be interesting to study the implementation of this system on the mezzanine area, which will not be carried out in this dissertation.

Summarizing, the study will adhere to the following three systems in the 708 storage area: Unit-Load SBS/RS (for pallets); Miniload SBS/RS (for totes); RCSRS.

5.4.2 Scenarios Development

Following the identification of the three automated systems that will be adapted, it was decided to first investigate two scenarios: As-Is and scenario 0. Then, four new scenarios were created. The six scenarios are summarized in Figure 21.

Scenario As-Is: Warehouse’s current situation.

Scenario 0: Future warehouse’s situation, maintaining the current storage systems. In other words, a warehouse without automation that stores the predicted quantity of products for 2025.

Scenario 1: Warehouse with the implementation of the automated Miniload SBS/RS - from now on referred as Miniload.

Scenario 2: Warehouse with the combination of two automated systems: Unit-Load SBS/RS - referred as Pallet Shuttle (for items stored in high pallets) - and Miniload for the remaining items.

Scenario 3: Warehouse with the combination of two automated systems: Pallet Shuttle (for items in high pallets) and AutoStore (a specific type of RCSRS) system for the remaining items.

Scenario 4: Warehouse with the implementation of the AutoStore system.

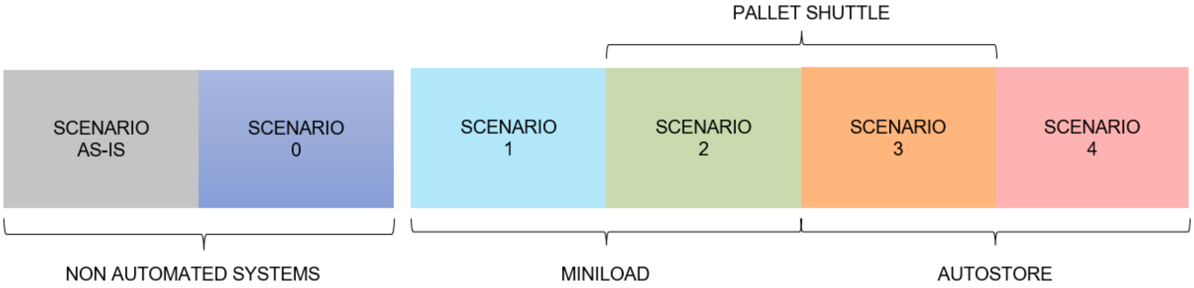

Figure 21 Developed Scenarios

Once the scenarios to study are defined, the assumptions and procedures followed in each scenario are presented. The procedure starts with the data treatment and ends with the discovery of the number of handling units to be stored in each storage system for all the scenarios.

5.4.3 Systems Design

This task consists in adapting the systems that will be present in each scenario, according with the products to be stored. Firstly, the forecasts for the quantities of products and number of SKUs to be stored are presented. Then, the general assumptions are listed. Finally, the specific assumptions and procedures for each scenario are explained.

Regarding the quantity of goods to be stored, they were considered as the values anticipated to be kept in the warehouse on June 6th, 2025, which is two years after the last day in the dataset provided by Worten. Two forecasts obtained with different timespans are considered, as the company usually does:

- Prediction utilizing data from January 2021, that considers all the historical registers available in the dataset, to allow for a wider analysis of the evolution in the number of SKUs and products stored.
- Year-to-date prediction: considers the data of the last year. In this case, the interval June 7th, 2022, to June 6th, 2023, is considered. More recent data may help predict future developments more accurately.

In both instances, graphs were drawn to indicate how the number of SKUs and products changed over time for each form of storage. As an example, the trend graph for the quantities stored in high pallet racks is presented according to the year-to-date method in Figure 58 (appendix). The equation for the corresponding trendline was then obtained.

The predicted values were obtained through the linear regression equation that describes the trendline. This procedure was repeated for all types of storage. The values obtained allowed for the construction of two future scenes, each one resulting from each type of prediction. An optimistic scenario (which, from the perspective of the Warehouse Management Team, entails the requirement for future storage of a smaller number of items) and a pessimistic scenario (contrary situation). These merely consisted of the minimum and maximum values, respectively, of each fulfilled prediction. The predicted values are shown in the Table 18 (appendix). The values utilized for the scenario analysis were those from the pessimistic scenario, to obtain conservative results.

General considerations and assumptions:

- Only 708 articles are considered.
- Data referring to November 20th, 2022 (with higher utilization than April) were used.
- The entire study is focused on articles for which the weights are known. The remaining data were not considered.
- The dataset used was the same for all the scenarios, to establish a fair comparison of the results.
- High-value products can be stored with the other ones.
- Totes' weight is disregarded.
- Totes' thickness is disregarded (outer and inner dimensions are assumed to be the same).
- DIN products remain stored in the same system (they will not be stored into automated systems).
- High pallet products already come on mono-SKU pallets, while everything else comes mixed in pallets.
- Each tote has a single SKU (mono-SKU storage assignment).

Specific assumptions and procedures for each scenario

Scenario 0

It is divided into three main storage types: DIN, high pallet racks, and racks for remaining products.

For **DIN,** the steps followed were the same for all the five future scenarios:

1) The dataset is filtered to keep only the products that are being stored in DIN.
2) Total quantity of products is summed, by SKU.
3) The quantity is divided by the TiHi, for each SKU, to determine how many high pallets are stored.
4) Based on the predicted increase in the quantity, the new number of high pallets is estimated.

For **high pallet products**, there are three separate procedures (for each type of product in: rack, SM and mezzanine) that consist in the same set of operations, using different datasets:

1) The dataset is filtered to keep only the products that are being stored in each type of location (rack, SM or mezzanine).
2) Total quantity of products is summed, by SKU.
3) The quantity is divided by the TiHi, for each SKU, to determine how many high pallets are stored.
4) Based on the predicted increase in the quantity, the new total number of high pallets is estimated. At this point, active and reserve locations are mixed.
5) Considering the percentage of active and reserve locations compared to the total number of locations will remain stable in the future, the number of each type of location is calculated.

For the **remaining location types**: (low pallet, medium pallet, shelves, and alveoli - both for racks and SM) the procedure is the following:

1) A correspondence is established between the current number of locations and the quantity of stored product. It is assumed that the future number of locations is proportional to the variation in the stored quantity of each type of product.

Scenarios with Automated Systems

Contrarily to non-automated systems, which exist in the warehouse, new systems require a search for different components' dimensions. As so, data utilized to design the systems and create the scenarios' prototypes is presented in Table 19 (Appendix). To facilitate the description of the process followed, the diagram in Figure 22 is provided with the key steps taken to determine the number of locations that will be required in each system in 2025.

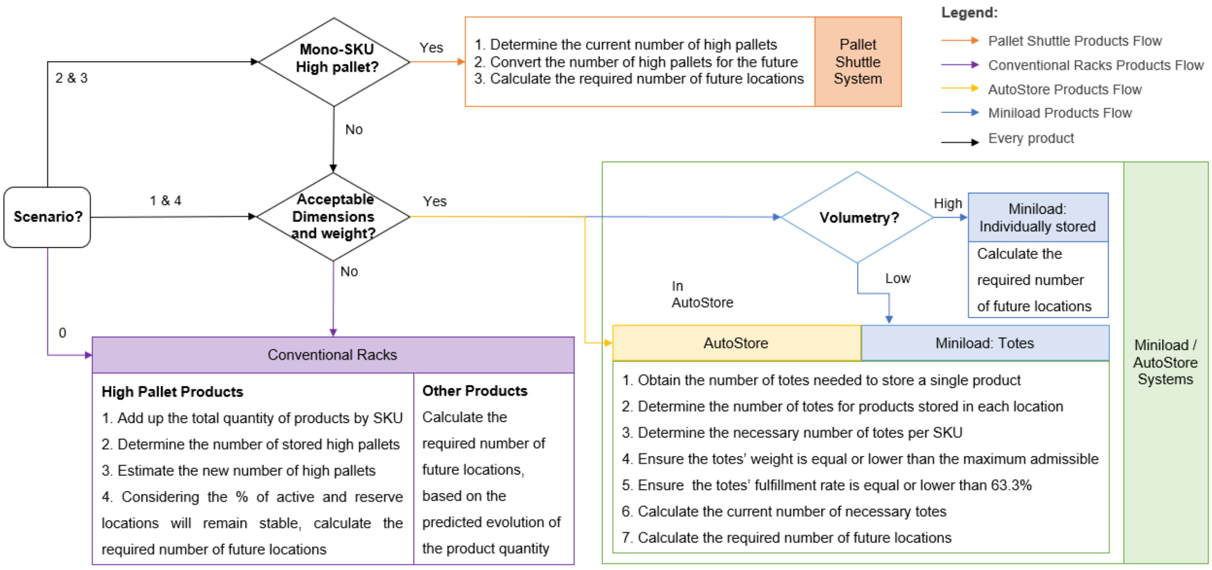

Figure 22 Procedure to Determine the Number of Future Required Locations

Scenario 1

Assumptions:

- Cyclone from Swisslog[2] was used as reference for the Miniload SBS/RS.
- Totes dimensions: (67x50x47) cm.
- The lift carries shuttles between tiers (tier-to-tier system), as represented in Figure 23.
- Each aisle has a single shuttle.
- The shuttle "picks up" the totes from the aisle (without going underneath them into the location), as depicted in Figure 24.
- The "pick up" time was not considered.

[2] Cyclone Swisslog: https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-retrieval-systems/boxes-cartons-small-parts-items/cyclonecarrier-shuttle-system-logistics

- Products with dimensions that do not allow them to be stored in this typology are stored in high pallet racks.
- Given that a tote will never be 100% filled, a maximum occupancy of 63.3% per tote was considered. This occupancy rate corresponds to the average occupancy rate verified for shelves with similar dimensions to the considered totes, that also store mono-SKU articles. The values utilized were from September, 11st, 2023.

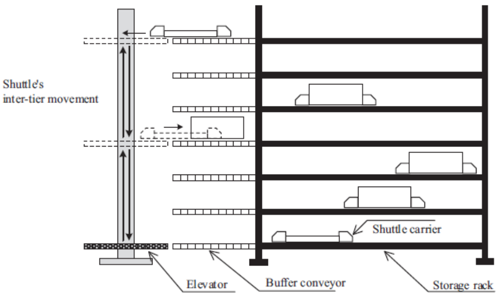

Figure 23 Miniload Tier-to-Tier Representation | Source: Ha & Chae, (2018)

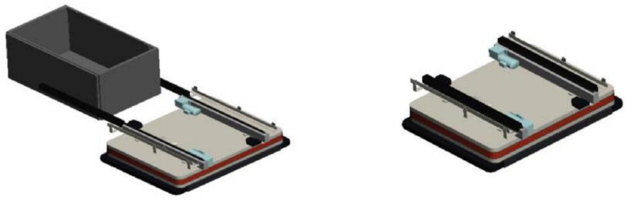

Figure 24 Shuttle Carrier Simulation Display | Source: Ha & Chae, (2018)

Procedure

1) Filter the dataset to keep only the products that fit the dimensions and maximum weight supported by the system, to distinguish the products that will be stored inside and outside it.

2) Articles that are stored in the automated system can be of two types:

- High volumetry: stored individually in a location (if the volume of the product is higher than 50% of the tote's volume).
- Low volumetry: grouped in totes before being stored (if the volume of the product is lower or equal to 50% of the tote's volume).

3) At this point, there are products in three different situations: stored outside the system, stored inside the system in totes, and stored inside the system without totes (individually stored).

3.1. For products stored in totes:

- The unit volume of the product is divided by the tote volume, to obtain the number of totes (a fraction) needed to store a single product.
- The quantity of articles is multiplied by the number of totes previously obtained, to find the necessary number of totes for all the products stored in each location.
- The number of totes per location is rounded to units by excess.
- The number of totes is grouped by product's item name, to find the necessary number of totes per SKU.
- It was ensured that the weight of all totes was equal to or less than 35kg. After determining the number of totes, the weight of each tote was analyzed and, whenever a tote weighed more than 35kg, the number of totes was adjusted for that SKU, up to the admissible weight.

- After the weight adjustment, an equivalent procedure was performed to correct for the fulfillment rate - 63.3% occupancy: given that a tote will never be filled to 100%, a maximum occupancy of 63.3% per tote was considered. Whenever a tote was more than 63.3% occupied, at a volumetric level, the number of totes for that SKU was adjusted.
- The current number of necessary totes is found. The future value is determined, assuming a direct proportion between the number of totes and the quantities stored through time.

3.2 For products stored alone:

- Every product has a corresponding location, hence the number of future locations corresponds to the number of future products.

3.3 For products stored outside the system:

- For high pallet products: What comes in mono-SKU high pallets is stored in high pallet racks. Therefore, the procedure is identical to the one presented in scenario 0 for high pallet products. The only difference is that here, all high pallet product types (rack, SM, and mezzanine) are treated together and not separately.
- For every other product: similar to scenario 0.

Scenario 2

In the second scenario, the data was firstly processed for the pallet shuttle system.

Assumptions for pallet system:

- PowerStore from Swisslog[3] was used as reference for the Unit-Load SBS/RS.
- All pallets weigh up to 1.5 tons.
- All pallets respect the maximum Europallet dimensions.

Steps:

1.1) For products stored inside the pallet system:

- Data was filtered for products that are stored in high pallets (SM, racks, and Mezzanine products). All the products that are currently stored in high pallets systems will be stored in the automated system. Everything else is stored outside this area.
- Divide the quantity by the products' TiHi to find the current number of high pallets.
- Converted the number of high pallets for the future based on the expected evolution of the quantities.
- Each high pallet corresponds to a location in the system.

1.2) For products stored outside the pallet system:

[3] PowerStore - Swisslog: https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-retrieval-systems/automated-pallet-warehouse/powerstore-shuttle-system-for-pallet-warehousing

- Test for the Miniload system: following an identical approach to the steps followed in scenario 1.

By the end of this scenario's procedure, excluding the DIN products, there are products in four situations: stored in the pallets' system, stored in Miniload in totes, stored in Miniload without totes, stored outside both systems (products that do not come in mono-SKU pallets and are too large or heavy for Miniload system).

Scenario 3

- AutoStore from Swisslog[4] was used as reference for the RCSRS.
- From the three available dimensions for this system's totes, the one selected was the largest (649x449x425) mm.
- It was considered 10% of free locations, for digging to be possible. This value was provided by a Swisslog representative.

This scenario's procedure is identical to the one presented in scenario 2. The results obtained for the pallet system will therefore be the same. On the other hand, the values obtained to the AutoStore differ from the ones obtained for the Miniload, due to the differences in the totes dimension, supported weights and the fact that all the products must be stored in totes. At the end of the process, as consequence of the necessity of additional space for digging, the number of locations increased by 10%.

Scenario 4

- Same assumptions of scenario 3 for AutoStore process.
- Products with dimensions that do not allow to be stored in AutoStore are stored in high pallet racks.
- Given that a tote will never be 100% filled, a maximum occupancy of 63.3% per tote was considered.

This scenario's procedure is identical to the one presented in scenario 1. Once again, the values obtained are not the same, due to the differences in the totes dimension, supported weights and the facts that all the products must be stored in totes and the number of locations is increased in the end by 10%.

5.4.4 Blueprints Development

In the current study it was necessary to develop the warehouse's blueprints that would result from the implementation of the future scenarios. This subchapter presents these prototypes, as well as the steps that were followed to obtain them. Then, the feasibility analysis was performed.

For the As-Is scenario, the number of locations currently occupied for each type of storage was given by Worten. Therefore, it was possible to directly represent this number of locations in the blueprint. There was no need to predict values or assume occupancy rates. For all the other scenarios, the number

[4] AutoStore – Swisslog: https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-retrieval-systems/autostore-integrator

of necessary locations was predicted as explained. The process used to draw the blueprints is now presented, starting from the moment when the number of locations was obtained.

For the non-automated systems present (for scenarios 0 to 4), the calculations performed to obtain the blueprints were the following ones:

Din:

1) As there are DIN with different capacities in terms of high pallets locations, the total number of locations existing in the current layout, with four DIN was calculated.
2) Comparing the currently available number of high pallet locations and the number of pallets that will be stored in 2025 (previously obtained), one concludes that there is no need to increase the infrastructure of this type of storage.

Since DIN products will remain in this type of high-density storage, it is estimated that four sets will be required in all scenarios. As the current number of DIN is sufficient to handle the rise in the MP number of pallets expected in 2025, the current DIN layout will remain unaltered.

High pallet racks:

1) For active locations: the high pallets can only be stored in the base level of the rack. Moreover, each level can only accommodate three pallets. In mathematical terms: the number of locations was divided by one level per rack frame and by three at each level.

2) For reserve locations: The number of locations was divided by four levels per rack frame and by three locations per level.

The total number of frames required equals the highest number of frames obtained between the two types of location.

Other storage types:

1) At this point, the number of locations is converted to high pallet locations, considering the following relationships:
    - Height: 1 high pallet location = 2 medium pallet locations = 3 low pallet locations= 4 shelf locations.
    - Length: 1 high pallet location = 1 medium pallet location = 1 low pallet locations= 2 shelf locations.
    - Width: 1 high pallet location = 1 medium pallet location = 1 low pallet location= 1 shelf locations.
2) The number of high pallet locations is divided by 5 in height and by 3 per level on each rack frame, to obtain the number of necessary frames.

Concerning the procedure for converting automated systems' locations into warehouse's dimensions and layout, the steps adopted are illustrated in Figure 25 and described in the following topics.

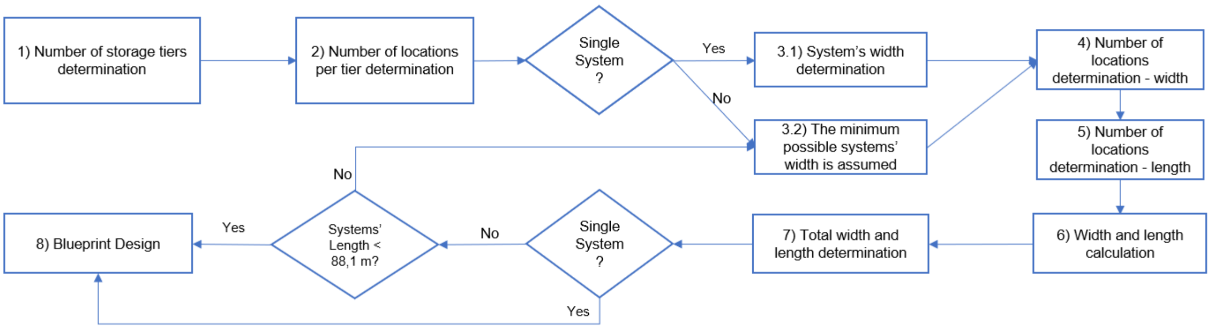

Figure 25 Procedure Followed to Dimension Automated Systems

1) Number of storage tiers determination: dividing the available height by the height required for each location (including buffers).
2) Number of locations per tier determination: dividing the total number of locations by the number of tiers.
3) Determination of the systems' width:

$$Available\ Width = Warehouse\ Width - \ DIN\ width - Racks\ Width \quad (4)$$

3.1 Single System: system's width corresponds to the available width.

3.2 Two systems: initially it is assumed the minimum possible width for both systems. It is then adjusted in each iteration until the pallet systems have a maximum length of 88.1 m (approximately 2/3 of the warehouse length, excluding inbound and outbound areas).

4) Number of locations determination – width: dividing the system's width by the totes' width (considering the respective buffers).

5) Number of locations determination – length: dividing the number of locations per tier by the number of locations determined in 4).

6) Width and length calculation: considering the number of locations and the buffer between them, the dimensions were calculated.

7) Total width and length determination: correspond to the value obtained in 6) plus the space needed to lifts, workstations, conveyors, etc.

8) Blueprint: Drawn for single systems at the first iteration. Drawn for scenarios 2 and 3 when the systems' lengths are lower than 88.1 m.

After the application of the described procedures, the blueprints for 6th June, 2025, presented in Figure 26, were obtained. In scenario As-Is blueprint, fulfillment and LAV products are not considered, as they are currently stored in the mezzanine. In the remaining blueprints, these products are included, assuming they can be stored at ground level, given the higher level of security of the automated storage systems. Concerning the As-Is situation and the expected scenario if the storage systems remain unaltered - scenario 0, the number of DINs remains the same because currently, only two full sets are necessary. Existing structures at the SM level can accommodate a potential increase in the amount of stored goods, as can be seen in the scenario's 0 blueprint.

Comparing the systems for narrow aisles and standard aisles, the increase in the warehouse's area used in SM is far less than the evolution concerning regular racks. This is due to the fact that there is no distinction between active locations and reserve ones in the SM. Or to put it another way, any SKU may be stored in height in one of the five locations. The percentual increase in the number of stored SKUs of high pallet products is higher for SM and it just implies a change from 5 to 8 sets of racks. Alternatively, the change in regular racks is from 33 to 45.

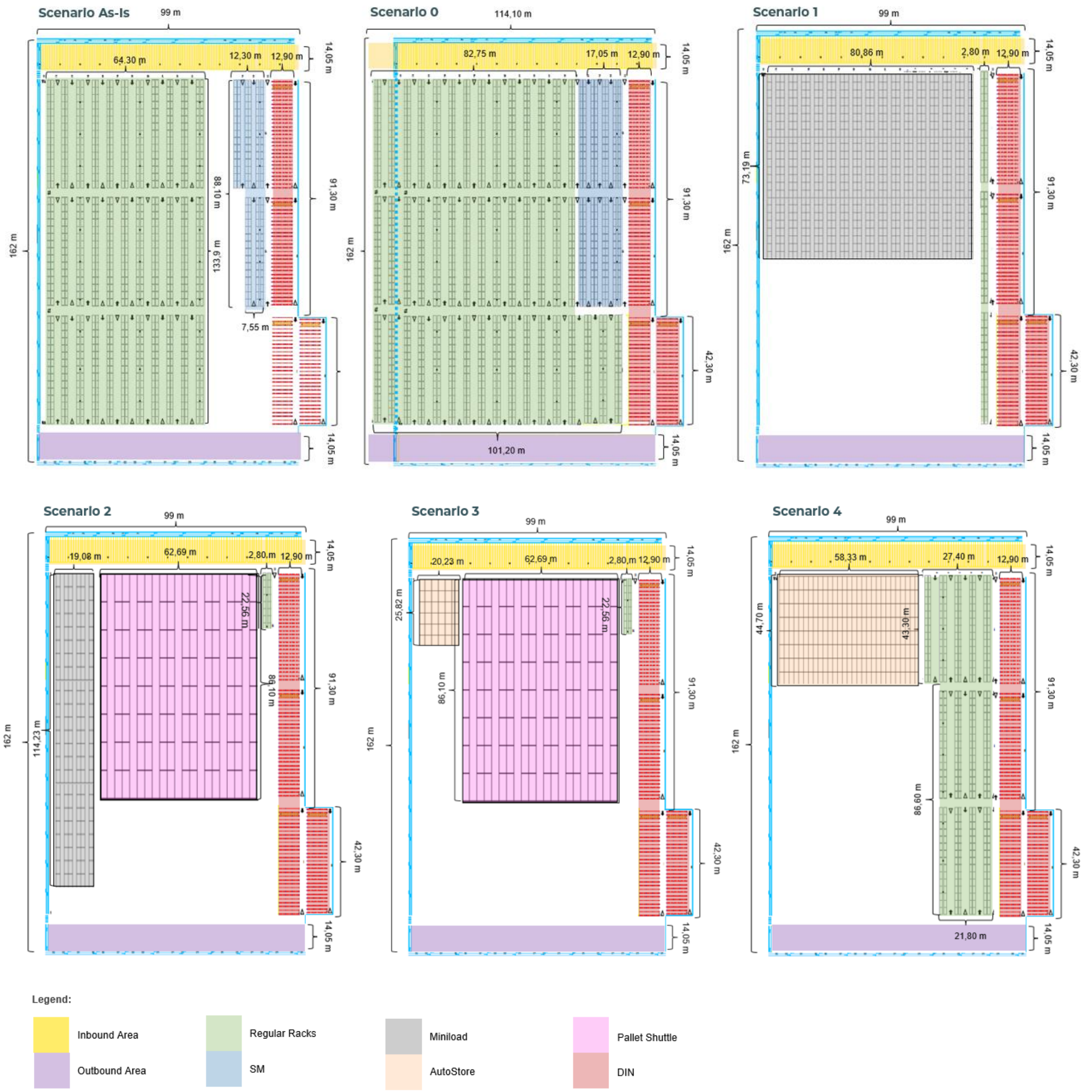

Figure 26 Blueprints for the Six Scenarios

The distinction between active and reserve locations comes with a need for a higher number of rack frames. In terms of picking, it has the advantage of being more productive because it only occurs at the floor level. In the case of the SM, picking in narrow aisles is accomplished using a trilateral forklift, which picks at higher levels. Given the high number of references stored, it would be unbearable to distinguish locations between actives and reserves for SM.

From the analysis of Scenario 0, it is evident that it would be impossible to accommodate the expected growth of 708 items in the warehouse. The company would be facing a situation where the warehouse expansion must be considered.

The blueprints of scenarios 1 to 4 consider a system with active and reserve locations for racks. It was decided that the company's current strategy would remain the same for regular racks to establish an accurate comparison between scenarios in terms of space and time. Since most SM are now stored in automated systems, the only significant difference was the decision to eliminate the narrow aisles method. As a result, the items that are not stored in automated systems, whether SM or not, will be stored in regular racks to avoid jeopardizing the picking productivity. It is important to keep in mind that the number of rack spaces required is now significantly lower since most of the products are stocked in automated systems.

Products that arrive in mono-SKU high pallets are stocked next to the DIN, placing traditional racks far from the operational area and automated systems closer to the operations. Even while it is now not strictly necessary to adopt volumetric organization, the small item storage is carried out next to the preparation area, as in the current company’s strategy. This decision is intended to reduce the travel time from picking to outward, as the picking will be more frequent for these type of products.

Regarding the inbound, MP products also arrive in mono-SKU high pallets. Thus, the allocation of products from the inbound zone to the storage is facilitated. It will be separated into one zone where the pallets are not disassembled and another one where the disassembly happens (AutoStore in scenarios 3 and 4, or Miniload in scenarios 1 and 2). For all the presented scenarios, inbound and outbound zones remain in the same space, maintaining the drive-through model. This way, the products have a one-way flow.

The space-related indicators, that will be presented in the next Chapter, were mostly obtained through the blueprints. In terms of throughput, the methods used to obtain the values for the shuttles and AutoStore systems were different.

For shuttle systems (both Miniload and pallet systems), the retrieval times were obtained with an Excel simulation, after establishing the number of positions to be considered for each system. Three dimensions that represent the positioning on each of the axes (x, y, and z) were used to identify each location. To replicate the picking in various locations, different values of x, y, and z, were randomly generated. To calculate the total distance required to pick the product or pallet in a certain position, three movements were considered: from the starting point to the location; from the location to the picking zone; and from the picking zone back to the location again. For each of the three axes, the distance traveled was determined separately. Then, the required time is determined using the speed of the shuttles (for the x, y axes) and the lifts (for the z axis).

It was not possible to model the retrieval time for AutoStore Systems in the same way. This was caused by the difficulty in simulating the operation of such a complex mechanism. In addition to the robots' vertical and horizontal movements, it would be necessary to simulate the digging process. The time spent digging changes based on the number of goods stored above the tote to be picked. Additionally, the retrieval time is influenced by the flow and quantity of robots as well as the temporal gap between order placement and the start of the picking process (during this time the robots rearrange the totes). Given all these limitations, it was decided to gather information from a Swisslog representative, who indicated the expected throughput of the system considering the number of robots (25 totes/hour/robot) and carrousel ports (250 totes/hour/carrousel). They were considered 20 robots for scenario 3, and 132 for scenario 4. This information is summarized in Table 20 (Appendix).

Chapter 6 – Results Discussion

This Chapter is organized into two subsections. Firstly, there is a comparison between scenarios, that results in the choice of the most suited one. Then, the proposed scenario is analyzed in more detail regarding location utilization, required workforce, and operational impacts. At this point, the impacts that will occur in the warehouse are emphasized, rather than focusing on the economic aspect, in accordance with the scope of this thesis.

First of all, Table 8 quantitatively presents the values obtained for some of the defined KPIs in three dimensions: time, quality, and productivity. The analysis of these results led to the selection of scenario 4 as the most suitable for Worten's reality. With green, are identified the best results for each metric, regarding the projected scenarios for 2025. The spaces filled with "-" indicate values that were not calculated because, in the identified cases, it would be difficult to obtain a reliable result that approximates reality.

Table 8 Predicted Scenarios Results (Scenario 0: Traditional Racks; Scenario 1: Miniload; Scenario 2: Miniload+Pallet System; Scenario 3: AutoStore+Pallet System; Scenario 4: AutoStore)

			Scenarios					
	KPI		**As-Is**	**0**	**1**	**2**	**3**	**4**
Time	Required Full-Time Equivalent (FTE)		105	165	-	-	-	142
	Put-Away Time (s/prod)	Racks	8.4					
		Miniload / AutoStore			1.0	3.9	7.2	1.1
	Order Picking Time (s/tote or s/pallet)	Racks	108 (s/product)					
		Miniload / AutoStore			19.5	30.7	7.2	1.1
		Pallet Shuttle				40.0		
	Pallet's End-to-End Time		2h30		-	-	-	1h44
Quality	Damaged Products (%)	Racks	0.51					
		Miniload/AutoStore			-	-	0.3	0.3
Productivity	Occupancy Rate (%)		64	100	51	60	48	45
	Effective Storage Space (%)		34	51	33	35	30	28
	Storage Efficiency (%)		53	53	64	60	63	63
	Average Storage Utilization Rate	Miniload / AutoStore			54.2	15.5	21.7	52.8
		Pallet Shuttle				85.7		
	Products in Automated Systems (%)		0	0	91	98	98	92
	Expected Throughput (products/h)	Racks	1 100					
		Miniload / AutoStore			5 500	1 080	500	3 500
		Pallet Shuttle				4 928		
	Location Utilization Rate (%)	Miniload / AutoStore			94.9	91.1	89.9	88.8
		Pallet Shuttle				94.1		
	Number of Products per Tote	Miniload / AutoStore			25	9	38	53
		Pallet Shuttle				56		

6.1 Scenarios Comparison

Starting by the non-automated scenarios (As-Is and scenario 0), the difference between them, in terms of occupancy rate, effective storage space, and storage efficiency is shown in Figure 27. The blue bars correspond to the percentage of the 708 zone necessary for the total system (including aisles and other empty spaces).

$$708\ Occupancy\ Rate = \frac{Storage\ Space}{Total\ 708\ Space} x\ 100 \tag{5}$$

The light grey bars are the effective storage space: percentage of the 708 Zone volume that effectively may contain products stored. The percentages for these two metrics are relative to the use of the total

708 space. The percentage of the third metric is not. Dark grey bars show the storage efficiency: ratio between effective storage space and the total space occupied by the system (storage space).

$$Storage\ Efficiency = \frac{Effective\ Storage\ Space}{Storage\ Space} x\ 100 \quad (6)$$

According to scenario 0, the warehouse's occupied volume would increase by 33% in comparison to the As-Is situation if the current storage systems are maintained in the future. The inbound and outbound zones occupy, together, more than 15% of the warehouse's volume, which means that the blue bar should never exceed 85%. As the occupancy rate would correspond to 97%, the current space would not be enough to accommodate the stock. The effective storage space would increase from 34% to 51%. The storage efficiency, which is naturally reduced in conventional systems, corresponds to 53%. This means that only 53% of the total racks space would be available to receive stock. In conclusion, more space would be necessary, and that space would be less effectively used. These numbers reflect the necessity to evaluate alternative methods of storage.

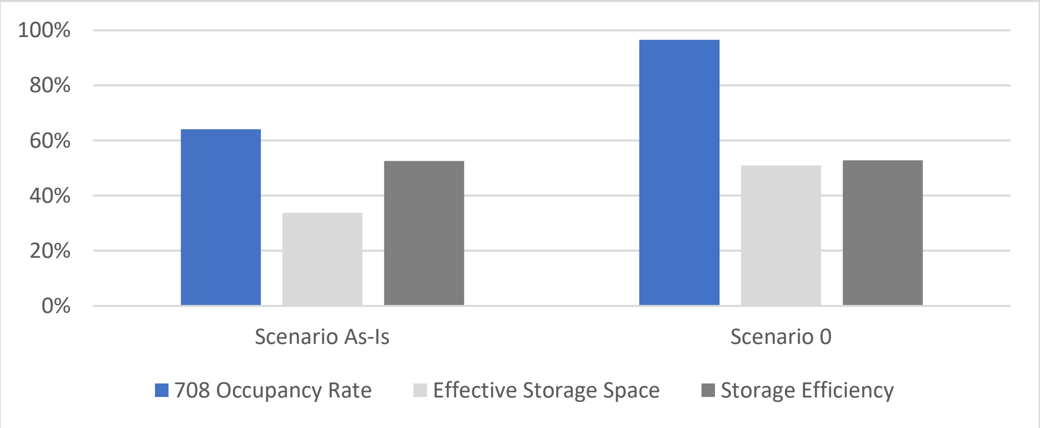

Figure 27 Occupancy Rate, Effective Storage Space, and Storage Efficiency - Scenarios 0 & As-Is

At this point, the five future scenarios developed will be analyzed and compared. This subsection has two main goals: the first one is to draw conclusions regarding the impact of implementing automated systems in the warehouse, through the comparison between scenario 0 and the remaining ones. The second is to choose the best scenario, which will be proposed to the company. To evaluate the scenarios, several metrics are considered in two main areas: occupied space and systems' throughput.

6.1.1 Space Analysis for Future Scenarios

The lack of space is the main driver for Worten to adopt different storage systems. Therefore, the analysis of the four scenarios starts with the following KPIs: occupancy rate, effective storage space, and storage efficiency. Comparing the scenario with no automation with all the others, it is the one with the worst performance, both in terms of space usage and storage efficiency, as depicted in Figure 28. In the same way, in the scenarios with automated systems, products that do not fit in an automated solution result in disadvantages for the warehouse layout and operations. On the one hand, by storing them in conventional systems, the presence of a dedicated area for that type of storage becomes mandatory. Besides, picking in this type of storage is less productive than using a parts-to-picker system. Moreover, there is still a need for replenishment, which is not necessary in automated systems.

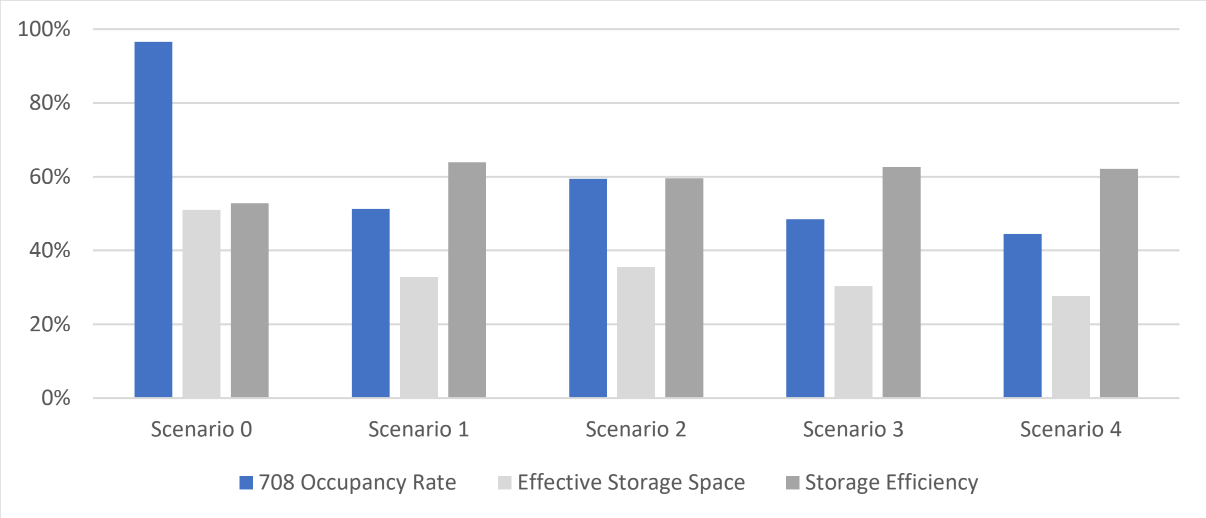

Figure 28 Occupancy Rate, Effective Storage Space, and Storage Efficiency - Scenarios 0-4

Among the four scenarios with automated systems, scenarios 1 and 2 require more space than the others (higher blue bars), which reveals an inefficiency by the Miniload system, in terms of space management, when compared with the AutoStore. In terms of storage efficiency, the results are approximatelly the same for all the four automated scenarios. Thus, scenario 4 is considered the most advantageous option, as is the one with lower space requirements. On the opposite side, scenario 2 is the least advantageous, as it is the one that requires more space.

The differences depicted in Figure 28 are not evident through the blueprints analysis given that AutoStore totes are smaller than those used in the Miniload so, the products' quantity stored in the system is lower and the quantity stored in the racks is higher. In addition, the AutoStore requires empty localizations for the digging process (which impacts the dimensions of the system), whereas the Miniload does not.

The average storage utilization rate for scenario 4 corresponds to 52.8%, which is greater than the current rack system's percentage (where high racks have the higher occupations with 52.2%, and the remaining racks fall below 20% (Figure 19). It is important to note systems 2 and 3 low rates in Miniload and AutoStore, respectively. As most of products would be stored in pallet system (which has a rate of 85.7%), the remaining systems' present low utilization rates (of 15.5% and 21.7%), respectively. In terms of location utilization rate, AutoStore presents a worse performance when compared to shuttle systems. This is due to the necessity of having 10% of the locations unoccupied for digging. Even though it is the lowest of the four automated scenarios, it is still higher than the As-Is scenario, where it is usually below 60% (Figure 20).

6.1.2 Throughput Analysis for Future Scenarios

Figure shows the distribution of the warehouse's volume by storage systems, for each scenario. For scenario 0, which only has rack storage, this will correspond to 100%. For the remaining scenarios, the percentage is distributed across different systems. Note that in scenarios 2 and 3, rack storage represents a residual value of less than 2% of products stored.

Figure presents the throughput for each of the systems. The values shown are in units per hour. However, the racking system is the only one where picking may occur unit by unit. In the cases of Miniload and AutoStore, picking is done using totes (with different quantity of items), and in the pallet system, it is done using pallets. Scenario 0 has the lowest throughput. All five scenarios show the same throughput for the rack system. The variation lies in the number of existing racks, not in the throughput. The considered throughput was obtained from the current picking productivity of 1.8 minutes per item. This assumption that the throughput remains constant when the number of racks decreases implies a variation in the number of pickers proportional to the reduction in rack locations for each scenario, as Table 21 (Appendix) shows.

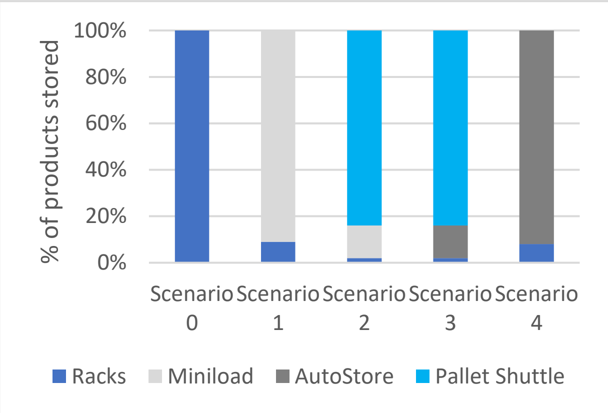

Figure 29 Products Stored per Automated System, in Each Scenario

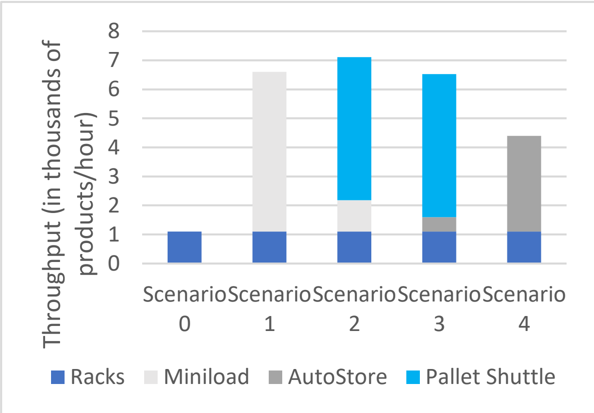

Figure 30 Systems' Throughputs in Each Scenario

Figure shows that, similar to what was observed in terms of space, automation would also bring benefits in terms of time, regardless of the system(s) adopted by Worten. This is because scenario 0 has only one type of storage for all products, which is the one with the lowest throughput. Regarding automated systems that store totes, Miniload proves to be more efficient than AutoStore. Miniload's throughput in scenario 1 is higher than in scenario 2, given the larger stored quantity. Scenario 2 stands out with the highest throughput values.

AutoStore reaches a throughput of 500 products/h (scenario 3) and 3 300 products/h (scenario 4) with the considered number of robots (as it will be further explained). Being equivalent systems, the throughputs for pallet shuttles in scenarios 2 and 3 are the same, as well as the quantity of products stored. It's important to note that this throughput value in units per hour is based on an average of 56 products per pallet and assumes that all these products are picked.

To select the most suitable scenario for the company, in terms of throughput, one must discover the capabilities that the systems should have to ensure the warehouse's smooth operation. With that purpose, the number of products that should be processed on Black Friday in 2025 was projected based on the quantity of products processed on Black Friday 2022 (27 700 products, on 20/11/22). The number of processed items in 2022 accounted for 90% off all the orders' products for that day. Based on the expected quantity evolution for the next two years, in 2025, 50 143 items will need to be processed. Considering a working day of 14 hours (2 shifts of 7 hours each), it will be necessary to process 3 582 products per hour.

Table 9 contains the steps followed to obtain the required capacity for each system. In the last columns, it is established the comparison with the designed capacity. Firstly, the total quantity of products is allocated to the systems. Then, the number of products per day is converted into products per hour and totes per hour (or pallets per hour) to be compared with the systems' throughput. The last column shows the ratio between products to be processed per hour and the processing capacity of each system. For scenario 0, it was assumed that productivity remains equivalent to the As-Is scenario. Racks were not considered for scenarios 1 to 4, as they represent a reduced percentage of stored items.

Table 9 Comparison Between Systems' Throughputs and Necessary Throughputs for Black Friday

			Predicted Demand - Black Friday			**Systems' Throughput**		**Ratio products / h (%)**
System	Units per tote or pallet	% of Products	Products p/ day	Products p/h	Totes or pallets p/h	Totes p/ h	Products p/h	
Scenario As-Is	-	100	30 778	2199	-	-	1979	90
Scenario 0 Racks	-	100	50 143	3 582	-	-	1979	55
Miniload Scenario 1	25	91	45 631	3 260	131	220	5 500	169
Miniload Scenario 2	9	12	6 018	430	48	120	1 080	251
Pallet Shuttle	56	84	42 121	3 009	54	88	4 928	164
AutoStore Scenario 3	38	14	7 021	502	14	14	500	100
AutoStore Scenario 4	53	92	46 132	3 296	63	66	3 300	100

Based on the analysis of scenario 0, if the current storage strategies are maintained, the order processing capacity on the Black Friday will decrease from 90% to 55%. Miniload's capacity is considerably higher compared to the necessary one. In scenario 1, Miniload's throughput is 1.7 higher than the required to meet the expected demand. In the same way, in scenario 2, Miniload presents a throughput 2.5 times higher than necessary, and the pallet shuttle system exceeds the required throughput by 1.6 times. While having a higher throughput than what is expected may not be a problem in terms of time and operations, these values indicate an over-dimensioning of the systems in question. It is possible to change the layout of the system (increasing the length and decreasing the width) to decrease the throughput, reducing the investment. However, space occupancy would remain high. Thus, the adoption of these systems is not advisable in this context, not only due to the costs of having an excessive number of aisles but also the unnecessarily high throughput. Instead, multi-deep storage alternatives could be studied in the future, to adjust the systems' throughput capacity with the necessary one, reducing the occupied space.

Lastly, AutoStore presents the closest throughput to expected values. This was only possible because the number of workstations and robots was defined considering the expected throughput values, unlike shuttle systems, which are limited by the number of existing aisles. For scenario 4, during Black Friday, it would be necessary to utilize 14 workstations and 132 robots for picking. However, for low and medium-demand seasons, a reduced number of robots and workstations may be used. One of the clear benefits of AutoStore is its high flexibility due to the ease of expanding the number of locations or the number of robots if the business demands it. As mentioned, the current demand patterns and the growth of e-commerce make this factor a key element for Worten.

In conclusion, the recommended scenario for the company is the fourth. As aforementioned, it is the best in terms of space, this being the company's priority. Additionally, the throughput analysis shows that this last scenario's throughput will not be a limiting factor for the company. Despite the lower rack throughput, we observe that only about 8% of the products are stored in this type of storage. Most picking will occur at a rate of 3 300 products per hour, which is suitable for the company's needs.

6.2 Scenario 0 Vs Proposed Scenario

Once scenario 4 was chosen as the most suited one, based on time and space KPIs, it is time to compare the proposed solution with the future one presented in scenario 0. The beneficial results achieved in scenario 4 are due to the fact that the AutoStore system allows for a high storage density, significantly improving the footprint usage, and offers high picking throughput. In this subsection, a deeper analysis was performed in terms of required workforce, end-to-end time and operational impacts.

Table 10 contains the work-related requirements. A comparison is established between As-Is situation and scenarios 0 and 4. The process for obtaining the number of employees needed for the rack system's put away was previously described. The number of workstations leads to the conclusion that the AutoStore picking and put-away will require 14 employees each. The new system puts an end to the replenishment activity, that currently requires 2 full-time-equivalent (FTEs). In the proposed scenario, it is assumed that some of the tasks (reception, PTL, billing, PTS, and shipping) will follow a linear increase based on the evolution of quantities of stock, like what was assumed for scenario 0.

Table 10 Workforce Dimension per Activity for Scenarios As-Is, 0 & 4

Activities	As-Is	Scenario 0	Scenario 4
Reception & conference	15	25	25
Put-away - Racks	15	25	6
Put away - AutoStore	-	-	14
Replenishment	2	3	0
Pickers (Retail and Online) - Racks	33	45	13
Pickers - AutoStore	-	-	14
PTL (Retail and Online)	10	17	17
Billing ONL	6	10	10
PTS	9	15	15
Shipping	15	25	25
TOTAL	105	165	139

For scenario 0, it is anticipated that the required number of operators will rise to 165, which consists in a 57% increase over the current number of workers. Besides the additional costs for the company, this could result in issues related to a lack of workspace for employees, which already occurs at the operational area, namely in the PTS. One can see that in the suggested scenario, the required workforce to ensure the warehouse's operations corresponds to 85% of the one needed in scenario 0. The end-to-end time is the indicator utilized to calculate how long it takes a product to move through the entire warehousing process. The information from Table 21 (Appendix) was used to derive the values for this metric.

A pallet's end-to-end time was found for both scenarios 0 and 4. This means that the route taken by a pallet whose products are to be stored in AutoStore (major system of the suggested scenario) was compared with a pallet that is supposed to be stocked in traditional racks (As-Is scenario). From its arrival to its shipment, the values considered for both scenarios are in Table 11.

Table 11 Pallet's End-to-End Time Calculation

	Racks	**AutoStore**
Reception	0.6 min/pallet	0.6 min/pallet
Pallet Disassemble	-	4.5 min pallet
Conference	0.16 min/product	0.16 min/product
Put-away	0.14 min/product	2 min/tote
Replenishment	0.25 min	-
Picking	1.8 min	1.1s/product
Shipping	0.8 min/pallet	0.8 min/pallet
End-to-end time	2h20min/pallet	1h30min/pallet

Some of the productivities are the same in both cases as they are not directly impacted by the storage system being used. This applies to the reception, conference, and shipping stages. Replenishment ceases to exist in scenario 4. The calculated values for the AutoStore scenario were: pallet disassembly, put-away, and picking. From the previously discovered AutoStore's throughput it is derived a picking time of 3 300 products/h, that is converted to 1.1 seconds per product. The pallet disassembly value is assumed to be half of the current pallet assembly value in the warehouse (9 minutes per pallet), given that it is a less complex and faster task. The put-away time is derived from the average time to fill a tote (like the put-away process in the AutoStore), obtained through experiments conducted in the warehouse, the results of which are presented in Table 22 (Appendix) and lead to an average filling time of 2 min/tote.

The time it takes for the tote to be organized within the system in its location was disregarded, considering that this process can occur simultaneously with the put-away of other products. The product's shelf life was not considered for neither the scenarios, as it varies from product to product and is not dependent on worker/systems productivity. There is an expected reduction from 2h20min to 1h30min in the pallets' end-to-end time. It other words, it represents a 36% reduction of the time it takes to process a pallet of products. This result may contribute to Worten's objective of transitioning to a "same day delivery" policy instead of the current "next day delivery". AutoStore also solves a lot of operational issues identified in section 5.3.1 Critical Points Identification.Picking productivity will be improved because of batch picking being restricted to products stored in racks. The end of the narrow aisles will also contribute to that improvement. In the proposed scenario, only bulk picking is utilized for most of the products. Picking is done to the grouped items, with those items then being sorted by stores in the PTS - Production Area. This comes with a restriction: PTS zone will not have enough room to support an increase in the number of employees. As a result, the PTS may be expanded as the available space in the storage area will increase, or it may be considered the implementation of an automatic sorter to avoid the PTS extension. Currently, the warehouse bottleneck occurs in the operations zone. However, the implementation of an automated sorter with a throughput of 8 000 products per hour is now being studied for this zone, to solve the issue. Thus, picking will become the new bottleneck if no automation is implemented. On the other hand, AutoStore has potential to reach the throughput of the operations' sorter (with the addition of robots and workstations).

AutoStore independently organizes its locations, so products' location changes in a completely dynamic way. This will end with the current fixed-picks system. Consequently, the empty locations caused by the lack of the product to which they are assigned cease to exist and are automatically assigned to another SKU that is actually in the warehouse, avoiding the honeycombing effect. This may be especially useful for references that have seasonal demand. This solution also solves the manual put-away issue that currently exists, because the system itself is responsible for allocating products to their correct locations rather than requiring human intervention. The operator only has to add items to the system. Additionally, it is the end of the distinction between active and reserve locations. It created issues regarding the available ground space. The increase in the number of mezzanine products is no longer an issue, as there is more available space and the system is expandable, also because fulfillment and LAV products already do not require to be stored in a separated area. At the operational level, the emergence of new product categories was already an issue due to the fixed-picks systems and the lack of active locations. The lack of space led to an improper use of SM racks to manage the expansion of the range by storing there new references. This would stop happening in the future.

The drawbacks associated with this system implementation, compared to others, include the reduced selectivity of products and the substantial investment. In terms of operations, adopting scenario 4 will have implications for both inbound and outbound processes. After receiving the products, it is necessary to disassemble the pallets since the products are individually placed into totes that are stored in the system. Nevertheless, the depalletization process already occurs for pallets that contain more than one SKU. In addition to a designated inbound area for depalletization and employees assigned to this new activity, it could be beneficial to implement a conveyor system to transport the products from the inbound area to the workstation. This ensures that a bottleneck is not created in the preparation process and is beneficial in terms of ergonomics. There needs to be a smooth flow between rack operations, with batch picking done by forklifts in the rack area and bulk picking with predominantly automated operations in the AutoStore zone. Regarding the significant initial investment, most of it comes from the grid, which, in the case of scenario 4, would be of considerable size (2 608 m^2) to store all the necessary items. In this sense, a potential adaptation to the presented scenario, which is commonly used in companies that implemented this system, is to store a smaller quantity of each reference in the AutoStore (enough to meet the expected demand for each week, for example), while the remaining stock is stored in racks. Certainly, this adaptation would require frequent restocking of the AutoStore, but it would reduce system costs by storing only what is strictly necessary in the more expensive system. It would also prevent the occupation of the system with products of very low popularity for extended periods. To further clarify this issue, an analysis of the popularity-cube movement profile of the products was conducted. The analysis of Figure allows to take some conclusions regarding the pertinence of implementing automation for the type of items in question.

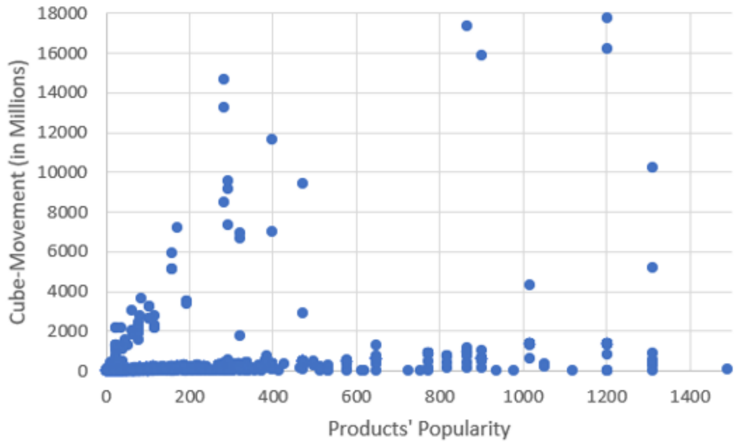

Figure 31 Cube-Movement Analysis

On the x-axis is represented the products' popularity (based on the turnover of each item, provided by Worten), and on the y-axis, is the cube movement - a measure that refers to products' movement, considering the three-dimensional space. The outliers were previously removed from the figure. According to Frazelle (2016): "Items with low popularity and low cube movement cannot be justifiably housed in an expensive storage mode". It is natural for a company like Worten to have articles with low popularity, given the quantity and variety of items sold. It is difficult to have many high-popularity items, and the ones that do exist are seasonal depending on when promotions are offered. The cube movement is generally low, which is expected, considering the products' low dimensions. The investment in automation for articles that fall in the bottom left corner of the figure must be carefully studied. There are products with high popularity (bottom right), and for these, automation can bring greater benefits, considering that they generate the most picking activity per unit of space. Typically, these are products classified as "A", stored in the most accessible pick locations. Throughout the study, product size and weight were the criteria for determining which products would be stored in automated systems and not on.

Chapter 7 – Conclusions, Limitations & Future Work

This last Chapter has three goals. Initially, it aims to briefly present the most relevant conclusions obtained throughout the study. Secondly, the main limitations of this Dissertation are outlined. Lastly, recommendations for future research are presented, aiming to give continuity to the developed work.

7.1 Conclusions

The first step aimed to present the Worten case study that served as the foundation for all the developed research. In Chapter 2, the current layout of the Azambuja warehouse was described, as well as the main flows and operations. It becomes clear that Worten requires improvements in its storage management for low-volume products, due to the increasing level of inventory that is being held. Furthermore, an extensive review of the literature was conducted in Chapter 3. The current storage systems were described, and potential automated systems to implement were identified, as well as their main characteristics, advantages, and drawbacks. At the end of the third chapter, it was concluded that there were some noteworthy gaps in the literature concerning the impacts of automated systems within a warehouse: there was a need for a holistic approach to deal with the consequences of implementing automated systems in a warehouse, particularly focusing on inbound processes. In addition, a gap was identified between the academic research on this topic and its practical applications in the industry, highlighting the relevance of this work. Moving on to Chapter 4, relevant frameworks, that could serve the purpose of this Dissertation, were also identified in the literature. The decision support framework presented by Baruffaldi et al., (2020) in the paper "Warehousing process performance improvement: a tailored framework for 3PL" was adapted and applied to the case study, in Chapter 5. Through this application, the As-Is scenario was extensively explored, as well as the available data, regarding the warehouse's storage area. Subsequently, relevant KPIs were defined, and five predicted scenarios for 2025 were created, and later tested, each one involving different storage systems. Scenario 0 consisted in the warehouse's situation, maintaining the current storage systems. Scenario 1: considered the implementation a Miniload SBS/RS. In scenario 2, the warehouse would combine two automated systems: Unit-Load SBS/RS - and Miniload SBS/RS. Scenario 3 combined Unit-Load SBS/RS and a RCSRS. Lastly, scenario 4 considered the implementation of a RCSRS. In Chapter 6, the most suitable scenario was identified -scenario 4 - and its impacts in the warehouse were explored.

The implementation of a RCSRS could represent a 52% reduction in the required space for 2025 and an increase of 9.4 % in storage efficiency. Additionally, it comes with a throughput that would allow for a 10% increase in the company's service level during the most demanding periods (Black Friday 2025). Finally, it could reduce by 36% the time it takes to process a pallet of products, contributing to Worten's strategic goal of implementing a "same day delivery" policy.

The main contributions of the present work consist of the application of a tailored framework for the implementation of automation in a warehouse; the proposal of a customized solution that fulfills Worten's specific requirements, and the exposition of the impacts across the warehouse's processes. Therefore, it can be considered that the objectives of this study were achieved, and it will contribute to Worten' future strategy and for the scientific community.

7.2 Limitations

After presenting the study's results, it is important to highlight its limitations. Firstly, a considerable amount of data had to be assumed due to a lack of information available. In other cases, some data had to be disregarded, for example, for product's weights that were not available. These assumptions were identified throughout the dissertation, namely in section 5.4.3 Systems Design.

Another significant limitation concerns the forecasts made regarding the evolution of stock held, for 2025. Data from previous years does not guarantee that the same patterns will be verified in the future. Nevertheless, it was assumed that the stock evolved linearly throughout the years, both in terms of products' quantities and number of SKUs, which can have direct impacts in the systems sizing and expected throughputs. Besides, it was assumed that the evolution in products' quantity would have a linear impact in the number of necessary totes to store them, which also impacts systems' dimensioning.

Additionally, concerning throughput, the calculation procedure for shuttle systems, both Unit-Load and Miniload ones, did not account for the capability of these systems to reorganize their stock to facilitate the most popular item's picking. Finally, when dimensioning the automated systems, the optimization of operations regarding retrieval times was not considered. Instead, only space optimization was taken into account.

7.3 Future Work

To finalize this Dissertation, some suggestions for future studies, that may bring valuable insights on this topic, are provided. Future work can extend the developed study by considering different storage policies (class-based approaches, for example) and their respective consequences in terms of throughput and operations.

Another area of research that could be delved into is the automated systems' impacts on workers interactions. In this study, only the workforce requirements were calculated. However, this topic constitutes a gap in the literature that has been increasingly explored recently. Sustainable operations is another field currently being studied, but still requires more research, particularly in the inclusion of environmental related metrics in warehouse management (Staudt et al., 2015). Environmental performance KPIs were not within the scope of this work, however, future studies could give continuity to the developed work by including the topic. Similarly, cost optimization can be considered. This project could serve as a basis to obtain a scenario with optimized costs.

Other metrics could be considered to determine which products are stored into the automated systems, such as the item's popularity and cube-movement, instead of only considering the dimensions and weight of the items to be stored.

Lastly, it is encouraged that the implementation of automated systems for other warehouse activities, such as receiving and sortation, is investigated further. The current work can be used to study the interactions between the automated storage and these two other automated activities. For Worten, it could be particularly interesting to study the implementation of a sorter in the PTS, as previously mentioned in Chapter 6 – Results Discussion.

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A. Supplementary Images to Chapter 2 - Case Study

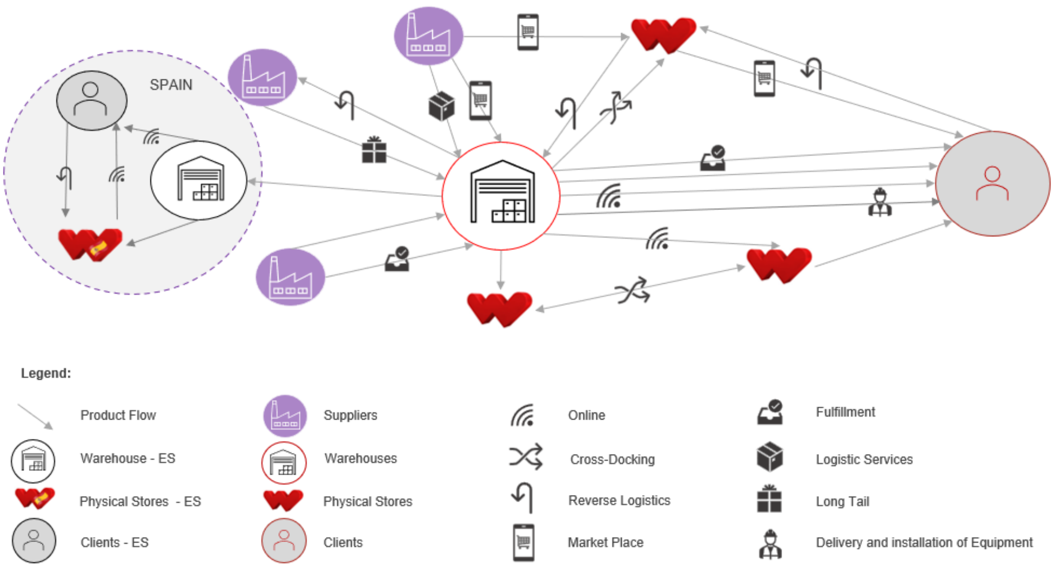

Figure 32 Networked Supply Chain

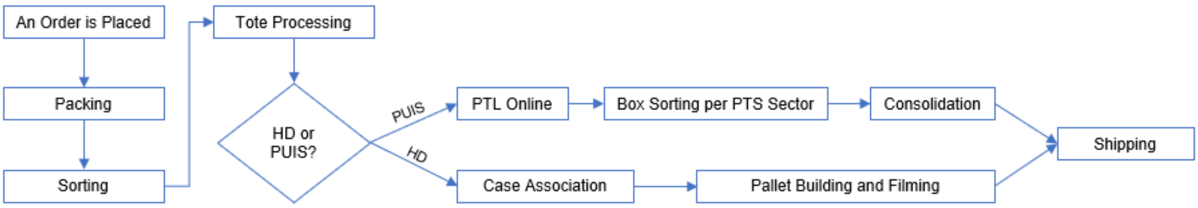

Figure 33 Online Area Operations

B. Supplementary Images to Chapter 3 - Literature Review

Table 12 Design Problems According with the Three Axes | Adapted from: Rouwenhorst et al., (2000)

<table>
<tr><td></td><td></td><td colspan="8">Level</td></tr>
<tr><td></td><td></td><td colspan="2">Strategic</td><td colspan="3">Tactical</td><td colspan="2">Operational</td></tr>
<tr><td rowspan="4">PROCESSES</td><td>Receiving</td><td>-</td><td>-</td><td rowspan="4">Layout; Peripheral Equipment and Workforce Capacity</td><td>Number of Docks;</td><td>-</td><td rowspan="4">Work Force Assignment</td><td>Dock Assignment</td></tr>
<tr><td>Storing</td><td>Storage System; Storage Unit</td><td>Separate Reserve Area?; Different Types of Storage Systems?</td><td>Technical Zones; Storing Equipment</td><td>Forward and Reverse Area; Storage Concept; Pick Zones</td><td>Replenishing Task Assignment; Storage Plan</td></tr>
<tr><td>Picking</td><td>Sorting System</td><td>Batching?</td><td>Picking Equipment</td><td>Batch Size</td><td>Batch Formation; Picking Task Assignment; Sequencing Picks; Dwell Point; Chute Assignment</td></tr>
<tr><td>Shipping</td><td>-</td><td>-</td><td>Number of Docks</td><td>-</td><td>Dock Assignment</td></tr>
<tr><td></td><td></td><td>Resources</td><td>Organization</td><td colspan="2">Resources</td><td>Organization</td><td>Resources</td><td>Organization</td></tr>
</table>

Table 13 Performance Metrics of a Warehouse | Adapted from Ramaa et al., (2012)

Category	Measure	Definition
Order fulfillment	On time delivery	Orders delivered on time per customer requested date
	Order fill rate	Orders filled completely on first shipment
	Order accuracy	Orders picked, packed and shipped perfectly
	Line accuracy	Lines picked, packed and shipped perfectly
	Order cycle time	Time from order placement to shipment
	Perfect order completion	Orders delivered without changes, damage or invoice errors
Inventory management measures	Inventory accuracy	Actual inventory quantity to system-reported quantity
	Damaged inventory	Damage measure as a % of inventory value
	Storage utilization	Occupied space (square footage) as a % of storage capacity (square footage)
	Dock to stock time	Average time from carrier arrival until product is available for order picking
	Inventory visibility	Time from physical receipt to customer service notice of availability
Warehouse productivity	Orders per hour	Average number of orders picked and packed per person-hour
	Lines per hour	Average number of lines picked and packed per person-hour
	Items per hour	Average number of items picked and packed per person-hour
	Cost per order	Total warehousing costs. Fixed: space, utilities, and depreciation. Variable: labor/ supplies
	Cost as a % of sales	Total warehousing cost as a percent of total company sales

Table 14 Classification of KPIs | Adapted from: Nantee and Sureeyatanapas, (2021)

Dimensions	Categories	Criteria
Environmental	Environmental impacts	Dust, odor, and air emissions
		Waste
	Consumption and conservation of natural resources	Electricity consumption
		Non-renewable energy consumption
		Non-recyclable materials used
Economic	Productivity and resource utilization	Equipment downtime
		Work simplicity
		Labor productivity
		Equipment utilization
		Space utilization
	Accuracy	Storage accuracy
		Shipping accuracy
		Picking accuracy
	Responsiveness and flexibility	Warehouse order cycle time
		Delivery flexibility
		Order size flexibility
	Financial outcomes and market presence	Damage and loss
		Customer satisfaction
		Operating costs
		Profit
Social	Human resource management and employee welfare	Employee perception of job insecurity
		Employee health and safety
		Employee skills development
	SC visibility and transparency	Information tracking and sharing capability

Table 15 Direct Indicators Classified According to Dimensions and Activities Boundaries | Adapted from: Staudt et al. (2015)

Dimensions		Receiving	Storage	Inventory	Picking	Shipping	Delivery
	Time	Receiving time	Put-away time		Order picking time	Shipping time	Delivery lead time
		Dock to stock time			Order lead time		
		Queuing time					
	Quality		Storage accuracy	Physical inventory accuracy; stock-out rate	Picking accuracy	Shipping accuracy; orders shipped on time	Delivery accuracy; on-time delivery; cargo damage rate
					Order fill rate; Perfect orders		
		Customer satisfaction; Scrap rate					
	Cost			Inventory cost			Distribution cost
					Order processing cost		
		Cost as a % of sales					
	Productivity	Receiving productivity		Inventory space utilization; turnover	Picking productivity	Shipping productivity	Transport utilization
					Outbound space utilization		
		Throughput					

Figure 34 Drive-in System. Picture from Worten Warehouse

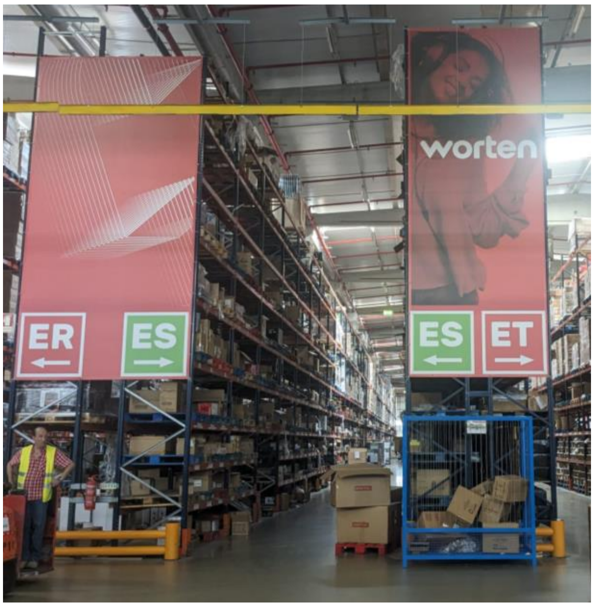

Figure 35 Racking System. Picture from Worten Warehouse

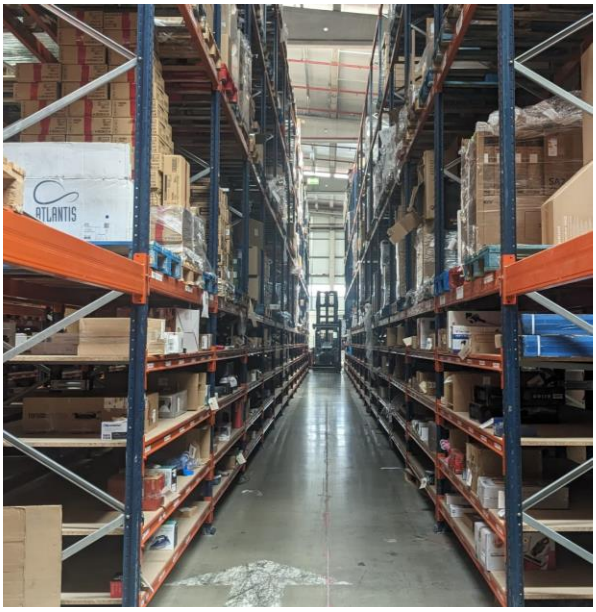

Figure 36 Narrow-Aisle Racking System. Picture from Worten Warehouse

Figure 37 Mezzanine System. Picture from Worten Warehouse

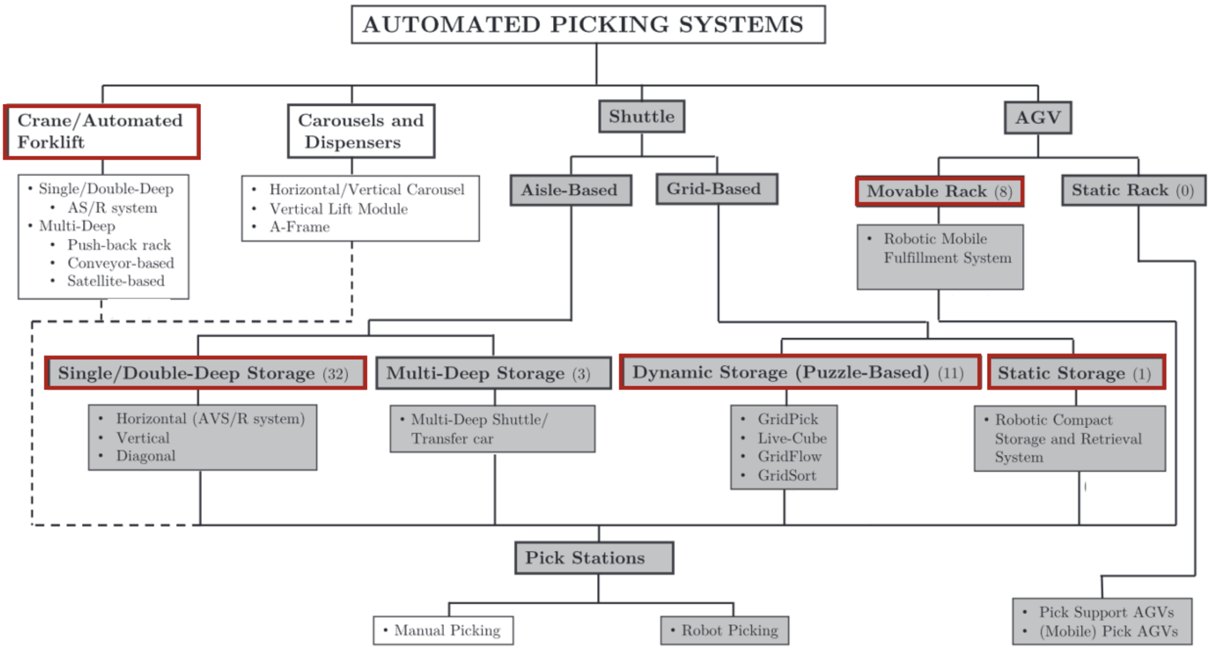

Figure 38 Classification of Automated Picking Systems | Adapted from: Azadeh et al. (2019)

C. Supplementary Images to Chapter 4 - Frameworks Presentation

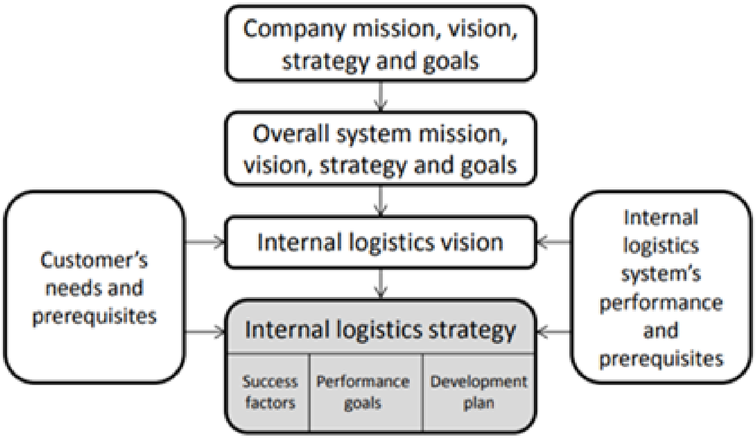

Figure 39 Overview of the Internal Logistics Strategy Model | Source: Granlund (2004)

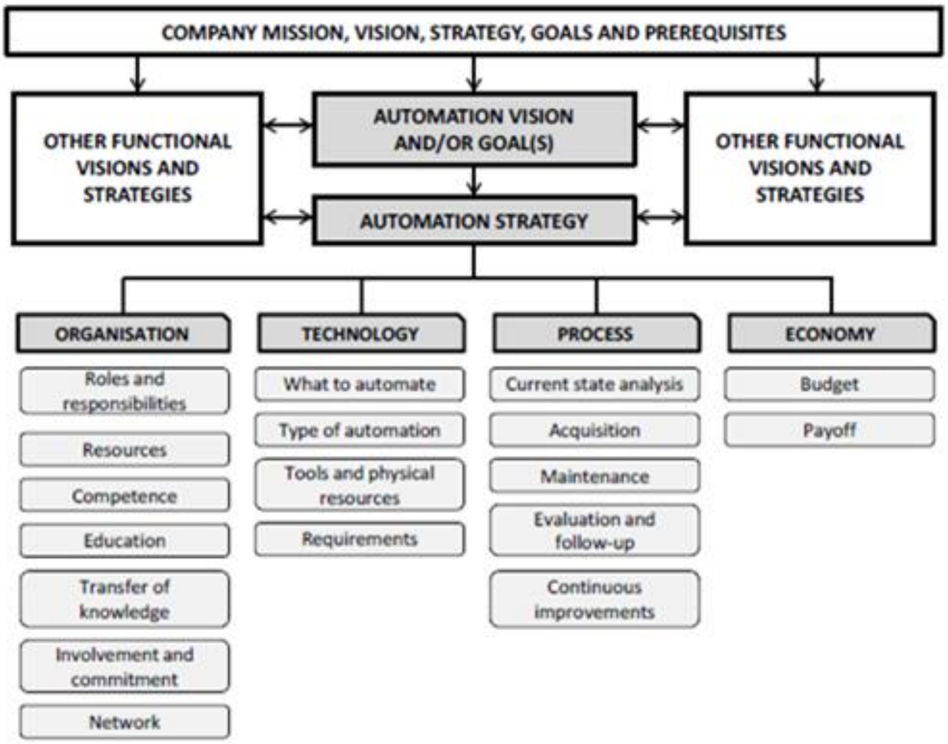

Figure 40 Overview of the Automation Strategy Model | Source: Granlund (2004)

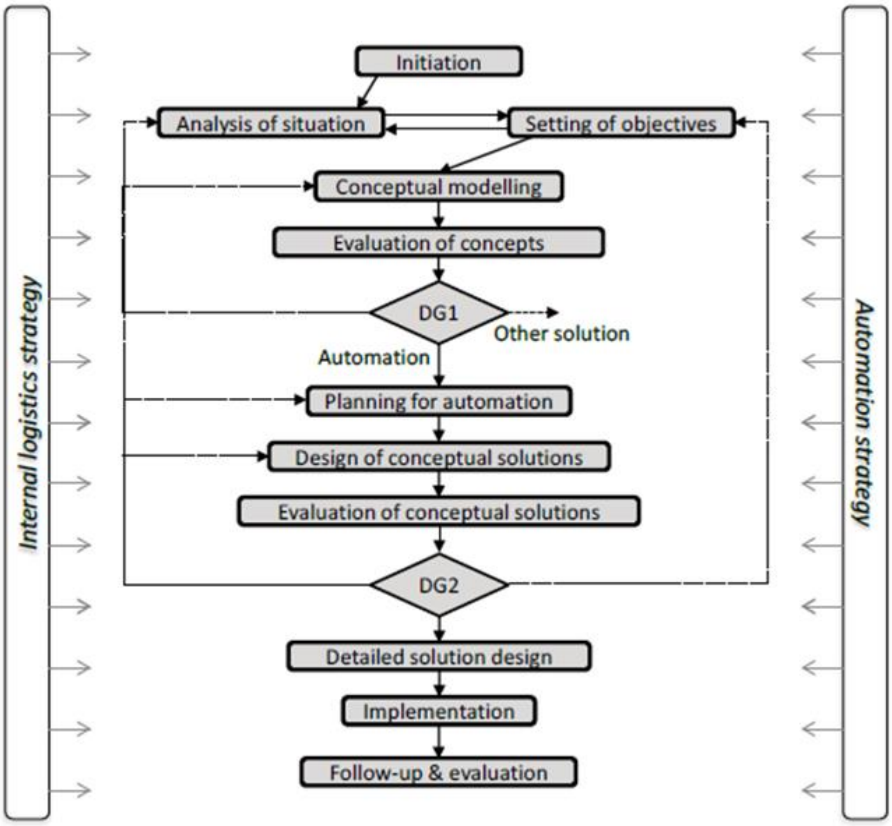

Figure 41 Process Model for Automation Development in Internal Logistics Systems | Source: Granlund (2004)

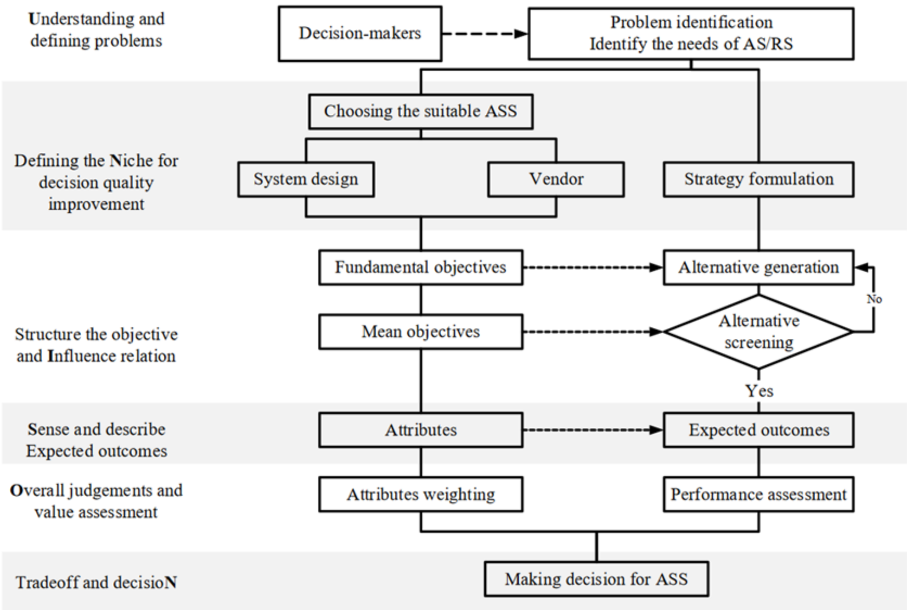

Figure 42 UNISON research Framework for Automated Storage System Selection | Source: Darmawan et al. (2022)

D. Supplementary Images to Chapter 5 - Framework Implementation

Table 16 Business Unit's Designations of 708 Products

Business Unit (UN)	Designation
29	New Business
51	Large Appliances
52	Entertainment
53	Image & Sound & Photo
54	Informatics
55	Telecommunications
56	Small Appliances
57	IT Accessories and Multimedia
61	Sports & Outdoor
63	Security Services
64	Technical Services
68	Telecom Services
69	Store Services
84	Repair parts
90	Home Decor & Services
91	DIY & Garden
93	Health & Well-being & Baby

Table 17 Measures of Each Feature

Warehouse's Feature	Measure (m)
Regular aisle width (vertical aisles)	3.35
Narrow aisle width (vertical aisles)	1.95
Aisle width (vertical aisles)	3.50
Rack length	42.30
Rack width	2.80
Warehouse's stacking height	11
Mezzanine's height	4.5

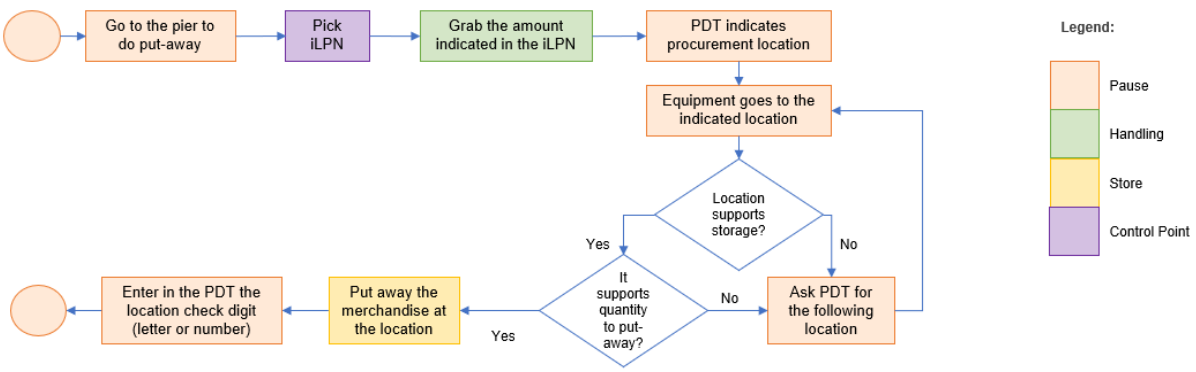

Figure 43 Diagram of Put-Away

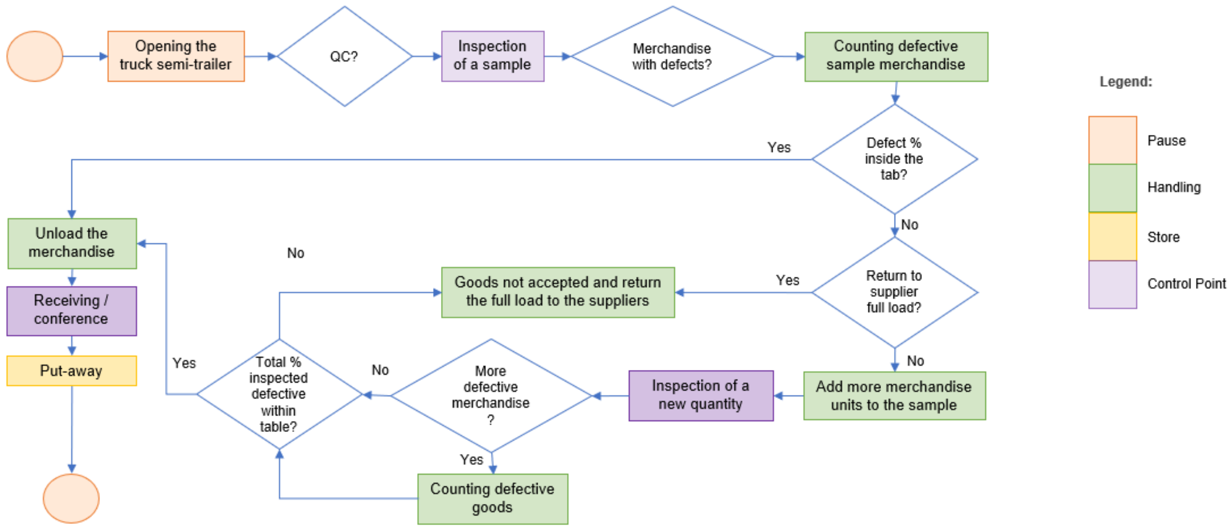

Figure 44 Diagram of the Unloading Operations

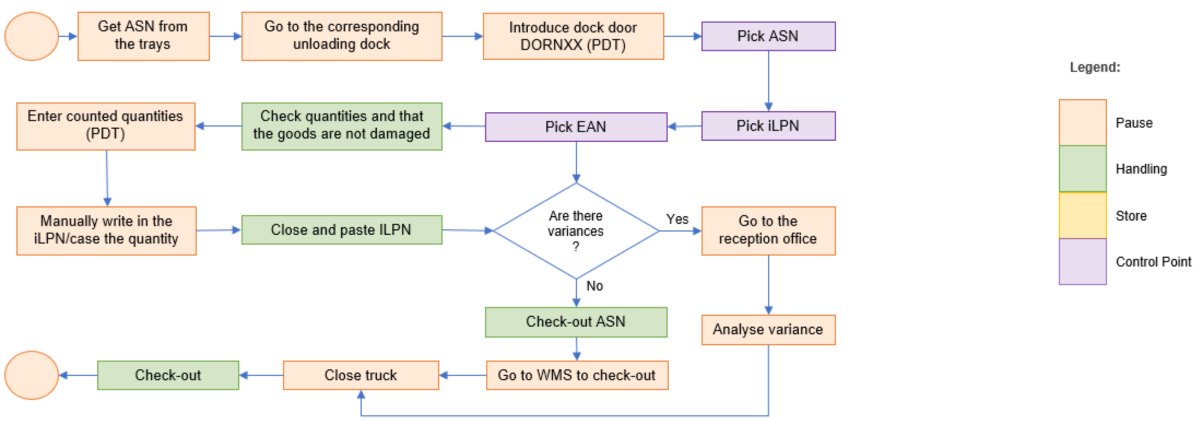

Figure 45 Diagram of the Check/Reception Process

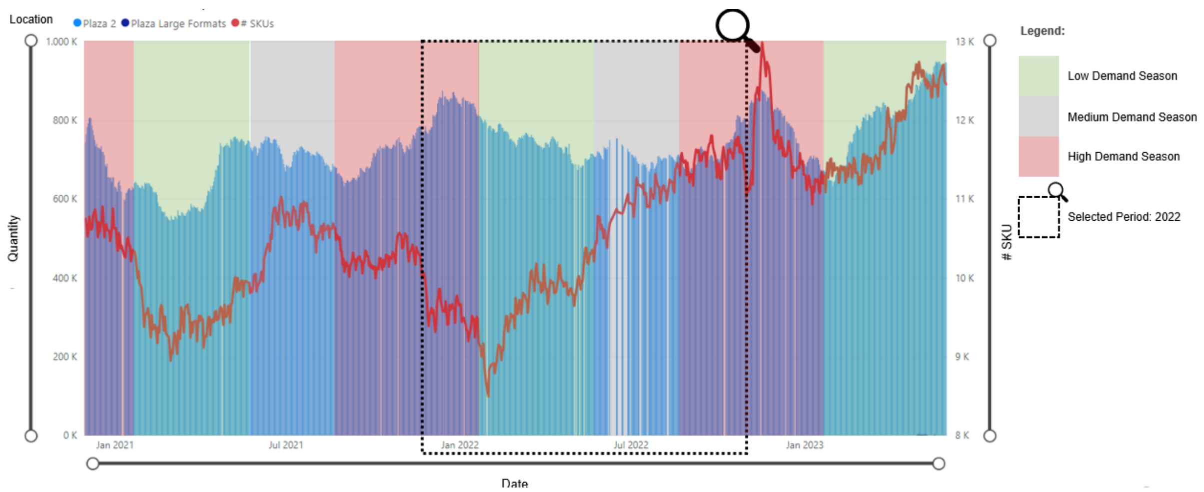

Figure 46 Demand Seasons from 01/21 to 06/23

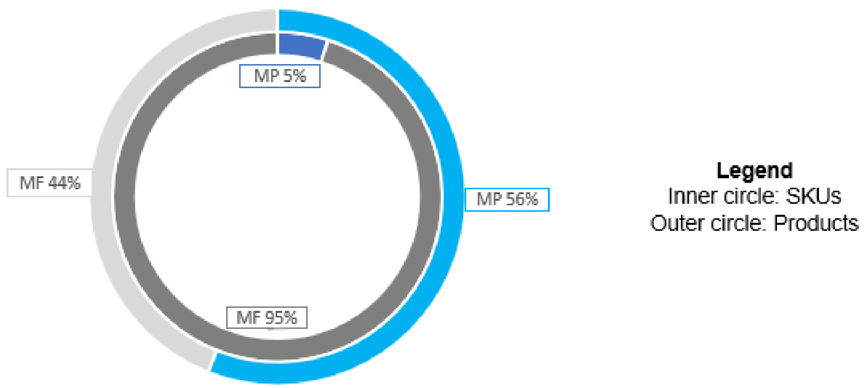

Figure 47 Percentage of Products and SKUs Stored per Brand Type

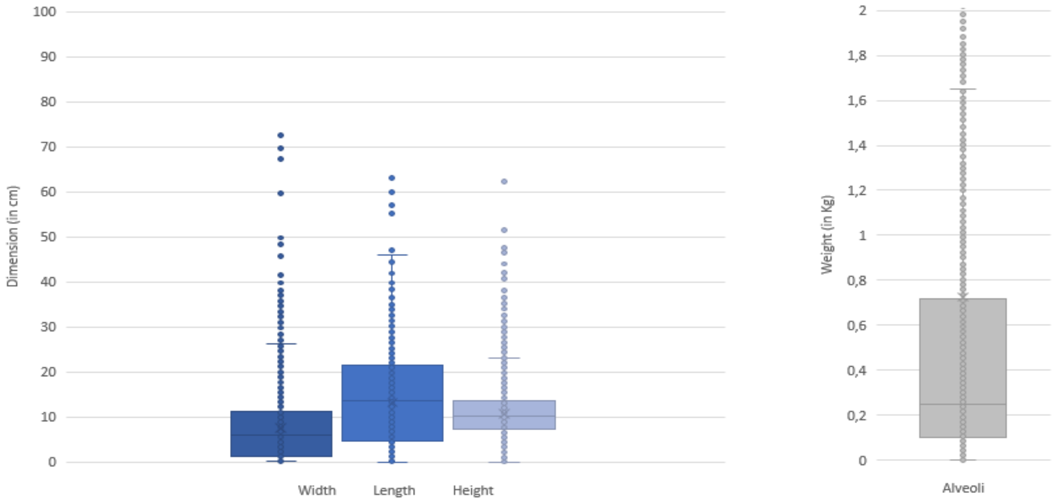

Figure 48 Alveoli Products Dimensions and Weight

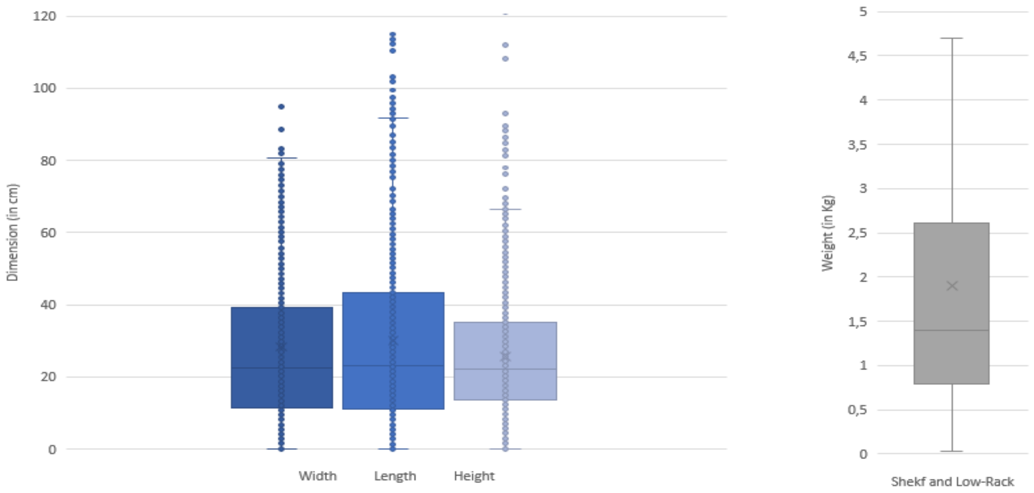

Figure 49 Shelves and Low Racks Products Dimensions and Weight

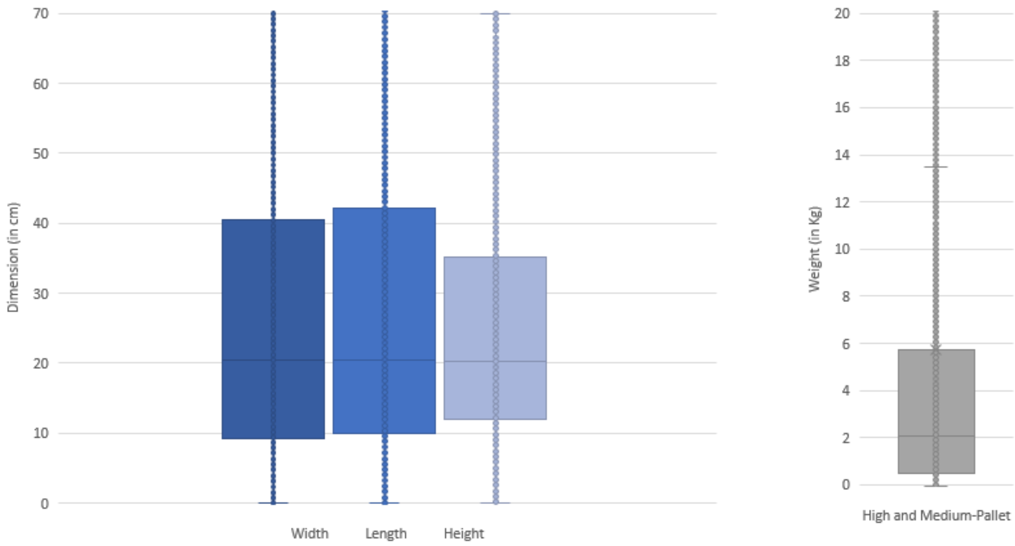

Figure 50 Roll-Cage, Medium and High Racks Products Dimensions and Weight

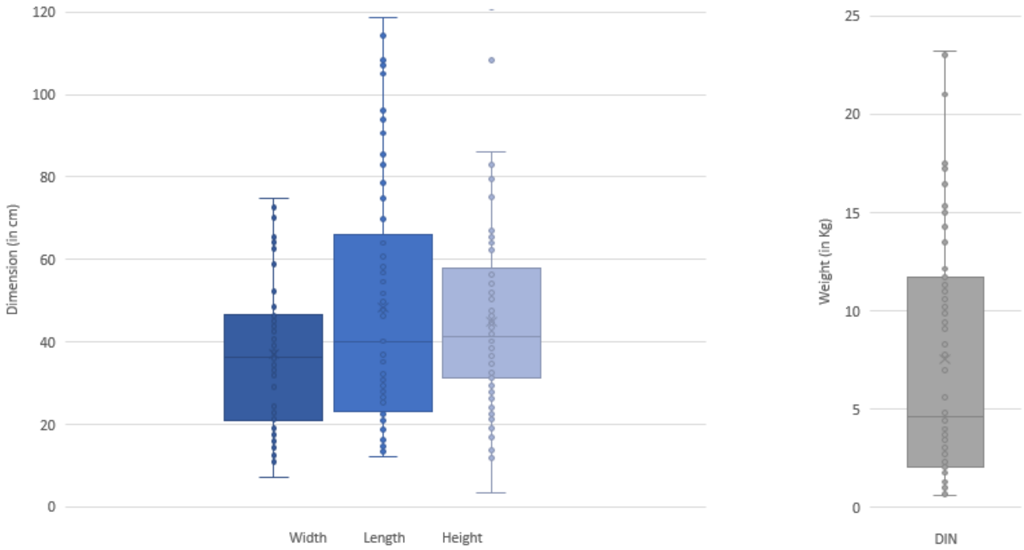

Figure 51 DIN Products Dimensions and Weight

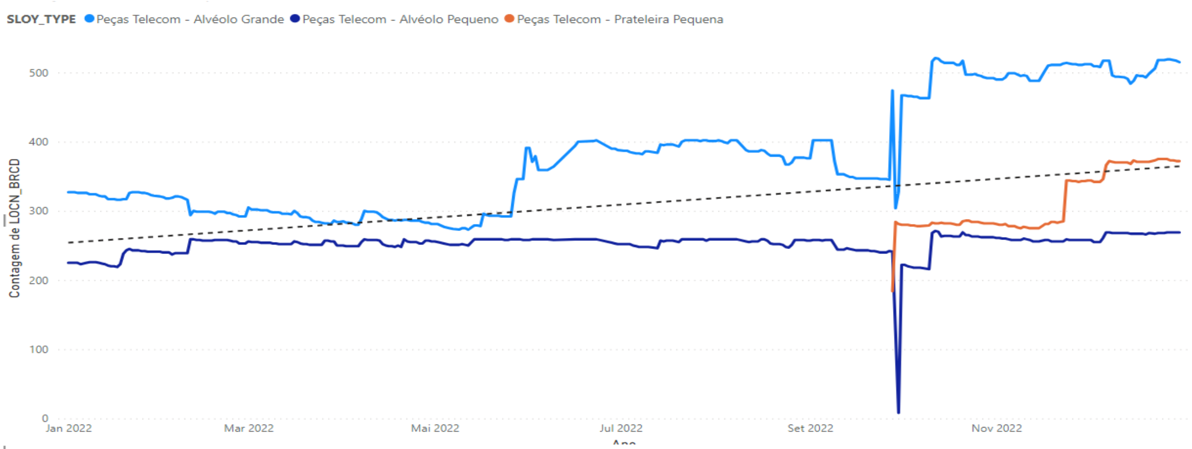

Figure 52 Evolution of the Number of Locations of PT - 2022

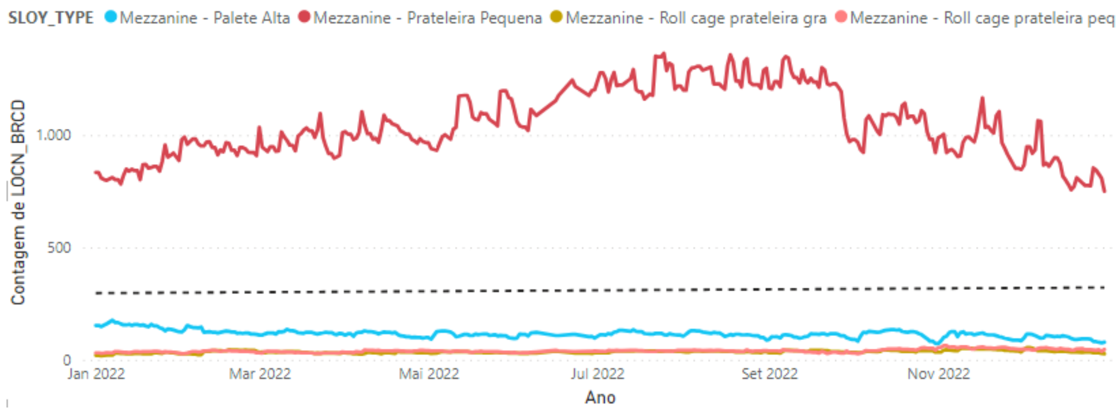

Figure 53 Evolution of the Number of Locations of LAV - 2022

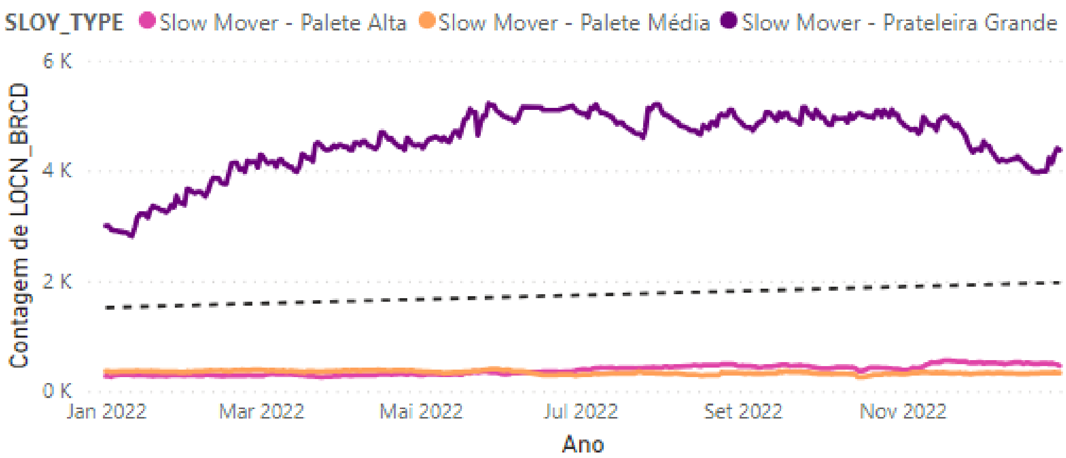

Figure 54 Evolution of the Number of locations of SM - 2022

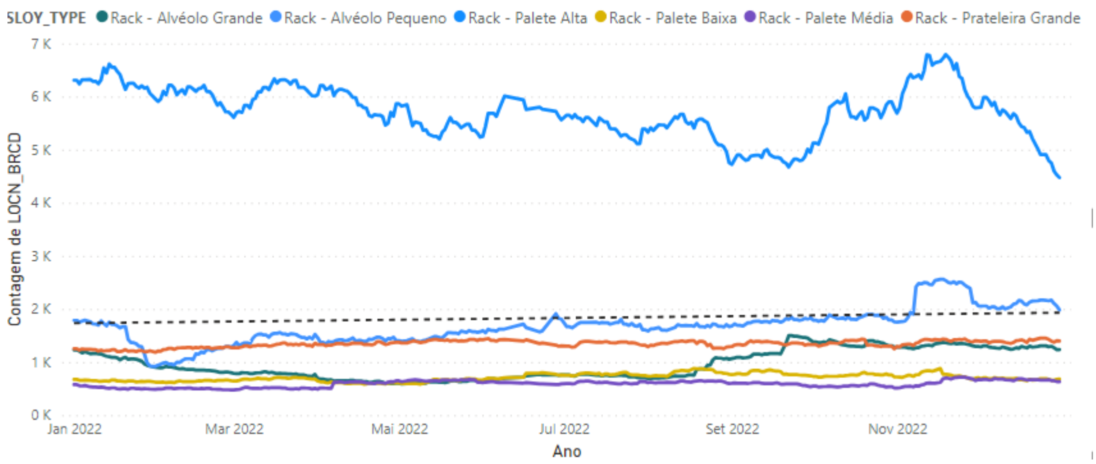

Figure 55 Evolution of the Number of Locations of Racks - 2022

Figure 56 Evolution of the Number of Locations of DIN - 2022

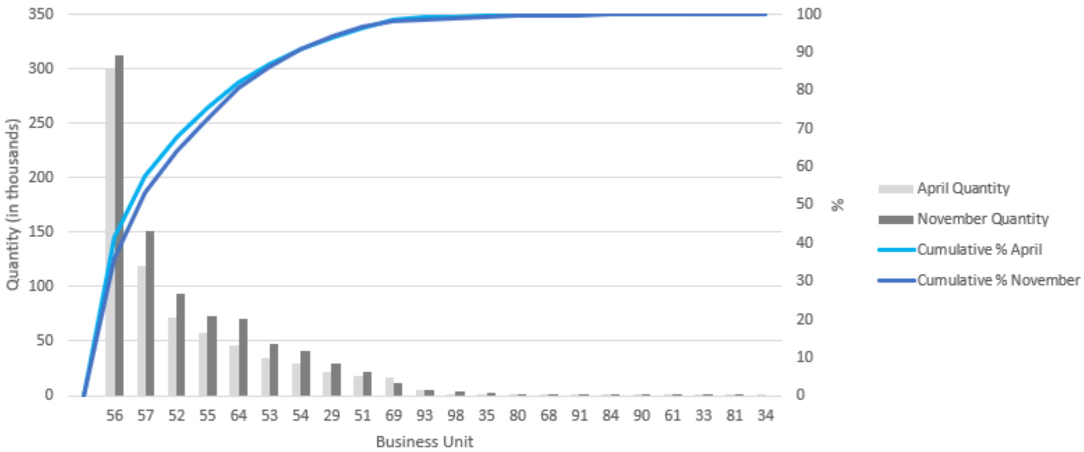

Figure 57 Pareto to the Business Units Stored in April and November

Figure 58 Year-to-Date Forecast for High Pallet Racks

Table 18 Predicted Values for Quantities and SKUs Stored in 2025

Type of Storage	Year: 2023		Year: 2025	
	Quantity	SKUs	Quantity	SKUs
Racks – High Pallet	539 814	7 502	715 261	11 319
Racks – Medium Pallet	24 534	681	51 360	1 310
Racks – Low Pallet	8 595	439	3 082	623
Racks – Alveoli	23 748	3 498	22 164	6 863
Racks - Shelves	48 982	1 402	60 441	1 412
SM - High Pallet	28 881	564	49 888	1 002
SM – Medium pallet	6 546	197	10 405	260
SM - Shelves	35 783	4 290	59 166	7 176
DIN	174 213	220	345 417	289
Mezzanine – High Pallet	14 087	138	2 183	898
Mezzanine -Shelves	40 112	1 359	52 103	2 146
Mezzanine -Roll-cages	6 967	120	17 058	224
Mezzanine -Alveoli	19 047	930	25 959	1 392

Table 19 Automated Systems' Data Collected from Several Sources

		Storage Type		
		SBS/RS pallets	SBS/RS units	RBCS/RS
System	Name	PowerStore - Swisslog	Cyclone - Swisslog	AutoStore - Swisslog
	Maximum height	45 m	25 m	7 m (14 totes)
	Maximum length	-	150 m	-
	Aisles length	1030 mm	600 mm	-
Shuttle/Robots	Dimensions	(1090x1030x160) mm	(990x600x310) mm	(988x700x645) mm
	Supported weight	1500 kg	35 kg	29.6 kg
	Speed	up to 3 m/s	Vehicle: up to 4 m/s	X: 3.1 m/s; Y: 1.6 m/s
	Tote/Pallet dimension	(1200x800x1900) mm	(670x470x500) mm	(649x449x425) mm
Lift	Velocity	1.2 m/s	4 m/s	-
	Dimensions	(1090x1030x160) mm	(990x600x31) mm	-
	Supported weight	1500 kg	35 kg	-
Buffer	Systems’ In and Out	(3500x1030) mm	(215x600) mm	-
	Around totes/Pallets	100 mm	50 mm	50 mm
	Between tiers	100 mm	50 mm	-

Table 20 Definition of the Number of Robots and Workstations for AutoStore

	AutoStore - Scenario 3	**AutoStore – Scenario 4**
Number of Bins	22 815	104 610
Number of Robots	20	132
Number of Workstations	4	28
Maximum throughput (adding robots)	1 000 totes/h	7 000 totes/h
Maximum throughput with the defined number of robots	500 totes/h	6 600 totes/h

E. Supplementary Images to Chapter 6 - Results Discussion

Table 21 Number of Pickers for Racks, in Each Scenario

Scenario	As-Is	0	1	2	3	4
Rack Frames	990	1350	90	16	16	390
Pickers	33	45	3	1	1	13
Picking Productivity	1.8 min/product					

Table 22 Data collected regarding the tote filling process

Activity	Time
Start	0.00
1º tote filled	3.45
2º tote filled	5.20
3º tote filled	6.20
Switch tote: Start	6.35
Switch tote: End	7.00
Switch tote: Start	14.30
Switch tote: End & Switch tote: Start	15.00
Switch tote: End	15.40
4º tote filled & Switch tote: Start	16.35
Switch tote: End	16.55
End of the experiment (5.5 totes were filled)	19.52