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Survey on automated systems for smart warehouses

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Abstract

In today's dynamic e-commerce and logistics landscape, the ''last mile'' has emerged as the ultimate frontier in the pursuit of seamless and efficient delivery services. As consumer expectations go for quicker, more convenient, and environmentally sustainable deliveries, the pressure on last-mile delivery businesses continues to intensify.

This thesis embarks on a voyage into the innovative realm of smart warehouse technologies, where automation, artificial intelligence, and data-driven decision-making converge to reshape the landscape of last-mile delivery. Efficiency, sustainability, and customer satisfaction are redefined in this transformative terrain, one delivery at a time.

The work delves deep into the modernizing wave of technologies revolutionizing warehouse operations. Through a comprehensive analysis of both research literature and market trends, the aim is to unravel the intricacies of existing solutions and the cutting-edge advances in the field. With a primary focus on enhancing safety, efficiency, maintenance, reliability, sustainability, flexibility, and energy consumption, our exploration encompasses the synergies between human expertise and the integration of digital systems and robotics. By scrutinizing these critical aspects, this study aims to pave the way for a new era of last-mile delivery solutions that not only meet the demands of today's dynamic market but also set a sustainable and innovative course for the future. While the focus is on the specific needs of e-commerce businesses, particularly those with diverse stock-keeping units differing in size, volume, and characteristics, it's important to note that the technologies explored may find applicability in various other industries with distinct product attributes. This concept of transferability underscores the versatility of these technological advancements.

The findings reveal a compelling narrative: the key to the future of warehousing lies in the seamless integration of human expertise with cutting-edge technology. It's not a question of choosing between humans or machines, but rather harnessing their combined potential. The ability to swiftly adapt to the ever-changing technological landscape emerges as a critical competitive advantage.

Table of contents

Lists of figures

Lists of acronyms

- AGVs (Autonomous Guided Vehicles)
- AMRs (Autonomous Mobile Robots)
- SKU - Stock Keeping Unit
- QR - Quick Response
- POS - Point of Sale
- UPC - Universal Product Code
- ISO - International Organization for Standardization
- FIFO - First In, First Out
- KPI - Key Performance Indicator
- WMS - Warehouse Management System
- LPN - License Plate Numbers
- RFID - Radio-Frequency Identification
- ERP - Enterprise Resource Planning
- 3PL - Third-party Logistics
- FTZ - Foreign Trade Zone
- RGB-D - Red, Green, Blue, Depth
- S/RS - Automated Storage and Retrieval Systems
- GTP - Goods-to-Person
- PTG - Person-to-Goods
- ATLS - Automated Trucks Loading and Unloading System
- ROI - Return on Investment
- CGH - Carbon Greenhouse Emissions
- VLM - Vertical Lift Module
- VSM - Vertical Sequence Module
- FOI - Factor of Inquiry

- PH - Product Height
- SSU - Storage Space Usage
- PD - Path to Dispatch
- ACI - Automatic Command Interface
- DOB - Dynamic Order-Based
- DOBT - Dynamic Order-Based with Threshold
- FCFS - First Come, First Serve
- LCFS - Last Come, First Serve
- SJF - Shortest Job First
- ACO - Ant Colony Optimization
- COI - Cube per Order Index
- CPS - Cyber-Physical Systems
- RMFSs - Robotic Material Handling Systems
- HRC - Human-Robot Collaboration
- AR - Augmented Reality
- Cobots - Collaborative Robots
- UWB - Ultra-Wideband
- IMU - Inertial Measurement Unit
- SLAM - Simultaneous Localization and Mapping
- AI - Artificial Intelligence
- ML - Machine Learning
- RL - Reinforcement Learning
- ANN - Artificial Neural Network
- IoT - Internet of Things
- NIOSH - National Institute for Occupational Safety and Health

Introduction

In today's fast-paced world of e-commerce and logistics, the 'last mile' has become the ultimate frontier in the quest for seamless and efficient delivery services. As consumers expect quicker, more convenient, and environmentally sustainable deliveries, the pressure on last-mile delivery businesses continues to mount. The key to meeting these demands lies within the walls of the smart warehouse.

This thesis delves into the innovative realm of smart warehouse technologies, where automation, artificial intelligence, and data-driven decision-making converge to reshape the landscape of last-mile delivery.

This work intends to go deep into the modernizing wave of technologies that are revolutionizing warehouse operations. Through a comprehensive analysis of both research literature and market trends, the goal is to give an overview of existing solutions and the cutting-edge advances in the field. With a primary focus on enhancing safety, efficiency, maintenance, reliability, sustainability, flexibility, and energy consumption, the exploration focuses on the synergies between human expertise and the integration of digital systems and robotics. By analyzing these critical aspects, this study covers the way for a new era of last-mile delivery solutions that not only meet the demands of today's dynamic market but also set a sustainable and innovative course for the future.

This thesis is specifically designed to address the needs of e-commerce businesses, particularly those with a wide variety of stock keeping units differing in size, volume, and characteristics. It is important to note that while the focus is on this specific sector, the technologies explored may find applicability in various other industries with distinct product attributes. This concept of transferability underscores the versatility of these technological advancements.

To make the content accessible to readers with varying levels of technical expertise, the language used will be clear and straightforward. To facilitate understanding, the thesis will feature an abundance of visual aids, including images and tables. These graphical representations will serve as valuable tools for comprehending complex concepts. Additionally, the writing style will remain objective and impartial, refraining from endorsing any solution or approach. This approach ensures that the thesis provides a balanced and informative overview of the subject matter.

The 'goods to men' strategy revolutionizes warehouse management by shifting from the traditional 'man to goods' approach. Through automated retrieval systems, it streamlines operations, reducing time and effort to locate items and maximizing space utilization. This approach minimizes human intervention, enhancing productivity and precision. Automated warehouses integrate robotics, conveyor systems, and advanced software for a self-orchestrated environment, ensuring efficiency, accuracy, and responsiveness to market demands. In the context of Industry 4.0, smart warehouses exemplify the transformative potential, incorporating digital technologies, AI, IoT, and cyber-physical systems for real-time data analysis and adaptive responses, revolutionizing the entire supply chain. Smart warehouses shifted operations by using data-driven insights for real-time decision-making. Through advanced analytics and predictive modeling, they optimize inventory, anticipate demand, and enhance resource utilization. This positions them as strategic assets in meeting the demands of fast-paced consumer-driven markets, especially in the growing last-mile delivery sector driven by increasing e-commerce transactions.

Market trend

According to the State Post Bureau of the People's Republic of China (PRC) in 2020, the annual volume of express deliveries in China alone surpassed a staggering 70 billion packages, a monumental milestone in the industry. This monumental figure underscores the phenomenal expansion of the delivery sector, reflecting an impressive annual growth rate of approximately 20% over the past few years. The European market has also experienced substantial growth. A recent study by the European Commission highlighted a 20% increase in e-commerce sales within the European Union in 2020, compared to the previous year (European Commission, 2021).

This explosive growth can be attributed to a confluence of factors. The rapid proliferation of online shopping platforms, coupled with the proliferation of mobile technology, has fundamentally transformed consumer behavior. Consumers now expect swift, convenient, and cost-effective delivery options, prompting e-commerce giants to invest heavily in optimizing their last-mile logistics operations.

Companies such as Amazon, Alibaba, JD.com, and DHL have been at the forefront of this evolution, pouring substantial resources into the development of cutting-edge technologies and infrastructures to meet the escalating demand. Additionally, the COVID-19 pandemic acted as a catalyst, further accelerating the adoption of e-commerce and reinforcing the importance of robust last-mile delivery networks.

While developed economies have witnessed a steady expansion, emerging markets have experienced particularly explosive growth due to a combination of factors including rising disposable incomes, improved access to technology, and increasing urbanization. The market's dynamic growth is also reflected in the increasing number of startups and technology-driven firms entering the last-mile delivery space, contributing to a competitive environment.

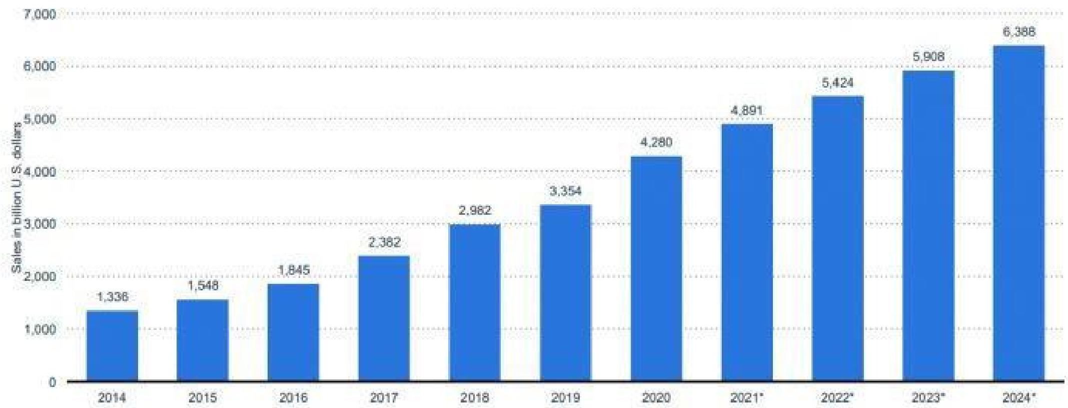

Figure 1. Global retail e-commerce sales worldwide from 2014 to 2021 (in billion USD).

The integration of smart warehouse technologies and advanced last-mile delivery solutions gives a multitude of competitive advantages upon companies willing to invest in these innovations. A comprehensive analysis conducted by Deloitte in 2021 revealed that businesses leveraging automation and data-driven logistics solutions experienced an average 30% improvement in delivery speed and accuracy (Deloitte, 2021). This level of precision translates directly into enhanced customer satisfaction, enhancing brand loyalty and positive word-of-mouth referrals. Moreover, the adoption of automated systems and robotics in warehouse operations has led to a remarkable reduction in operational costs: ''The Boston Consulting Group'' reported that companies incorporating automation technologies achieved an average of 25% reduction in labor costs and a 20% decrease in operational expenses related to inventory management and order fulfillment (The Boston Consulting Group, 2021).

In response to the convincing benefits offered by these technologies, companies have committed substantial resources to their implementation. For instance, Amazon, a global e-commerce titan, announced an investment of over $1.4 billion in 2020 to enhance the safety and efficiency of its last-mile delivery operations through the deployment of electric vehicles and advanced routing algorithms (Amazon, 2020).

Similarly, Alibaba, a prominent player in the Asian e-commerce market, allocated approximately $2.9 billion towards the development of its smart logistics network in 2021 (Alibaba Group, 2021). These strategic investments in technology and infrastructure have positioned these industry as leaders in the last-mile delivery sector.

In addition to operational efficiencies and cost savings, the integration of these technologies also serves as a powerful benefit for environmental sustainability. A study by the ''World Economic Forum'' revealed that companies adopting greener last-mile delivery solutions, such as electric vehicles and optimized route planning, experienced an average 30% reduction in carbon emissions. This not only aligns with global sustainability goals but also resonates positively with environmentally conscious consumers, further enhancing a company's competitive advantages.

Figure 2. Supply Chain trends and impact.

Literature

With the goal of deeply understanding of the subject, this thesis extensively relies upon a diverse array of articles from the scientific literature. A preliminary survey reveals that in the past decade alone, over 5,000 peer-reviewed articles and conference papers have been dedicated to this evolving field (Google Scholar, 2023). This surge in academic interest underscores the significance and importance of the subject matter. Furthermore, prestigious journals such as the International Journal of Logistics Management, Logistics and Transportation Review, and the Journal of Business Logistics serve as major platforms for the research in this domain. Additionally, international conferences such as the IEEE International Conference on Automation Science and Engineering and the International Conference on Information Systems Logistics and Supply Chain enhance a vibrant intellectual exchange, attracting contributions from scholars and professionals.

Chronological evolution

Over the past half-century, the evolution of warehouses has been extraordinary, marked by a dramatic technological transformation that has revolutionized every aspect of their operation. In the 1970s and 1980s, warehouses were primarily characterized by manual labor-intensive processes, with workers manually picking and packing items for shipment. The adoption of basic material handling equipment like forklifts and conveyors represented a significant technological leap during this period, enabling more efficient movement of goods within the facility. The technological shift in the 1990s saw the emergence of warehouse management systems (WMS) which introduced computerized control and tracking of inventory, optimizing storage space and enhancing order fulfilment accuracy. This transition contributed to the way for a more systematic approach to warehouse operations, reducing human errors and improving overall efficiency. The introduction of barcoding technology further streamlined processes, allowing for quicker and more accurate tracking of products.

The 2000s have been a new era with the advent of automated storage and retrieval systems (AS/RS), robotics, and advanced warehouse control systems. These technological marvels significantly reduced reliance on manual labor and brought about a remarkable increase in operational speed and precision. AS/RS allowed for dense storage of goods while robotics took over tasks like picking, packing, and even transportation within the warehouse. The shift towards a more automated, data-driven operation became the benchmark of modern warehousing.

In tandem with this technological evolution, there was a notable shift in working types within warehouses. The labor force transitioned from predominantly manual workers to a blend of skilled technicians, engineers, and operators proficient in managing and maintaining complex automated systems. This necessitated a corresponding shift in training and skill development programs to equip workers with the expertise required for operating and troubleshooting advanced warehouse technologies.

Layouts of warehouses underwent a radical transformation as well: the traditional static layouts gave way to dynamic, flexible designs that accommodated the movement of automated equipment and facilitated efficient goods-to-person workflows. High-density storage systems, multi-level mezzanines, and optimized racking configurations became standard features of modern warehouse designs, maximizing storage capacity and retrieval efficiency.

Simultaneously, the business dynamics surrounding warehouses evolved in response to these technological advancements. The focus shifted from being primarily storage-centric to a more dynamic, customer-centric approach. Warehouses transformed into critical nodes in the supply chain, strategically positioned for rapid order fulfillment and last-mile delivery. Customer demands for faster delivery times and greater product variety necessitated warehouses to become more agile and responsive.

In conclusion, the evolution of warehouses over the past 50 years represents a tribute to the incredible strides in technology and innovation. From manual labor-intensive operations to highly automated, data-driven facilities, the transformation has been revolutionary.

This shift has not only impacted the technology and operations within warehouses but also influenced the nature of work, the layout of facilities, and the overall business strategies surrounding warehousing operations. As we are in an era of even greater technological integration, the future promises even more remarkable advancements in warehouse design and operation.

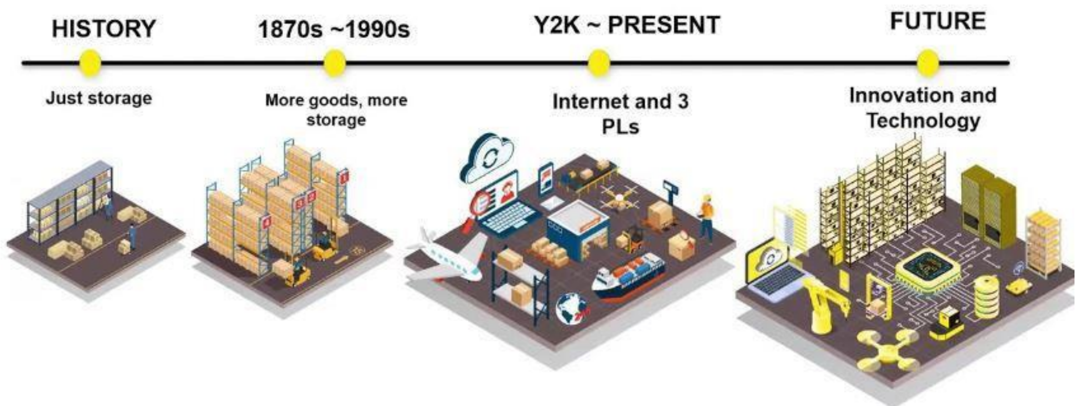

Figure 3. Warehouse evolution

Structure

The structure of this work is designed to provide a comprehensive exploration of smart warehousing and last-mile delivery. The thesis is organized into five chapters, each serving a specific purpose and following a logical order.

In the inaugural chapter, ''Structure and scope of the warehouse and distribution centers '', a comprehensive overview of the supply chain is taken into consideration. Key Performance Indicators (KPIs) are explained and included in the narrative, providing crucial metrics for evaluating and benchmarking warehouse performance. By explaining these fundamental concepts, the reader is given with essential knowledge, setting the fundamentals for the next chapter.

In the second chapter, ''Innovative automated systems for smart warehouses'', a detailed journey through the warehouse steps of the product's lifecycle within the facility analyzed. Through an extensive review of both market-leading technologies and research findings, the intention is to give an overview of the most promising existing technologies following the logical flow of the product storage in the warehouse.

In the third chapter, ''Automated storage and retrieval systems'', the core of the matter is analyzed, focusing on the storing phase within the warehouse. This section delves deep into the realm of fully automated storage solutions, which uses mixture of workings of various technologies. The chapter provides a detailed examination of how these diverse systems synergize to form an integrated and seamless storage environment. This intricate usage of technologies underscores the sophisticated orchestration required to optimize storage efficiency in the modern automated warehouse.

In the fourth chapter ''Robotics automated warehouse technologies'' the focus is shifted into two promising technologies: AGVs (Automated Guided Vehicles) and Autostore systems. Here an analysis of the merits, drawbacks, and technical intricacies of these specific technologies is taken into account. By going into the details, the reader is given with an understanding of how these solutions function, helping him to make informed decisions regarding their potential implementation in warehouse operations.

The final chapter, '' Software technologies and human collaboration'', the software technologies that drive the warehouse are deeply studied.
Additionally, the evolving role of humans in this increasingly automated landscape is considered, emphasizing the critical symbiosis between human expertise and technological advancements. This chapter illuminates how the dynamic interplay between software technologies and human capabilities is at the base of shaping the future of last-mile delivery.

In conclusion, as we embark on this exploration of smart warehousing and last-mile delivery, is clear that we are actually in a transitional era of technological advancements. The anticipated results are unequivocal: the warehouse of the future will be based on the technological progress and the adoption of cutting-edge technologies will be imperative. However, while this technological surge, the importance of human centrality cannot be underestimated. Companies are faced with the dual imperative of investing significantly in both technological infrastructure and the cultivation of human expertise.

In essence, the paradigm of the future is an evolved vision of warehouses, where advanced technologies and human capabilities converge to empower a new frontier in last-mile logistics.

1. Structure and scope of the warehouses and distribution center

The warehouse is a crucial logistical structure responsible for receiving, storing, and making materials available for production or distribution. It serves as a reservoir for a company, reconciling procurement and utilization needs, as well as production and sales requirements. The warehouse's organizational structure is fundamental, requiring well-designed physical structures and equipment to optimize space and preserve stocks efficiently.

The objectives of a warehouse are diverse, including promoting production efficiency, providing buffers for seasonal demand, ensuring raw material availability, acting as a barrier against rising material prices, creating reserves near sales points, and responding to unexpected sales increases. Warehouses play a crucial role in the supply chain, evolving beyond mere storage facilities to become distribution centres and logistical hubs.

Despite their significance, the cost-effectiveness of warehouses depends on specific situations. Poor time management and underutilized bulk products can increase warehousing costs, while products with minimal transportation costs may be better suited for direct delivery. Nevertheless, for products falling outside these categories, distribution centres and warehouses contribute to cost-effectiveness by reducing transportation costs, streamlining shipment management, and providing additional services.

Proper warehouse management enhances the overall supply chain, especially during emergencies, where well-organized products can be swiftly accessed. Technological advancements optimize warehouse space utilization and workforce management. Industrial real estate developers need to consider various factors for effective warehouse management before investing in a property:

- *Location*: The strategic placement of a warehouse plays an important role in establishing efficient networking within the supply chain. Factors such as transportation rates, available workforce, accessibility for different modes of transport, and overall cost-effectiveness depend on the warehouse's location.

- *Design & Operations*: Warehouse design influences the type of items to be stored, the loading and unloading processes, the service types offered, and the mode of transportation. The staging area plays a vital role in product movement within the warehouse, making design and operations integral aspects of warehouse functionality.

- *Information Technology***:** In the technologically advanced landscape, warehouses rely on sophisticated software and computer systems for various operations. Advanced technologies are utilized to optimize space usage, manage the workforce, and store vital information essential for the smooth functioning of the entire supply chain. Hence, during the purchase of a warehouse, careful attention must be given to its IT infrastructure.

By carefully considering these factors, companies can ensure effective warehouse management, which will contribute to the operation of the supply chain and ultimately lead to improved overall performance.

1.1 Costs impact

The warehouse, by its very definition, represents a significant economic burden, and the associated expenses are entirely unproductive (i.e., stockpiling a commodity adds no value to it). The costs related to warehousing can mainly be categorized as follow:

- *Time Costs*: These costs are closely tied to the nature of the specific item's storage, considering both the increased time it takes to traverse the production process and the actual calendar time spent in the warehouse.
- *Capital Cost*: As the warehouse forms part of the working capital, it incurs immobilization and opportunity costs (the capital could have been employed differently, yielding alternative returns).
- *Deterioration, Obsolescence, and Theft Costs*: Deterioration may lead to complete loss or necessitate costly repairs; obsolescence results in profit loss, and theft not only causes profit loss but also impacts delivery fulfillment and customer satisfaction.
- *Space Costs*: These costs are directly related to the space occupied for storing inventory and can be determined by considering land and building rental costs and amortization.
- *Procurement Costs*: Relating to order management, they encompass preparation and issuance of orders, receipt, inspection, and allocation of goods, as well as administrative and transportation costs.

- *Handling Costs*: Associated with internal material movement, transportation systems, and containment methods.
- *Stock-out Costs*: Represent the marginal profit lost for each item demanded but not immediately available in the warehouse, considering potential missed profits if customer satisfaction is compromised.
- *Insurance Costs*: Refers to insurance premiums covering fire and theft risks.
- *Fixed Management Costs*: Consist of fixed expenses like personnel, electricity, heating or cooling, and facility maintenance.

It is evident that storage costs significantly impact a company's final revenue, and reducing them poses a complex challenge, as they depend on numerous factors.

1.2 Safety impact

Warehouse safety is very important in modern-day supply chain operations and automation plays a crucial role in enhancing safety measures and mitigating the inherent risks associated with warehouse environments. Traditional warehouses can be hazardous, with numerous potential safety hazards ranging from collisions between workers and moving equipment to the physical strain caused by repetitive tasks. These risks can lead to accidents, injuries, and long-term health issues for employees. One of the primary benefits of automation in warehouse safety is the ability to delegate strenuous and hazardous tasks to robots, thereby reducing the exposure of human workers to dangerous activities. Manual lifting and pallet handling, which can lead to musculoskeletal disorders and chronic pain, can now be performed by robots, sparing employees from physical strain and reducing the risk of long-term injuries (ref. chapter 5). By taking on these physically demanding tasks, robots help alleviate the ergonomic risks associated with repetitive motions, heavy lifting, and prolonged physical exertion.
Automation technologies in warehouses are equipped with advanced sensors, collision avoidance systems, and navigation capabilities, ensuring safe and intelligent operation. Programmed to follow optimized pathways, detect obstacles, and adhere to controlled speeds, these robots minimize the likelihood of collisions and accidents. They can navigate efficiently through narrow spaces, negotiate blind corners, and work alongside human workers safely. Features like slow-down zones and no-scrub zones enhance safety by ensuring cautious robot operation around workers and delicate equipment.
Beyond physical safety, automation solves concerns related to inventory handling. Automated Mobile

Robots (AMRs) can access high shelves and hard-to-reach inventory, eliminating the need for human workers to operate at elevated heights. This reduces the risk of falls and injuries associated with working in elevated areas. Automation also improves inventory management accuracy, minimizing the chances of errors and ensuring secure storage, reducing the risk of falling objects or improper material handling.

Automation can extend work hours without compromising employee well-being, as robots don't experience physical fatigue or require breaks. This allows for longer shifts, optimizing warehouse productivity and reducing the need for overtime labour, thereby minimizing worker fatigue and associated accident risks. Additionally, automation contributes to a safer work environment by eliminating potential hazards linked to night shifts and prolonged working hours.

Furthermore, automation simplifies onboarding for new and temporary workers, reducing safety risks associated with unfamiliarity with warehouse operations. Precise programming ensures consistent and safe robot performance from the outset, minimizing the potential for human error and associated safety risks.

Warehouse accidents and injuries are a significant concern in the warehousing and storage sector, with statistics highlighting the need for improved safety measures. Reports from the US Bureau of Labor Statistics reveal that the sector experiences nearly 15,000 injuries and illnesses, along with an average of 16 fatalities, each year. These incidents cause a substantial financial burden on employers, with serious non-fatal injuries costing $84 million per week in the industry. Forklifts, commonly used in warehouses, pose a significant hazard when operated improperly, leading to damage to users, nearby workers, and property. In fact, 36% of nearly 100,000 forklift accidents in 2015 resulted in critical injuries or death. Loading docks also contribute to industrial accidents, accounting for 25% of all reported incidents. Additionally, back and shoulder pain accounts for approximately 40 to 50% of claims filed by warehouse workers. The staggering numbers continue a broader scale, with a report from the National Safety Council and the US Bureau of Labor Statistics revealing that 4.6 million workplace injuries occur in the USA every year, resulting in the loss of 104 million days of production. Automation presents a solution to mitigate these risks, as it addresses common causes such as overexertion, contact with objects or equipment, and slips, trips, and falls. In 2018 alone, the U.S. Bureau of Labor Statistics recorded a rate of 5.1 illnesses and injuries per 100 warehouse workers, emphasizing the urgent need for enhanced safety measures in the industry.

SAFETY IMPACT ON WAREHOUSES

US yearly

15 000 injuries
5,1 injuries over 100 workers
16 fatalities

↓

84 millions per week
104 million days of production

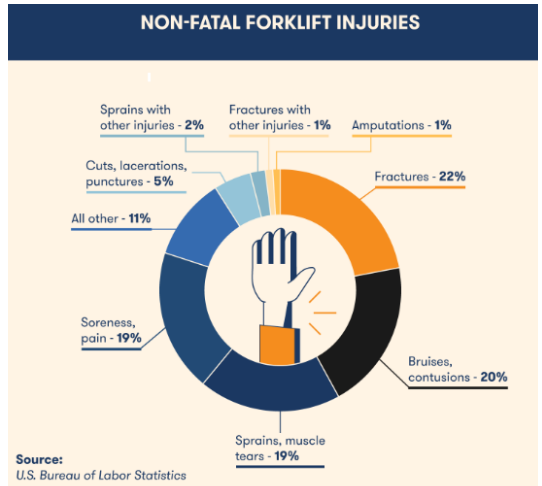

Figure 4. Safety data.

1.3 Different type of warehouses

Warehouses vary significantly within the supply chain type of businesses, adapting to diverse needs. Various types include:

- *Public Warehouses:* Managed by governmental bodies, these offer storage space to private sector companies.
- *Private Warehouses:* Owned by individual entities, such as wholesalers, distributors, or manufacturers.
- *Bonded Warehouses:* Specialized for imported goods, allowing duty-free storage until customs clearance, beneficial for cross-border trade.
- *Smart Warehouses*: Embracing technology with AI, automation, and robotics, these enhance efficiency, reduce errors, and optimize inventory management.
- *Cooperative Warehouses:* Owned by cooperative organizations, providing storage access to members and external businesses.
- *Government Warehouses*: Owned and controlled by the government, strategically located, often near seaports.
- *Distribution Centres:* Pivotal hubs in the supply chain, efficiently distributing goods to resellers and retailers, crucial for fast-moving consumer goods and perishable items.

The thesis focuses on automation, particularly smart warehouses for distribution centres handling a range of products, from small packages to larger items like washing machines, catering to the needs of e-commerce businesses.

1.4 Warehouses vs distribution centers

Back in the day, when the supply chain was much less complicated, walking up and down the aisles of a warehouse or distribution center was approximately the same. Both places were for storing and dispensing products. But nothing is fixed to change, and the purposes of the traditional warehouse and distribution center have evolved.

A warehouse is a place where goods are stored. It's more than just a storage facility; it involves various processes, such as receiving orders, storing goods on shelves or racks, tracking inventory, and fulfilling shipments. Warehouses do not manufacture or process goods but focus on their proper identification, storage, and retrieval. These buildings are commonly found near seaports, airports, and railways, and they often feature equipment like cranes and forklifts for moving goods. Depending on the type of warehouse, it may have temperature-controlled interiors to accommodate perishable goods or engineered to specific industries such as pet food, electronics, or medical and pharmaceutical storage.

On the other hand, a distribution center, often referred to as a DC, plays a fundamental role in the order fulfillment process. It serves as a warehouse stocked with products specifically for redistribution to wholesalers, retailers, or direct-to-consumer shipping. A distribution center is more than just a warehouse; it handles order processing, order fulfillment, and other tasks such as light assembly, quality control, and repackaging. The primary focus of a distribution center is receiving orders and promptly shipping the items out. It acts as a bridge between suppliers and consumers, ensuring products are packaged and sent to their intended destinations.

While both warehouses and distribution centers share common activities such as receiving, storing, managing, picking and pulling, and delivering goods, there are key differences between the two. Warehouses primarily store products until they are needed, whereas distribution centers perform additional functions like product mixing, cross-docking, order fulfillment, and packaging. Warehouses tend to store products for longer periods, while distribution centers have a faster flow rate, reducing the time products spend in storage. Distribution centers have a more consumer-focused role, serving as the link between suppliers and customers, while warehouses are more focused on storing items. Orders for retail and warehouses often pass through a distribution center due to its involvement in order processing, while warehouses typically do not directly serve customers. Distribution centers handle more complex operations, including order processing, transportation management, inventory and warehouse management, and other tasks, making them more intricate than warehouses.

1.5 Characteristics of the warehouses

In this paragraph the main purpose is to analyze the components of a warehouse system both material and numerical components.

This must be considered only as a general introduction, so that the further comprehension of the following topics will be easier for the reader.

1.5.1 Sku and Upc

A stock-keeping unit (SKU) is a unique scannable code used by vendors to efficiently track the movement of inventory. These codes are commonly seen as bar codes or QR codes printed on product labels in retail stores. The primary purpose of SKUs is to provide a quick and accurate method of inventory management and control. By utilizing SKUs, vendors can automate the tracking process and obtain insights of the product sales and stock levels.

Each SKU consists of an alphanumeric combination of eight or more characters, forming a code that encodes essential information about the product. This information typically includes details such as the product's price, specific characteristics, manufacturer information, and the point-of-sale location. Thus, SKUs act as a vital tool for inventory management, allowing vendors to monitor stock levels, sales performance, and reordering needs.

Moreover, SKUs are not limited to tangible products. They can also be applied to intangible services or billable items, such as units of repair time in an auto body shop or warranties offered with products.

For various industries, including retail and e-commerce, SKUs play a crucial role in tracking inventory levels and facilitating seamless logistics. By using scannable SKUs in conjunction with a Point-of-Sale (POS) system, managers can efficiently identify which products require restocking and which ones are in high demand. When a customer purchases an item at the POS, the SKU is scanned, and the POS system automatically updates the inventory records and other relevant data, such as the sale price.

It's important to note that SKUs should not be confused with model numbers, although businesses may embed model numbers within the SKU for added specificity. For instance, a store selling shoes might use internal SKUs that encode product details like color, size, style, price, manufacturer, and brand.

Beyond facilitating inventory tracking, SKUs offer several other advantages. They enable shoppers to compare characteristics of similar items, allowing online retailers to display similar products purchased by other customers based on SKU information. This approach can bring to additional purchases, boosting a company's revenue and success.

As said, SKUs provide valuable sales data by analyzing scanned SKUs and POS data: stores can identify which products are selling well and which ones are underperforming. This information helps in making informed business decisions and optimizing product offerings.

In contrast, universal product codes (UPCs) are standardized and identical for the same type of product, regardless of the seller. SKUs and UPCs serve distinct purposes and are both crucial in the modern retail landscape.

SKU numbers are typically displayed on products alongside their UPC barcodes. Since SKU numbers are meant for internal tracking by the producer, they are not standardized universally and are company specific. This provides flexibility for businesses to create their own SKU systems that suit their unique needs. To ensure consistency, most companies establish a logical structure for their SKU system, often starting with top-level identifiers and followed by more specific product- and vendor- specific codes.

In conclusion, SKUs are valuable tools that allow vendors to efficiently manage inventory, logistics, and analyze sales data. By incorporating unique SKUs into their operations, businesses can improve accuracy, reduce shipping errors, and enhance the overall customer experience.

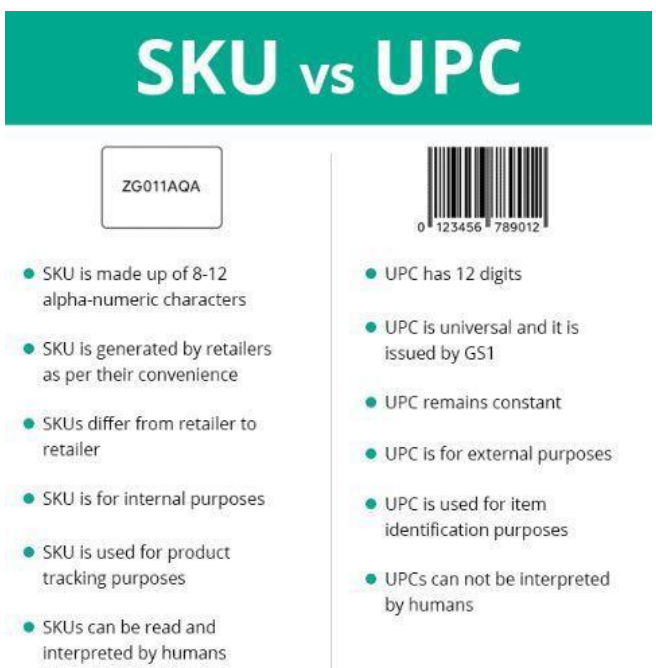

Figure 5. Sku vs Upc.

1.5.2 Pallets

A pallet serves as the primary structural interface in warehousing, providing a standardized platform for storing and handling unit loads. It plays a crucial role as the backbone of the warehousing system, facilitating efficient inventory management and distribution processes. One of the key functions of pallets is to safeguard products, acting as a protective layer that prevents damage during transportation and storage, ensuring that goods reach their destination in optimal condition.

Pallets come in various types, categorized based on dimensions, number of entry points, and materials used. For instance, the Euro pallet, measuring 1200mmx800mm, is widely used in Europe, with the European Pallet Association overseeing its operations. On the other hand, the American Pallet, measuring 1200mmx1000mm, is prevalent in American and Japanese supply chains and is often referred to as universal or ISO pallets. The International Organization for Standardization (ISO) has provided certification for many pallet sizes, including 1016x1219mm, 1165x1165mm, 1067x1067mm, and 1100x1100mm. However, the popularity of these sizes is less compared to the Euro pallet and American Pallet.

Different types of pallets offer distinct advantages and drawbacks.

Wooden pallets are the most used, accounting for a significant market share of about 90-95%. They are reliable, resistant to damage, and easy to repair and recycle, extending their lifespan. However, cleaning wooden pallets can be challenging.

Plastic pallets are gaining popularity due to their ease of cleaning, lightweight nature, and higher resistance to damage. Nevertheless, they can be deformed easily and are relatively costlier than wooden pallets.

Metal pallets, typically made of steel or aluminum, find application in industries dealing with metal products due to their durability. They are easy to clean but tend to be heavier, which may increase transportation costs.

Cardboard pallets are mainly used for light loads and have a short lifespan, but they are affordable, easy to handle, and eco-friendly.

The benefits of using pallets are many: faster loading and unloading processes enhance transportation efficiency and ensure timely dispatch of goods. The adoption of pallets reduces labor requirements significantly, as it mechanizes storage and transportation, minimizing manual handling and related issues. Standardization is another advantage of pallet usage since most pallets follow predetermined sizes specified by standard guidelines, enabling precise planning for storage and transportation.

Figure 6. Different types of pallets

1.5.3 Layout

Warehouse operations rely on the right space configuration to achieve success. Creating an optimized warehouse layout involves careful consideration of different configurations to meet specific needs and objectives. A well-designed layout streamlines overall operations, improves production flow, and enhances inventory accessibility.

A warehouse layout is a planned design that includes the arrangement of various elements within the facility. It aims to improve the flow of production and distribution, making the entire workflow more efficient. To achieve this, warehouse management software is sometimes utilized to automate processes, providing better visibility and tracking of product movement between locations.

An effective layout contributes to cost reduction and increased productivity.

Here are some benefits that an optimized warehouse layout helps achieve:

- *Optimize Warehouse Space:* One of the primary objectives is to make the best use of available space. Utilizing warehouse space effectively reduces the waste: offers points into what works best and ensures inventory organization at every stage. Every meter of the warehouse should be maximized at its fullest potential, considering the area and size for better results.

- *Increase Productivity*: Improved productivity and efficient order fulfillment are critical for any company. The right warehouse layout minimizes bottlenecks, errors, and interruptions, optimizing operations and enabling faster and accurate order processing.
- *Utilize Labor and Budgets Effectively*: Different warehouse layouts come with varying costs and resource requirements. A suitable layout considers available floor space, materials, and workforce placement. This allows for more efficient resource allocation, warehouse maintenance, and the right number of employees for smooth operations.
- *Keep the Space Clean*: Warehouse tidiness plays a crucial role in avoiding significant issues. An organized warehouse floor plan reduces the chances of misplaced items, ensuring that each element fits seamlessly within the workflow.
- *Improve Overall Warehouse Management*: A well-designed warehouse layout contributes to effective warehouse management. This includes organized inventory, quick replenishment, fair treatment of staff, and efficient order fulfillment.

Dynamic storage, which holds inventory without specific locations (i.e., high-demand items located closer to packing areas) is nowadays more used thanks to the new technologies.
Static storage, on the other hand, stores inventory products with a fixed location using racking systems. The staging area is used for incoming and outgoing packages, preparing them for packing or placement in the warehouse. The shipping area handles completed order packages, loading them onto trucks for delivery, while the receiving area receives and records incoming items.

In the next page different types of warehouse flows include the U-shaped, I-shaped, and L-shaped configurations:

- *U-Shaped Warehouse Flow:* This common layout is suitable for beginner warehouses. Major warehouse traffic flows in a semicircle with shipping and receiving areas on parallel sides and storage in the middle. This design optimizes the separation of incoming and outgoing materials, minimizing bottlenecks, and reducing the space needed for packages.

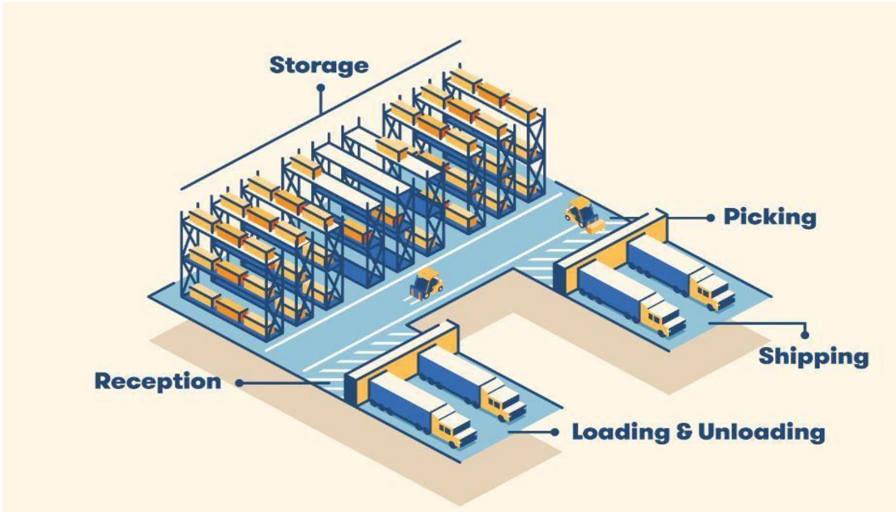

Figure 7. U-Shaped Layout.

- *I-Shaped Warehouse Flow:* Preferred by larger corporations with higher production volume, this layout features a straight flow from receiving to shipping. It optimizes warehouse space, keeps similar products separated, and minimizes back-and-forth movements. However, it requires optimal loading and unloading space on two sides of the warehouse

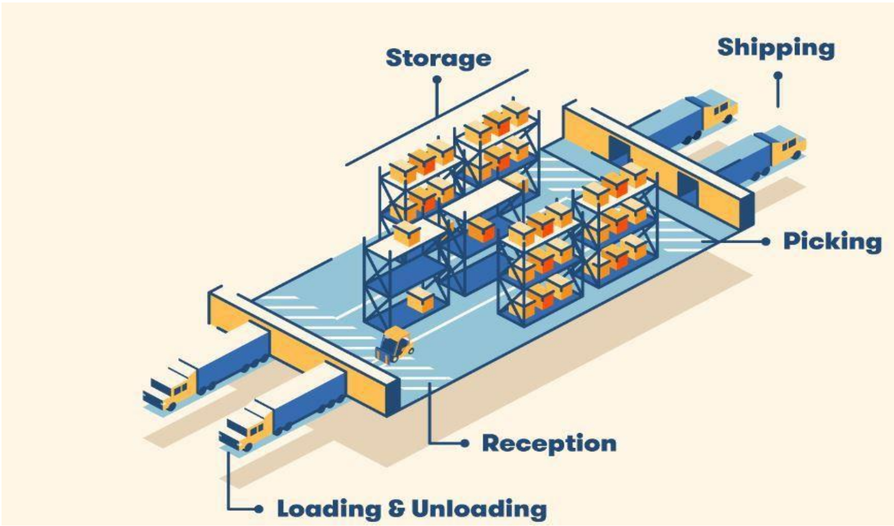

Figure 8. I-shaped layout.

- L-Shaped Warehouse Flow: The least common layout, this configuration accommodates an L-shaped building. The shipping and receiving areas are on adjacent sides at a 90-degree angle. It minimizes congestion, effectively separates products, and shares advantages with the I-shaped flow. However, it demands a significant amount of space.

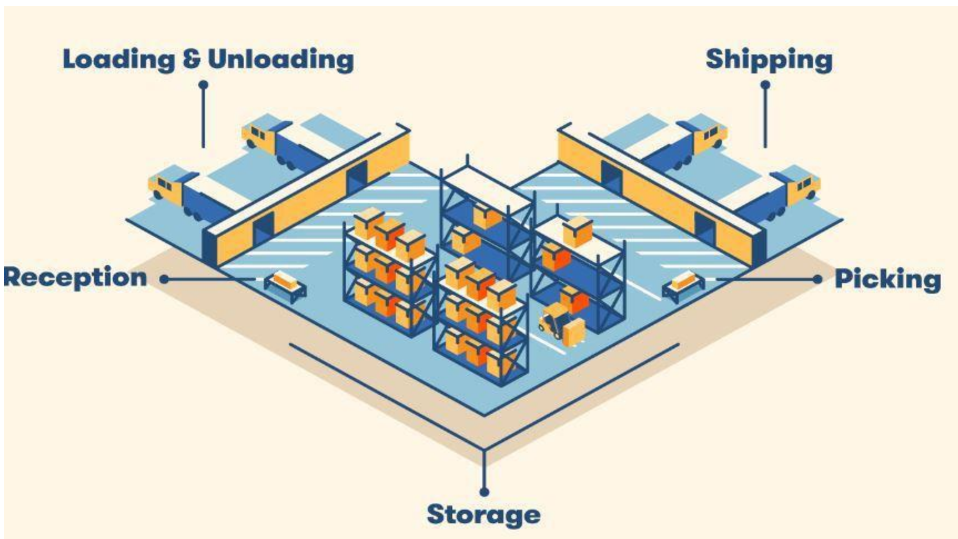

Figure 9. L-shaped layout.

When choosing the right warehouse layout, factors such as storage and inventory organization, inbound receiving docks, picking and packing areas, outbound shipping docks, and employee space must be carefully examined. These considerations ensure a well-organized and optimized warehouse, enabling smoother order fulfillment and more efficient overall operations.

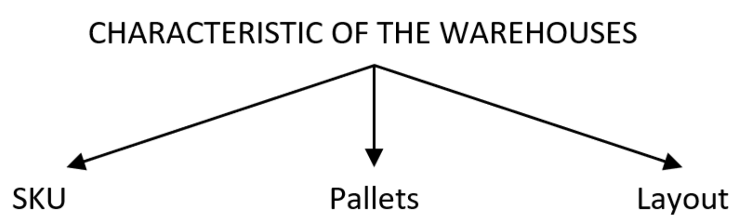

Figure 10. Characteristic of the warehouses.

1.6 Logistic warehouse KPIs

In this paragraph the main logistic KPIs for the warehouses will be considered in order to give the reader the basics mathematical and numerical benchmark for the solutions, to better understand which parameters are usually taken into account when the choice of the layout must be accomplished.

1.6.1 Stock rotation index (R)

The rotation index of a specific item expresses the number of times the material "renews" or "rotates" in the warehouse during a certain period. For example, an annual rotation index of 3 means that the material rotates three times in twelve months: after an initial stock-in and subsequent stock-out, there is a second receipt followed by another stock-out, and finally a third stock-in and stock-out. A high rotation index indicates that the inventory rotates many times (or quickly), while a low rotation index means that the inventory remains more static or rotates more slowly.
The rotation index can be computed as follow:

$$R = \frac{annual\ sales\ (quantity/year\ )}{average\ stock\ (quantity/year)}$$

Or using the same formula expressed in €/year.
Talking about the rotation index is equivalent to talking about the average stock holding time of an item. By knowing the rotation index, you can determine how much time, on average, that product remains in the warehouse from its receipt until it is sold.

$$Average\ stock\ time = \frac{365}{R}$$

By knowing the rotations of each material, it is possible to allocate the materials in the warehouse in such a way as to minimize movements for withdrawals, following the simple rule of placing high-rotation items in easily accessible and closer areas. If we consider a shelved warehouse, one could think of placing the high-rotation items on lower shelves.
In the realm of warehouse logistics, goods rotation plays a crucial role in determining the speed at which goods are sold and replenished. The frequency of goods rotation can be measured per year, month, week, or day, depending on the specific industry and business requirements. To classify articles

based on their sales volume, businesses often employ an ABC analysis that categorizes items as fast-moving A-items or slow- moving C-items (analyzed later). Fast movers, characterized by their rapid sales and short duration in the warehouse, typically encompass products of daily use with high consumer demand. Conversely, slow movers have a low sales speed and tend to remain in the warehouse for extended periods. Identifying fast and slow movers is instrumental in optimizing inventory levels and ensuring efficient utilization of warehouse space.

1.6.2 Selectivity index (S)

The selectivity measures the performance of a storage system and is defined as the ratio between the number of directly accessible Load Units (SKU) and the installed storage capacity. It ranges between 0 (exclusive) and 1 (inclusive). A selectivity of 1 means direct access to each SKU, achievable with single-depth shelving. If the selectivity is less than one, not all SKUs are directly accessible, requiring the movement of some units to access the needed ones.

$$S = \frac{SKUs\ accessible}{\text{SKUs total}}$$

1.6.3 Surface saturation index (Ss)

This ratio represents the actual surface used for storing load units compared to the total storage area's surface. It reveals how efficiently the storage areas are being utilized by the company and should ideally tend toward one to maximize storage space utilization.

$$Ss = \frac{Storage\ surface}{Total\ surface}$$

1.6.4 Volumetric saturation index (Sv)

This ratio compares the actual volume used for storing load units to the total volume of the storage area. It provides insights into how efficiently the available storage space is being utilized by the company.

$$Sv = \frac{Storage\ volume}{Total\ volume}$$

1.6.5 Moving index (M)

This index represents the number of withdrawals, including those for incomplete load units in a reference time frame T*. It accounts for possible recirculation and may differ from the flow of units leaving the warehouse.

$$M = (SKUs\ moved)_{T^*}$$

1.6.6 Access index (A)

This index represents the average number of accesses to a specific section within a given reference period T*, proportional to the probability that a generic access is related to that section.

$$A = \frac{M}{Dedicated\ cells}$$

1.7 Management KPIs

The myriad of KPIs (key performance indicators) available to merchants presents a treasure amount of data, instrumental in managing peak performance. From the inception of goods at the loading bay to the point where they are entrusted to shipping carriers, online retailers stand poised to meticulously assess (and augment) an expansive spectrum of operational processes.
Below the most important management KPIs are listed following the logical and temporal path of the SKU in the warehouse.

KPIs Encompassing Receiving:

- *Receiving Timeliness Definition*: Measures efficiency in processing incoming stock, assessing time from acceptance to storage preparation. Addressing delays in this phase improves overall warehouse flow.

- *Receiving Cost per Line Definition*: Calculates total expenses for receiving a product line, providing a clear financial perspective on operations. Higher costs per line signal areas needing efficiency improvements.

- *Receiving Efficiency Quotient Definition*: Benchmarks warehouse productivity during inventory intake, considering volume received and operational hours. Factors like equipment use and layout influence this KPI, offering insights for improvement.

KPIs Encompassing put away:

- *Put away Precision Quotient:* Measures accurate initial storage placement, crucial for smooth downstream operations. Barcode scanning enhances accuracy.
- *Put away Cost per Line*: Totals expenses for storing a product line. Higher costs indicate suboptimal put away processes.
- *Put away Cycle Time:* Calculates average time to store an item, emphasizing efficiency and guided put away with WMS directives.
- *Dock to Stock Chronology:* Tracks time from receipt to storage, highlighting the critical link between receiving and put away. Efficient dock management is essential for overall operational flow.

KPIs Encompassing Storing:

- *Inventory Veracity Quotient*: Measures the percentage difference between actual stock and recorded inventory in the management system. Factors like disorganized storage and suboptimal management affect accuracy. Well-organized warehouses with robust systems enhance automation and oversight, reducing reliance on manual record-keeping.
- *Inventory Turnover Tempo*: Reflects how often inventory is sold and replenished. It is basically the turnover ratio seen before.
- *Inventory Carrying Cost Quotient:* Represents the percentage of total inventory value spent on maintaining stock. Calculated by dividing the sum of inventory service, risk, capital, and storage costs by total inventory value. Reflects efficiency in goods movement, demand projections, marketing effectiveness, and warehouse layout. Elevated costs require a thorough analysis for targeted reduction.

KPIs Encompassing Fulfillment:

- *Order Picking Precision Quotient*: Measures the percentage of orders accurately selected and verified before shipping. Eliminating picking errors is crucial for customer satisfaction and cost savings. Controlled receiving, organized put away, rigorous barcode scanning, and automated picklists contribute to achieving near- perfect picking accuracy.

- *Orders Picked per Hour Attainment*: Productivity-focused KPI for evaluating picking efficiency. It calculates the total count of orders picked divided by the hours spent on picking. Automation enhances productivity and accuracy in picking operations.

- *Lines Picked/Shipped Rate*: Benchmarks fulfillment efficiency across various product lines. It calculates the total count of order lines picked and shipped divided by the hours spent on picking and shipping. This KPI reveals efficiency differences between product lines, prompting potential adjustments in strategies for improved operational efficiency.

- *Rate of Customer Returns*: Quantifies the percentage of shipped items that are later returned. While returns are natural in eCommerce, reducing them is crucial for cost reduction. Analyzing this KPI helps uncover underlying reasons behind return patterns.

KPIs Encompassing Safety:

- *Time Lost Due to Injury Rate*: Measures the percentage of potential worker hours lost due to workplace accidents within a specific period. It is calculated by dividing the hours lost due to accidents by the total number of hours worked. Addressing safety concerns not only promotes employee well-being but also demonstrates the organization's commitment to a culture of safety.

- *Time Since Last Accident and accidents per Year*: These metrics speak to the safety record of the workplace. The time since the last accident and the annualized count of accidents are important indicators of employee well-being and safety in the warehouse. Implementing protocols for accident prevention, including measures like spill cleanup, lighting maintenance, and other preventive actions, cultivates a safety-conscious culture.

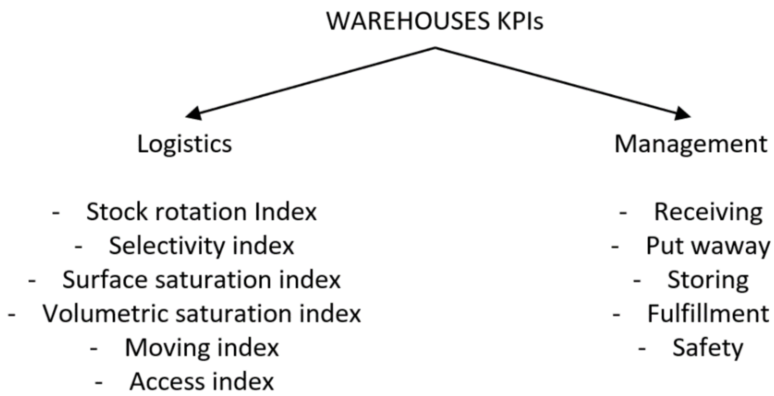

Figure 11. Warehouse KPIs scheme

In this chapter a comprehensive exploration of warehouses and distribution centers has been carried out, laying the foundational knowledge essential for going deeper into the next chapters, by providing a detailed overview of these elements in the supply chain. From understanding the core functions of warehouses to analyze the key performance indicators and operational metrics.

In the following paragraphs, the focus will be shifted into specific systems, technologies, and strategies that drive efficiency, accuracy, and optimization in warehouse and distribution center management.

2. Innovative automated systems for smart warehouses

In the dynamic landscape of modern logistics, the emergence of automated systems for warehouses represents a crucial shifting point. These systems, driven by revolutionary technology and sophisticated algorithms, promise to revolutionize the way materials flow through distribution centers.

In the pursuit of optimizing operations, it becomes crucial to evaluate the advantages and disadvantages of each automated approach, focusing on the transformative potential they bring, as well as the challenges they might bring.

In the following paragraphs the focus will be on the latest used technologies for the different steps of the material in the warehouse; the logical and effective flow of the materials throughout the warehouse is considered as a logical order, starting from the receiving phase of the material to the effective storage technologies options and finally to the palletization and the final loading to the shipping carrier.

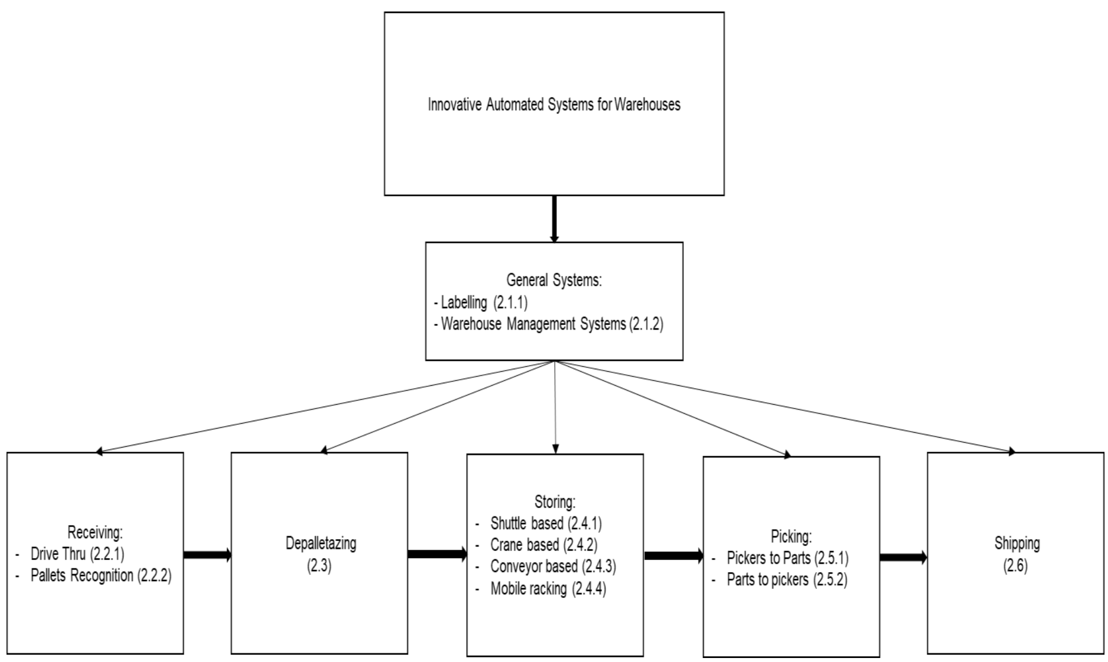

Figure 12. Overview of the chapter.

2.1 General: Labelling and warehouse management system

Warehouse labeling is one of the most undermined aspects of supply chains across the globe. Labeling here refers to identifying items within the storage facility with reference to the areas assigned for stacking it. However, it is not limited to the products as the storage areas but also to aisles, shelves, material handling equipment, and packing/shipping stations. Warehouse labeling depends on the nature of the businesses, the volume, and a variety of SKUs.

Inventory tags and labels are physical markers placed on items for counting, identification, and traceability. These include barcode labels, stickers, colored plastic tags, and more, carrying human-readable and scannable data.

Their use extends beyond stock items to office supplies, equipment, and storage areas, encompassing asset labels, repair tags, and more. These convey essential information along the supply chain.

Labels typically feature item basics like names, SKU codes, lot numbers, and quantities. Additional details can cover item locations, receipts, expiry dates, and quality control.

Employing these tags organizes stockrooms and enhances supply chain traceability. Barcodes and QR codes on labels enable data scanning into inventory management systems.

Preliminary actions prior to applicate the extensive application of labeling strategies, careful consideration of the following factors is imperative:

- *Plan Warehouse Layout*: Allocate specific areas for different inventory types for easy access and proximity to points of use.
- *Implement SKU and Serial Numbers*: Assign unique Stock-Keeping Unit (SKU) codes and consider using serial numbers for individual item monitoring.
- *Ensure Clear Label Content:* Use concise information on labels, incorporating barcodes or QR codes for efficient data communication.
- *Choose Label Generation Tool*: Select an appropriate label generation mechanism, integrated into inventory management systems or consider external tools.
- *Opt for Barcode Scanning:* Use specialized scanners or compatible devices like smartphones or tablets for efficient barcode scanning.
- *Integrate Inventory Management System*: Implement an ERP system or dedicated software for comprehensive organizational structuring and traceability.

- *Provide Employee Training*: Ensure all relevant personnel are well-trained in the operational aspects and foundational principles of the labeling system.

2.1.1 Labelling

LPN labels, or license plate numbers, are sequential barcodes for tracking mobile units in warehouses. Integrated with a management system, they enable comprehensive tracking, providing item details through scanning. ID Label offers customized designs with various options. Corner-wrap pallet labels, with duplicate barcodes, enhance visibility for workers.

Figure 13. LPN Labelling.

The prevalent type of warehouse label is located on rack beams, designating rack bay positions for storage, picking, and inventory control. Comprising barcodes and human-readable elements, these labels are often crafted from durable polyester or polypropylene stocks, enabling accurate scans.

Figure 14. Rack labelling.

Floor labels serve to mark rack or bulk storage locations, requiring robust durability due to frequent contact with lift trucks, pallets, and foot traffic. ID Label offers durable floor plate location labeling kits as a practical solution to identify bulk storage in diverse environments.

Figure 15.Floor labelling.

In warehouses, plastic bins and containers are used to store individual products and parts. Just as warehouse racks are labeled with barcodes for easy item retrieval and inventory management, these bins should also be appropriately identified. Reusable warehouse totes also necessitate proper identification.

Figure 16.Containers labelling.

2.1.2 Warehouse Management System (WSM)

As the world is advancing toward the future, technology is rapidly shifting. Automation is taking over industries and the days when technology was merely used in hi-tech labs by scientists are done. Currently, almost every item in a household can be controlled with just one click, and nothing is untouched by the automation.

Conventionally, the goods reaching the inventory are identified at the check-ins by either the Sales Order (S/O) or some ID, associated with them in the production department. An efficient way is to use automated tags or IDs; nonetheless, it is pertinent to tag every item or product reaching the inventory, which makes it easier to be tracked by the system.

Currently, for Warehouse Management Systems (WMSs), many tracking mechanisms are used. Several algorithms have been designed for smart management systems based on the IoT that are used for tasks such as product placement and product retrieving by visualizing and relating data in terms of space, position, and volumes. From picking goods to arranging them on the shelves and pallets, all the tasks have to be optimized in a way that constructively improves the flow of the supply chain. Techniques such as adaptive task planning and path planning algorithms have been put into practice in order to manage large autonomous systems with limited resources.

Although there have been previous works in the domain of warehouse automation and inventory management systems, nonetheless, there is always room for improvement. The past research has mostly addressed partial automation on one or more sections of an inventory. There is also little to no research on the implementation of a complete architecture of a warehouse automation system, conforming to the modern standards of the Industrial IoT and providing practicality, feasibility, and efficiency [1].

The functions of a Warehouse Management System (WMS) cover various aspects of warehouse operations, both within the warehouse itself and throughout the extended supply chain.

A comprehensive WMS enhances activities from receiving and storage to picking, packing, and shipping. Its core features are designed to improve these operations in the following ways:

- *Receiving and Put-away Process*: A WMS aids in efficiently receiving, processing, and storing items based on business rules and warehouse flow. It replaces manual methods, such as pen and paper, with RFID technology and barcode scanning, automating item reception, validation, and reconciliation against digital purchase orders.

- *Inventory Management*: WMS software offers real-time visibility into inventory across multiple locations, including items in transit. This is achieved through automatic identification technologies like barcodes or RFID. The system supports cycle counting and demand forecasting using advanced analytics, enabling adjustments to inventory levels to meet customer demand accurately.

- *Order Picking, Packing, and Fulfilment*: WMS systems optimize picking, packing, and fulfillment activities within the warehouse. They guide efficient storage, retrieval, and packing processes and support various picking technologies, such as radio frequency, pick-to-light, pick-to-voice, robotics, and algorithms that optimize picking paths. Different order fulfillment techniques like batch picking and zone picking are also accomplished.

- *Shipping*: WMS systems integrate with transportation and logistics software to optimize the fulfillment process. They generate shipping documents, invoices, and automatic shipment notifications. Real-time tracking features allow companies to monitor package delivery, ensuring timely and accurate shipments.

- *Labor Management*: WMS provides real-time visibility into warehouse workers, labor costs, productivity trends, and response times. Insights help optimize labor-related costs and improve efficiency. Task allocation and planning features minimize travel time and optimize scheduling for the workers.

- *Yard and Dock Management*: Yard and dock management features assist truck drivers in quickly locating loading docks. Support for cross-docking is facilitated by the WMS, ensuring goods are placed directly into outgoing shipments without interim storage.

- *Warehouse Metrics and Analytics:* WMS automates data collection, reducing errors and speeding up the process. This data can be integrated with analytics to track vital metrics like on-time shipping, inventory accuracy, distribution costs, order cycle time and more. Visual reports created by the system aid stakeholders in making informed decisions.

In summary, a Warehouse Management System offers a suite of features that optimize warehouse operations from material reception to shipping, enhancing efficient storage, accurate inventory tracking, streamlined order fulfillment, labor management, and comprehensive analytics. Its integration supports data-driven decision-making and enhances overall operational efficiency.

The WMS can be integrated with ERP (Enterprise management system) as better explained in the following paper:

''The integration and application of a warehouse system and manufacturing system has become a manufacturing problem for enterprises. The main reason is that the information control system based on automation and stereo warehouse is inconsistent with the production and management information system of the enterprise in terms of business, data, functions, etc. Based on this, this paper studies the implementation of an automated warehouse based on the integration of ERP (enterprise resource planning) and WMS (warehouse management system) with the method and technology of the intermediate table. Moreover, MES (manufacturing execution system) is the brain and the core part of a sustainable digital factory. The enterprise adopts advanced intelligent and information technology to build and deploy the MES, realize fine management and agile production, and meet the personalized needs of the market.'' [2]

Numerous industries utilize WMS software, with six sectors being the foremost users. Manufacturing firms require WMS to monitor diverse inventory types, ranging from raw materials to final products. Retail businesses utilize WMS to manage online orders and allow customers to view inventory at physical stores, enabling convenient pickup or delivery. WMS is crucial for Food and Beverage and Healthcare sectors to handle perishable products and ensure timely shipment. Third-party Logistics (3PL) companies rely on WMS to maintain separate and independent stock for various clients. Wholesale Distributors, dealing with large inventories, employ WMS to enhance efficiency and minimize labor expenses.

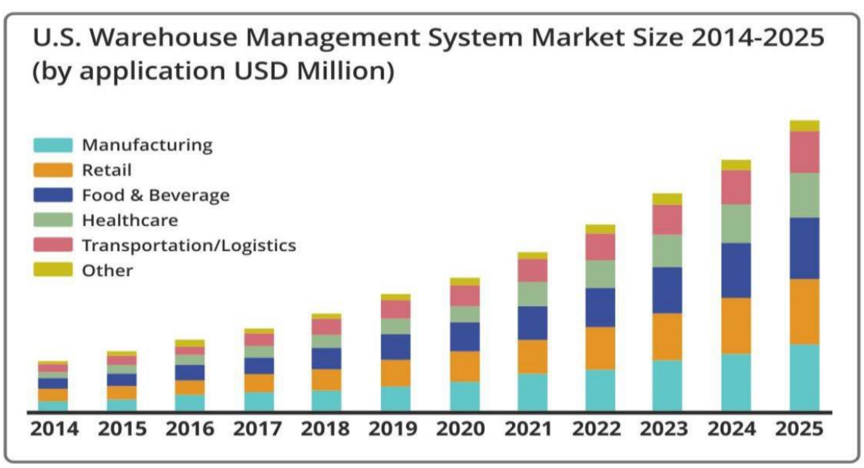

Figure 17. WMS Market size.

2.2 Receiving: Automated systems for reading barcodes.

The contemporary automated manufacturing warehouse features sensors that identify the characteristics of each SKU, including type, dimensions, weight, and expiration date. Additionally, the warehouse includes robots responsible for SKU movement, control algorithm and an interface to engage with external services.

In the following paragraph the focus will be on the innovative solutions present on the market for scanning the products and automatically storing them properly in the shelves, after the information is given to the algorithm that optimizes the storage of each SKU.

In this receiving phase usually an entire pallet with multiple SKU of the same type and already labelled is entering the warehouse from both the production floor and inbound logistic (in the case of retailing businesses).

2.2.1 Drive thru barcode scanning

This technology is under the category of RaPTr (Rapid Pallet Tracker) and it is a system to scan pallet ID labels automatically and boost both speed and accuracy.

RaPTr functions as an automated system designed for scanning and tracking pallets in the warehouse. This self-contained module, equipped with camera(s), a server, and accompanying software, is capable of scanning barcode labels on pallets as they traverse warehouse dock doors or other designated checkpoints. The touchless scanning mechanism operates while the barcodes are in motion, eliminating the need to halt or disembark from forklifts. This technology proves to be a more efficient and cost-effective alternative to RFID-based pallet tracking systems.

Each scan is meticulously timestamped along with capturing an image, ensuring that the data is promptly recorded within the system for the purpose of scanning visibility and validation. The included web-based dashboard and reporting tool facilitate seamless data retrieval and analysis.

Figure 18.Camera scanning drive thru.

Manually scanning with handhelds in the warehouse introduces human error and profit loss because it is slow, labor-intensive, and prone to missed scans and mis-routed pallets.
Forklift drivers do not have to manually scan or even stop and can receive clear and immediate feedback that product and pallets are dispatched to the correct truck. Shipments can leave warehouses faster, with the accuracy and data needed to avoid compliance fees such as OTIF.

- If shipping 5-10 trucks per day, the system gives one year payback against the cost of RFID tags alone.
- Save 25 minutes of loading time per truck.
- Retrieve timestamped scanning data with photographic proof.
- Improve forklift safety by eliminating need to mount/dismount to scan and reducing distracted driving - drivers can keep both hands operating the vehicle and eyes ahead.
- Enables better inventory control and visibility to reach and maintain FTZ warehouse requirements.
- This is the fastest large area scanner on the market (scan area of 1m x 1m or larger).

2.2.2 Recognition and Location Algorithm for Pallets in Warehouses Using RGB-D Sensor

A real-time approach based on an improved label template matching algorithm with an RGB-D sensor was proposed in [3] to recognize and locate pallets in a warehouse environment. The application of this technology can reduce labor and cost savings, as well as provide a level of warehouse automation.
Forklifts are widely used handling equipment known for their benefits, like increased productivity and reduced manual effort. The demand for forklifts is rising yearly, with projections suggesting substantial market growth. Despite their popularity, accidents involving forklifts are prevalent due to operator errors. Developing automatic-drive forklifts has become crucial, requiring advancements in technologies like autonomous navigation and pallet recognition.
Researchers have explored various algorithms for pallet recognition, mostly relying on single sensors like cameras and laser scanners. However, such methods often lack accuracy and struggle with complex environments. This research introduces an RGB-D sensor-based algorithm to accurately recognize and locate pallets in semi-structured environments, even when dealing with multiple and differently shaped pallets. The proposed algorithm employs labeled template

matching and simplifies the operation of autonomous forklifts, making them more adaptable and effective in intricate settings.
From the study the results show that the algorithm is performing well also in dynamic condition when the forklift is moving or when an operator is around the pallet. In addition to that the system is also performing well in multiple pallet recognition.
This system and approach could be useful in the future where it can be improved with automated forklift, in the case the system will have data from pallets thanks to the RGB-D system and the advantage of having multiple data across the entire cloud system of the warehouse.

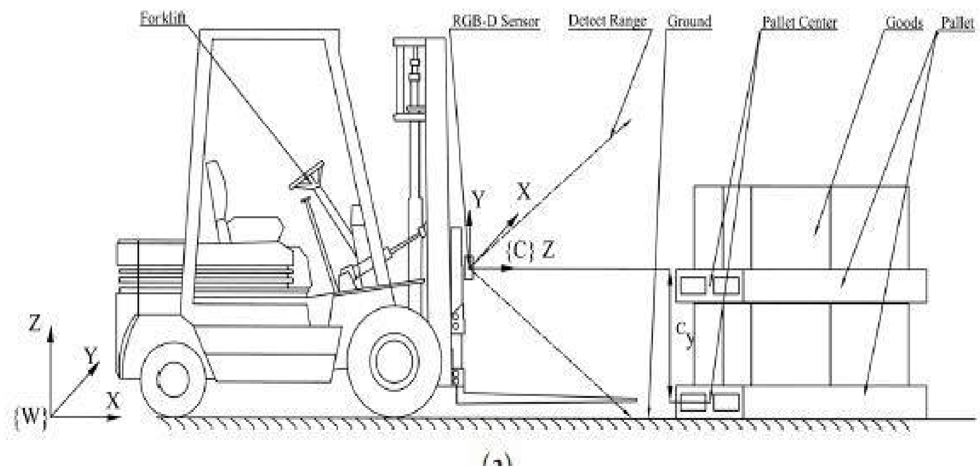

Figure 19. Scheme of the system.

2.3 Depalletizing

After entering the warehouse, the pallets are systematically depalletized: a procedure designed to break down the incoming shipment into its constituent SKUs. This deconstruction allows the warehouse to organize and store items with precision, considering factors such as demand patterns, item weight and volume.

In the research article [4] a cobot system is considered.
In the paper it's introduced a mobile manipulation platform designed for autonomous depalletizing tasks in industrial environments, particularly warehouses. The solution integrates machine vision, control, and mechanical components to enhance flexibility and deployment ease. The core features a collaborative robot (cobot) on a mobile base, equipped with a 3D in-hand vision system and a manipulation tool for extracting parcel boxes from pallets. This eliminates the need for

complex pick-and-place operations, improving efficiency. The 3D vision system estimates box poses and gap detection accurately. Force measurement and admittance control ensure manipulation task correctness.

The system separates object displacement and lifting operations, delegating object manipulation to the cobot and lifting to an automatic device on the mobile base, addressing payload constraints. This approach simplifies tasks while adhering to safety and payload limits common in collaborative mobile robots in industry.

This platform combines safety, flexibility, and ease of interaction, serving as a prototype for versatile multi-purpose platforms in shared warehouse environments. It offers potential efficiency and adaptability improvements in depalletizing tasks within modern industrial scenarios.

The paper describes the depalletizing process of cardboard boxes placed on a Euro Pallet (EPAL), arranged in up to four vertical layers with rigid interlayers. The sequential steps include robot self-localization, autonomous navigation to the target pallet, pose detection of boxes on the top layer, and extraction and placement of boxes onto the robot. To overcome limitations such as restricted robot payload and the requirement for packages to sustain their weight, a manipulation strategy involving dragging the goods onto the mobile robot is employed.

The proposed solution involves a serial collaborative manipulator UR10e by Universal Robots, mounted on a Mir100 Autonomous Mobile Robot (AMR) by Mobile Industrial Robots. A scissor lifting mechanism is integrated to facilitate box collection, decoupling displacement and lifting functions. The top of the lifting mechanism features an idler-roller conveyor for dragging and collecting items. During manipulation, a swivel hatch can be set in open or closed configurations to control box movement during AMR navigation. The system's operational capability depends on how the cobot and lifting mechanism are integrated on the AMR. The choice of hardware architecture also considers the AMR's footprint, either longitudinal for stability or transverse to overcome limitations. Ultimately, the cobot on a fixed support with a transverse arrangement was selected.

Regarding the lifting mechanism, it consists of two parallel scissor linkages and a linear electric actuator that operates a transverse ledger. A four-bar linkage facilitates the swivel hatch's rotational movement, as shown in Figure 20. To ensure simplicity, lightness, and cost-effectiveness, they opt for a passive approach in the four-bar actuation. By utilizing a crank-slider mechanism, the linear motion of the top wheel within the scissor lifting mechanism is transformed into an angular rotation of the four-bar crank.

To prevent undesirable interlayer sliding caused by friction during box manipulation, a pair of rotating clips is employed. These clips serve to secure the interlayer in place and prevent it from slipping. Each clip comprises an RC-Servo motor, a main body firmly attached to the motor, a sliding rod, and a compression spring. The RC-Servo actuates the main body's rotation, leading to spring compression and the application of force on the interlayer.

(a) Longitudinal layout. (b) Transverse layout.

Figure 20. Depalletizing cobot.

2.4 Storing

Fundamental part of the entire warehouse is the storing phase; in this paragraph we will deeply go into the main components and type of storing solutions present nowadays on the market.

2.4.1 Shuttle based solution

Shuttle-based system represent a paradigm shift in storage solutions. These innovative systems incorporate autonomous shuttles equipped with state-of-the-art sensors and advanced navigation algorithms, ensuring swift and precise handling of goods within the racking infrastructure. Studies conducted [5] have demonstrated an impressive throughput rate of up to 1000 movements per hour, showcasing a substantial enhancement in overall warehouse efficiency. This notable achievement has positioned shuttle-based systems as a crucial element in modern warehousing strategies. The adaptability of these systems is further underscored by their capability to accommodate an array of load sizes, supporting weights of up to 1500 kilograms. Such versatility enables businesses to efficiently manage a diverse range of products within their warehouse space, making them particularly valuable for industries with varying product profiles and demand patterns.

An important benefit of shuttle-based systems lies in their commendable energy efficiency. In the most used technologies is reported a remarkably low power consumption rate of 0.5 kWh per shuttle per hour. This data highlights the system's environmentally conscious design, contributing to sustainable warehouse operations. Notably, this not only reduces operational costs but also aligns with broader corporate sustainability initiatives.

In assessing the performance of shuttle-based systems, several Key Performance Indicators (KPIs) prove instrumental. Metrics such as Storage Density, Throughput Rate, and Energy Consumption per Movement offer invaluable insights into the efficiency and effectiveness of the system. By optimizing these KPIs, warehouses can realize substantial improvements in operational productivity and cost-effectiveness.

Implementing a shuttle-based solution has the potential to yield significant benefits for warehouses. Research indicates that businesses may experience throughput increases of up to 50%, illustrating the transformative impact of this technology. Additionally, energy costs can be reduced by as much as 30%, further bolstering the economic viability of these systems. Considering these compelling statistics, shuttle-based solutions emerge as a formidable asset, poised to shape the future of warehousing and distribution.

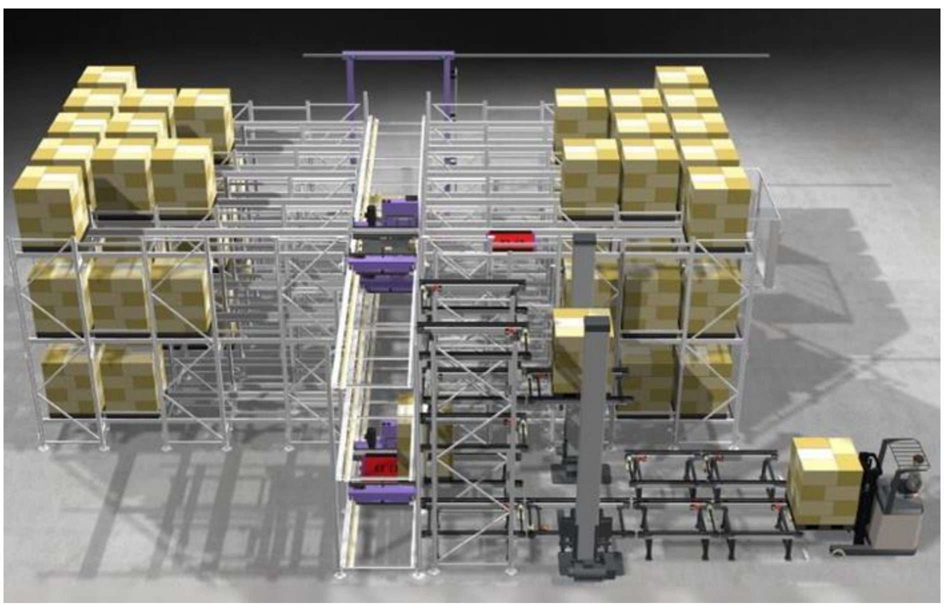

Figure 21. Shuttle layout.

Shuttle technical data	
Pallet width	1,200 mm
Pallet depth	800 / 1,000 / 1,200 mm
Load capacity	Up to 1,500 kg
Wheels	4
Unloaded travel speed	Ambient: 90 m/min Cold: 55 m/min*
Loaded travel speed	45 m/min
Lifting time	2 s
Working temperature	Ambient: 5 °C to 45 °C Cold: -30 °C to 5 °C
Batteries	Lithium

Figure 22. Shuttle detail

2.4.2 Crane based solution

These automated systems integrate advanced crane technology with sophisticated software, enabling precise and efficient movement of goods throughout the warehouse. According to research studies crane-based systems have demonstrated an impressive throughput capacity, handling up to 1500 picks per hour. This substantial increase in handling capacity is a proof to the efficacy of crane-based solutions in enhancing warehouse productivity.

One of the standouts features of crane-based systems is their ability to effectively utilize vertical space, making them particularly advantageous for warehouses with limited floor space. Research [6] highlights a 30% increase in storage capacity compared to conventional racking systems. This remarkable improvement in space utilization underscores the transformative impact of crane-based solutions on warehouse storage efficiency.

Energy efficiency is another key consideration in evaluating the performance of crane- based systems. Studies have shown that these systems exhibit a notably low energy consumption rate of 0.2 kWh per pick. This efficiency is attributed to the optimized movement patterns and regenerative braking technology employed by the cranes. By minimizing energy consumption, crane-based solutions not only contribute to lower operational costs but also align with sustainability initiatives.

In assessing the effectiveness of crane-based solutions, several Key Performance Indicators (KPIs) prove invaluable. Metrics such as Storage Density, Pick Accuracy, and Energy Consumption per Movement provide critical insights into the efficiency and reliability of the system. By optimizing these KPIs, warehouses can realize substantial gains in operational efficiency and cost-effectiveness.

Furthermore, adopting crane-based solutions has the potential to boost significant returns on investment for warehouses. Research indicates potential labor savings of up to 40%, demonstrating the substantial impact on operational costs. Additionally, suggest a potential reduction in storage footprint by up to 50%, further emphasizing the economic benefits of crane-based solutions. Considering these compelling statistics, crane-based systems emerge as a transformative technology, meant to reshape the landscape of warehouse storage and retrieval.

Figure 23.Crane based solution.

2.4.3 Conveyor based system

Research underscores the importan role of conveyors in enhancing operational efficiency. The research demonstrated a remarkable 30% reduction in order processing time, indicative of the substantial gains in productivity and throughput achieved through the implementation of conveyor systems.

One of the most significant advantages of conveyor systems lies in their ability to facilitate continuous and seamless material flow.

Conveyors enable a steady flow of goods at a rate of up to 200 items per minute. This consistent flow minimizes bottlenecks and congestion points, ensuring a smooth and efficient movement of goods from one point to another within the warehouse.

Furthermore, conveyor systems contribute to a significant reduction in manual handling, thereby minimizing the risk of injuries and ergonomic issues among warehouse personnel till 50% decrease in manual lifting activities, resulting in a notable reduction in musculoskeletal disorders and related injuries. This marked improvement in workplace safety underscores the positive impact of conveyor systems on employee well-being.

In evaluating the performance of conveyor systems, Key Performance Indicators (KPIs) such as Throughput Rate, Order Accuracy, and Conveyor Downtime prove to be pivotal metrics. Optimizing these KPIs leads to enhanced operational efficiency, reduced lead times, and improved customer satisfaction.

Moreover, the implementation of conveyor systems can improve substantial returns on investment for warehouses, they can achieve a return on investment within a span of two to three years through the adoption of conveyor technology. This rapid payback period highlights the economic viability and long-term benefits associated with conveyor systems.

In conclusion, conveyor systems stand as a important technology that not only streamlines warehouse operations but also enhances overall productivity and safety. With their ability to ensure continuous material flow, reduce manual handling, and improve key operational metrics, conveyor systems represent a strategic investment for warehouses looking to stay competitive in today's dynamic logistics landscape.

Figure 24. Layout with pallet conveyor system

2.4.4 Mobile racking solution

Research illustrates the substantial gains in storage density, with mobile racks reaching up to 80% more storage capacity compared to traditional static racking configurations. This transformative impact on warehouse space utilization underscores the crucial role of mobile racking systems in modern logistics.

Furthermore, mobile racking solutions offer a dynamic approach to inventory management, allowing for flexible storage configurations to meet evolving operational demands. Mobile racks can be reconfigured to accommodate varying load sizes and types. This flexibility in storage arrangements ensures that warehouses can efficiently handle a diverse range of products, from small components to oversized items, without the need for constant reorganization.

In terms of safety, mobile racking solutions provide enhanced protection for both goods and personnel. In the modern technologies the integrated safety features of mobile racks, including motion sensors, automatic braking systems, and aisle obstruction detection are very important for the safety aspect. These safety mechanisms mitigate the risk of accidents, such as collisions or unintended movements, ensuring a secure operating environment for warehouse staff.

Key Performance Indicators (KPIs) such as Storage Density, Accessibility Ratio, and Retrieval Time Efficiency are instrumental in evaluating the effectiveness of mobile racking solutions. Mobile racks excel in achieving high storage density while maintaining excellent accessibility, resulting in shorter retrieval times compared to traditional static racking configurations.

Moreover, the economic benefits of mobile racking solutions extend beyond increased storage capacity. These savings arise from reduced square footage requirements, lower energy consumption for climate control, and a decrease in maintenance and repair costs associated with static racking.

In summary, mobile racking solutions represent an advancement in warehouse storage technology, offering gains in storage density, adaptability, safety, and operational efficiency.

With their ability to maximize warehouse space utilization and streamline inventory management, mobile racking systems are a strategic investment for warehouses seeking to optimize their storage capabilities and overall operational performance.

Figure 25.Mobile racking solution

In Chapter 3, we will enrich the discussion by exploring the Automated Storage and Retrieval Systems, examining their design, functionality, and applications. Following this, in Chapter 4, our attention will shift towards a comprehensive analysis of automated vehicle solutions.
This will conclude a detailed examination of various types of automated vehicles, their integration with existing systems, and the potential advantages they bring to modern logistics and warehouse management.

2.5 Picking

According to the paper [7] order picking (OP) involves the process of retrieving products from the defined storage locations to meet the customer requirement, which accounts for about 55% of warehouse operations and OP is also considered to be the most labor-intensive warehouse operation.

In warehouse management, selecting the appropriate picking strategy is crucial for optimizing operational efficiency. Two primary approaches, "pickers to part" and "parts to picking" form the core of this decision-making process.

The "pickers to part" method consists in the human operators physically moving to the location of stored items for retrieval. This approach is good for situations where careful handling or specialized knowledge is required, as well as for environments with irregularly shaped or fragile items. Conversely the "parts to picking" employs advanced technologies to transport items to a central picking station. It is advantageous for high-volume, standardized inventory situations, standard the process and potentially reducing labor costs.

Ultimately, the choice between these strategies rely upon a multitude of factors including warehouse layout, inventory characteristics, and order volume.

2.5.1 Pickers to parts OP: assisted picking

Since the goal of this thesis is to take into account automated solutions, a manual picking is not considered and the lower level of automation will be assisted picking.

The most widely adopted technologies in the current market for assisted picking include various innovative solutions:

- *Pick-to-light systems* involve the installation of pick-to-light LEDs and barcode scanners on racks and shelves throughout the warehouse. When a picker scans the barcode on a shipping carton containing items for a specific order, the LEDs corresponding to the SKUs in the order illuminate. Workers then effortlessly follow these illuminated lights to locate and retrieve the listed items.

Figure 26. Pick to lights system.

- *Voice Picking*: pickers receive real-time verbal instructions regarding which items to pick and their respective locations. These instructions are transmitted through headsets worn by the pickers, connected to an order management This method significantly accelerates the picking process and enhances accuracy. Once the picking task is completed, pickers verbally confirm its fulfillment.

Figure 27. Voice picking.

- *Mobile Scanner-Based Picking* relies on unique barcodes for all items in the warehouse. Workers are equipped with mobile scanners that display pick lists along with the locations of each SKU. As pickers collect items, they scan them and if an item not on the pick list is scanned, the mobile scanner promptly notifies the picker enhancing picking precision. Warehouse managers can also provide optimized picking routes for increased efficiency.

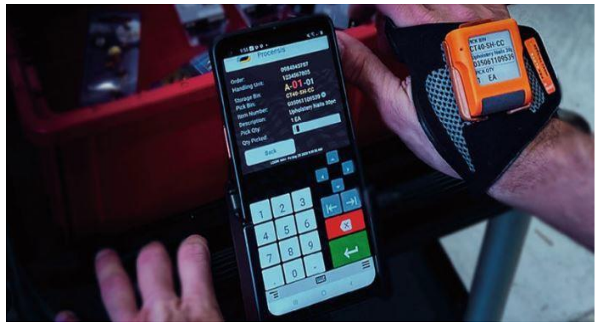

Figure 28. Mobile scanner picking

- *Collaborative Mobile Robots* have been integrated into order picking operations. Previously, workers manually navigated their carts between racks and aisles to retrieve items listed on pick lists. With the introduction of collaborative mobile robots, human operators now have access to robots that can augment their efforts and automate item movement.

Figure 29. Collaborative robots.

- *Augmented reality* is fundamental in vision picking to achieve an automated order processing, ensuring a 100% error-free operation. This innovative approach employs a head-mounted display containing a wearable PC, integrated camera, and control software, all seamlessly integrated with the WMS. The incorporated navigation system guides the picker along an optimized route, guiding them precisely to the targeted SKU and visually confirming its accuracy. With continuous quality control included in this system, the need for frequent warehouse audits is significantly reduced, enhancing operations effectively.

Figure 30. Augmented reality picking

2.5.2 Parts to picker OP: automated picking

The current automated systems on the market offer a diverse range of solutions tailored to warehouse needs. These systems include:

- *Automated Storage and Retrieval Systems (AS/RS)* utilize robotic cranes or conveyors for efficient movement of products to and from storage. These Goods- to-Person (GTP) systems significantly enhance productivity, reduce worker foot traffic, and maximize storage density. However, it's important to note that their implementation requires a substantial investment in infrastructure due to their considerable cost.

- *Autonomous Mobile Robots (AMRs)* characterized by their adaptability and compactness autonomously navigate warehouses using advanced onboard sensors.

  There are various mobile robotic picking systems available:

  - Cobot/Smart Cart AMRs are collaborative self-driving carts directed to specific aisles and shelves holding the target inventory container. Here, an associate retrieves the item, scans it for accuracy, and places it into the mobile robot. This approach is based on the Person-to-Goods (PTG) fulfillment method.

- Racks-to-Person AMRs are low-profile robots that slide beneath entire shelving units, lift them, and transport them to an order-picking station. While an improvement over order-picking cobots, this Goods-to-Person automation system maintains some dependencies between humans and robots, potentially causing bottlenecks. It's crucial to consider potential bottlenecks and the potential need for modifications to existing shelving units and warehouse infrastructure.
- Totes-to-Person AMRs further enhance Goods-to-Person automation by enabling mobile robots to extract inventory containers from storage shelves containing items slated for picking. The robot then proceeds independently, delivering the tote from warehouse shelves to an associate.

Figure 31. AMRs solutions.

- Pick and Place Robots find application in eCommerce fulfillment distribution centers. These robots automate the process of selecting individual items from storage locations and depositing them into shipping cartons or totes. They typically feature a robotic arm equipped with a gripper or suction cup, ensuring precise and accurate item manipulation.

These two solutions will be analyzed further in chapter 3.

2.5.3 Types of picking logics

According to the ''*6-river systems''* company there are these classification about the picking logics:

• *Single Order Picking:* In single order picking, pickers move through the warehouse and retrieve SKUs one by one to fulfill one order at a time. This picking system works well for small warehouses that handle simple orders with just a few items.

• *Batch Picking: Batch* picking optimizes picking activities by retrieving SKUs in bulk to fulfill multiple orders at a time. This minimizes travel time and speeds up fulfillment operations, especially for warehouses that receive multiple orders containing the same SKUs. Workers use a consolidated pick list to pick SKUs for multiple orders in one pass.

• *Multi-Batch Order Picking*: The multi-batch order picking system reduces picking times by simultaneously picking items for multiple orders. Workers typically use multi-tiered picking carts to pick multiple SKUs for several orders at a time. This picking system is used for orders coming from different areas in the warehouse and minimizes overall travel time since workers go through the facility once to fulfill multiple orders.

• *Cluster Picking*: This picking in a warehouse methodology is used to fulfill multiple orders at the same time. Workers travel through the warehouse retrieving SKUs on multiple pick lists and placing them into separate bins/containers. Each container is associated with a separate order/pick list. This eliminates repeated trips to the same pick location and removes the need for sorting since this is done by pickers at each pick location. However, it requires the use of sophisticated WMS solutions for proper scheduling and assignment of clusters.

• *Wave Picking:* Wave picking is a variation of batch and zone picking that is particularly useful for large warehouses that regularly receive multiple high-volume orders. Orders are grouped into sets or waves according to factors like customer location, order frequency, order type, picking zones and delivery date. Workers simultaneously pick SKUs from multiple zones and forward them for sorting and consolidation into individual shipments. Waves are assigned to pickers and schedules to maximize efficiency.

• *Zone Picking*: With zone picking, the warehouse is divided into zones and dedicated workers are assigned to each zone. Workers fulfill orders by going through the pick list and retrieving SKUs stored in their zone. Once all the items in that zone have been picked, the order carton is passed to other zones. In this way, SKUs are picked and passed from zone to zone and packed for shipping in a central consolidation location. This picking system significantly reduces travel time through fulfillment centers since workers stay within their assigned zones when picking items. For more information, read about the differences between zone and wave picking.

2.6 Shipping: Automated trucks loading and unloading system (ATLS)

Automatic truck loading and unloading systems have emerged as pivotal solution for enhancing efficiency and safety in the goods receipt and dispatch process at warehouse docks. These docks serve as critical junctures in distribution centers, with higher dock capacity directly correlating to increased goods flow and truck traffic.

Manual unloading typically consumes around 30 minutes per truck, varying by product type and weight. Automation has the potential to reduce this timeframe to under 10 minutes.

Positioned in the docking area, the system's layout requires meticulous planning, including the selection of dock type based on available space and determination of the precise number of docks, influenced by material flows, delivery volume, and operational timeframes.

Operationally, a truck backs up to the loading dock with its doors open, aligning itself for the process. Once in position, the dock door opens, and the truck connects to the loading dock power source. The loading/unloading process then commences, facilitated by conveyor systems in fully automated warehouses. Within minutes, the goods are loaded or unloaded with minimal staff intervention, ensuring safety and efficiency.

The specific components of an automatic loading dock system vary depending on the chosen solution. As of now, no standard system exists, as suppliers tailor solutions to suit factors like cargo type, truck specifications, and dock layout. Key components typically include roller and/or chain systems, extendable forks, and skids, complemented by lifting platforms, hydraulic tables, and conveyors for seamless interaction with the automated loading and unloading process.

''WDX Automated Truck Loading and Unloading System'' minimizes the time to load and unload an entire truck (33 Euro pallets or other loads) to less than 10 minutes. Below it is explained how the system works:

- The truck is placed on a positioning ramp located in the loading dock.
- The truck is automatically positioned on the ramp to ensure safe unloading of the semi-trailer.
- The forks of the Q-Loader system automatically drive under the entire load, when the load is lifted, the forks carrying the products automatically return to their original position.

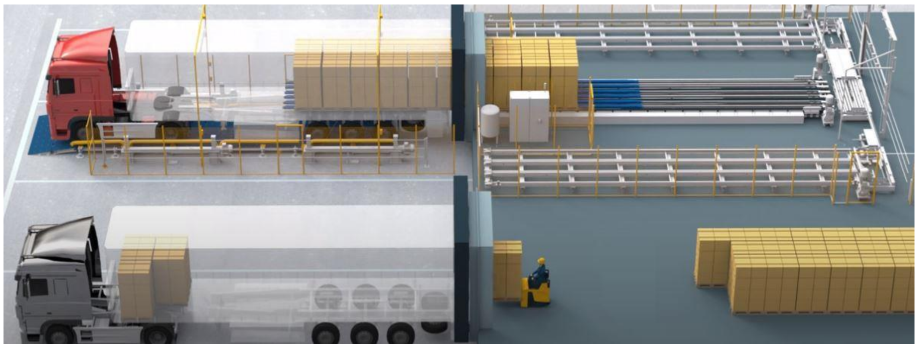

Figure 32. Difference between traditional and automatic truck loading systems

Automatic loading docks offer a myriad of advantages that significantly enhance a business's profitability. Firstly, they boost productivity by enabling the swift loading and unloading of a full truck containing up to 33 pallets in a matter of minutes. This translates to an increased frequency of goods dispatches and receipts. Furthermore, streamlined truck unloading reduces the time required for the dock-to-stock process, optimizing surface area utilization. This allows for the reallocation of space in the staging area for other operational needs.

Automation also ensures the protection of goods by eliminating hazardous movements during loading and unloading, thereby preventing potential damage. This reduction in product contributes to a decrease in reverse logistics activity. Additionally, automatic truck loading and unloading systems lead to workforce optimization. Since docks are among the busiest areas in a warehouse, automating this process reduces the number of workers needed in this zone, allowing them to be deployed to other tasks.

Moreover, operator safety is greatly enhanced. The loading and unloading process is a critical and high-risk operation in a warehouse. Automation eliminates the potential for accidents, creating a safer and less congested environment.

Finally, these benefits collectively result in lowered operating costs. With reduced staffing requirements, decreased wear and tear on handling equipment, improved safety, and increased productivity, automatic loading and unloading systems offer a rapid return on investment (ROI).

3. Automated storage and retrieval systems

As specified in [8] one of the most important part of logistics is intralogistics, also known as internal logistics, which claimed the second position in the global logistics market share of 2018. Intralogistics entails the intricate coordination, execution, and optimization of internal material flow spanning various logistics hubs.

In response to the pressing need for reducing Carbon Greenhouse Emissions (CGH), curbing energy consumption, and addressing the perennial challenge of workforce scarcity, a slew of innovative technologies and conceptual frameworks have been set forth.

Automation and robotization, inclusive of the integration of collaborative robots have risen to the forefront as an imperative to effectively surmount these challenges.

Below some definitions from literature:

''One of the most common automated warehouse solutions is the well-known Automated Storage and Retrieval System (AS/RS). It consists of one or more aisles, each equipped with storage racks on either side, a stacker crane (named S/R machine), and input and output stations (called I/O stations). Although these automated systems guarantee a high storage density, they are characterized by poor space efficiency due to the limited lanes depth (i.e., rarely more than double). Moreover, they are low flexible due to having one S/R machine per aisle that performs all the storage and retrieval (S/R) transactions. To overcome these limits, companies are moving toward Autonomous Vehicle Storage and Retrieval Systems (AVS/RS).'' [9].

''Automated storage and retrieval systems have been widely used in distribution and production environments since their introduction in the 1950s. An automated storage and retrieval system (AS/RS) usually consists of racks served by cranes running through aisles between the racks. An AS/RS is capable of handling pallets without the interference of an operator; thus the system is fully automated. Both in production and distribution environments AS/RSs are used for putting products (e.g., raw materials or (semi-) finished products) in storage and for retrieving those products from storage to fulfill an order.'' [10]

An Automated Storage and Retrieval System (AS/RS) combines a range of digital, robotic, and shelving components to create a customized automated warehouse capable of efficiently managing a diverse array of products, all under the control of digital automation software.

A personalized AS/RS solution can be adapted from a diverse set of options, including Cube

Storage, Autonomous Mobile Robots (AMRs), horizontal and vertical carousels, cranes, shuttles, Vertical Lift Modules (VLMs), Micro, Unit, and mini-Loads.

These systems are all managed by a Warehouse Management System (WMS), serving as the central intelligence of the operation.

AS/RS leverages warehouse robots, enabling a Goods-to-Person (GTP) automation approach, where goods are transported to workers, drastically reducing the need for manual walking. This approach significantly enhances efficiency, safety, and ergonomic conditions within the warehouse.

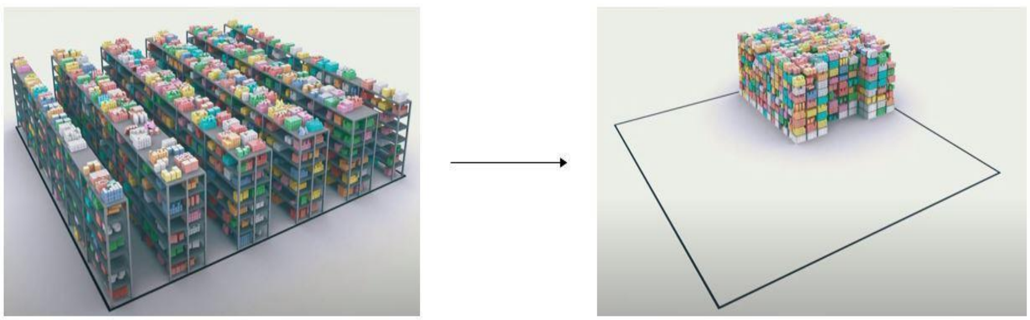

Figure 33. From traditional to modern warehouse layout.

3.1 AS/RS Configuration

Broadly speaking, AS/RS systems cater to three primary load types:

• Unit-Load AS/RS (e.g., for pallets).
• Mid-Load AS/RS (customized for specific inventory types).
• Mini-Load AS/RS (suitable for split-case picking).

In addition to these load types, various AS/RS options are available, including:

3.1.1. Cube Storage AS/RS
3.1.2. Mini-Load AS/RS Cranes (Fixed-Aisle)
3.1.3 Shuttle AS/RS
3.1.4. Carousel-based AS/RS
3.1.5. Vertical (VLM) AS/RS
3.1.6. Vertical Sequence Systems (VSM) AS/RS

3.1.1 Cube storage

The Cube Storage Automated Storage and Retrieval System (AS/RS) employs a new technology to achieve exceptional storage density, surpassing traditional shelving systems. By eliminating the unused spaces that are prevalent in conventional setups, it utilizes a sophisticated system of bins, stacked adjacent to and atop one another, akin to arranged building blocks, all within a robust aluminium grid framework.

Precision-guided robots travel along tracks with remarkable precision, consistently excavating, retrieving, and transporting these bins to designated ports, transforming them into highly efficient workstations within the vast expanse of the warehouse. Here, skilled workers access the inventory for order fulfilment and swift restocking operations, ensuring the warehouse operates with maximum efficiency.

Subsequently, the robots gather the emptied bins, returning them to their designated slots within the grid. This intricate process naturally organizes products based on their popularity, guaranteeing that high-demand items are strategically positioned at the top for easy access, while less frequently used items gracefully descend to the lower levels, thus optimizing the overall picking speed.

The Cube Storage AS/RS system combines an extraordinarily efficient utilization of space with state-of-the-art modular robot technology and a design concept of construction blocks, not only allowing for new installation but also providing a framework for future expansion, ensuring the system can evolves in tandem with the dynamic storage demands of the enterprise.

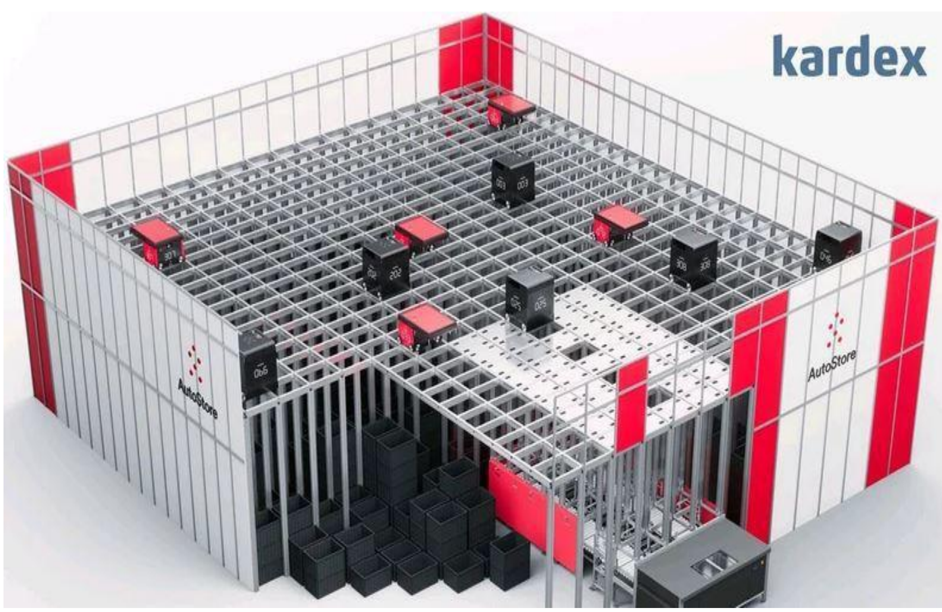

Figure 34. Cube storage.

3.1.2 Mini-Load AS/RS Cranes (Fixed-Aisle)

The Mini-Load AS/RS excels in managing smaller items, typically weighing no more than 75 pounds. This AS/RS variant frequently utilizes totes, trays, or cartons, either individually or in combination, to transport inventory. It is sometimes referred to as a "case-handling/tote-stacking" AS/RS. This system finds notable use when dealing with Stock Keeping Units (SKU) in situations where space is a precious commodity, rendering traditional carton shelving impractical. The Mini-Load AS/RS also offers versatility as a buffer for organizing products for picking or packaging, and it can be employed for replenishing pick storage.

However, these systems have limitations related to both weight and size, which somewhat restricts their versatility when compared to other AS/RS systems.

Figure 35. Mini load AS/RS Cranes.

3.1.3 Shuttle AS/RS

This system employs shuttles or robots to transport items, navigating a designated track both horizontal and vertical within the warehouse or workspace. These versatile systems can operate across multiple levels, efficiently delivering a diverse variety of items in totes or cartons to their designated destinations. Shuttles are programmed to retrieve items and transport them, either to a workstation or a secondary conveyor, often utilizing the exterior of the storage racks. The design of these shuttles can vary significantly to specific product and warehouse needs. However, it's worth noting that maintenance may render entire product aisles inaccessible, and shuttle-based systems typically require more space compared to alternative systems.

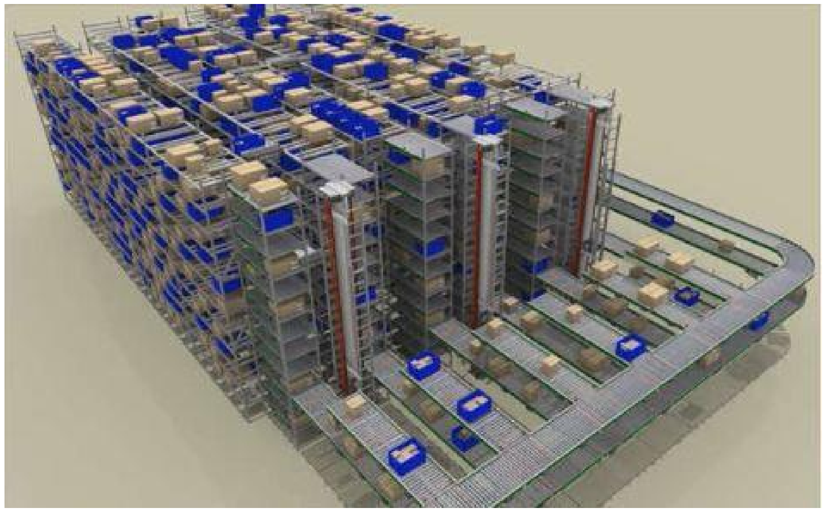

Figure 36. AS/RS shuttle.

3.1.4 Carousel-based AS/RS

The Vertical Carousel Module has a long history, dating back several decades. It consists of a series of carriers connected to a chain drive, with a motor powering these carriers to travel in a vertical loop along a track, much like a Ferris wheel. These automated storage and retrieval systems efficiently transport slow to medium-velocity items to an ergonomically positioned work counter at the operator's command. While manufacturers continually introduce new features with each update, the core technology remains unchanged. These systems offer throughput rates ranging from 100 to 400 lines per hour, and even higher rates can be achieved by incorporating light-directed picking technologies and batching stations that enable the fulfilment of multiple orders simultaneously. With a robust capacity of 1,430 pounds per carrier, the Vertical Carousel Module presents a reliable and cost-effective solution that should not be underestimated.

Horizontal Carousel Modules, on the other hand, feature densely packed storage bins mounted on an oval track that rotates horizontally. They are designed to efficiently handle slow to medium-moving items and cases, with a maximum weight capacity of 2,000 pounds per carrier. To maximize picking speed and throughput, these modules are often grouped together in pods. This setup allows a picker to access products from one carousel while others rotate to prepare the next required item, resulting in impressive throughput rates of up to 600 lines picked per hour. Achieving these rates is possible by integrating light-directed picking technologies and batching stations that facilitate concurrent order fulfillment.

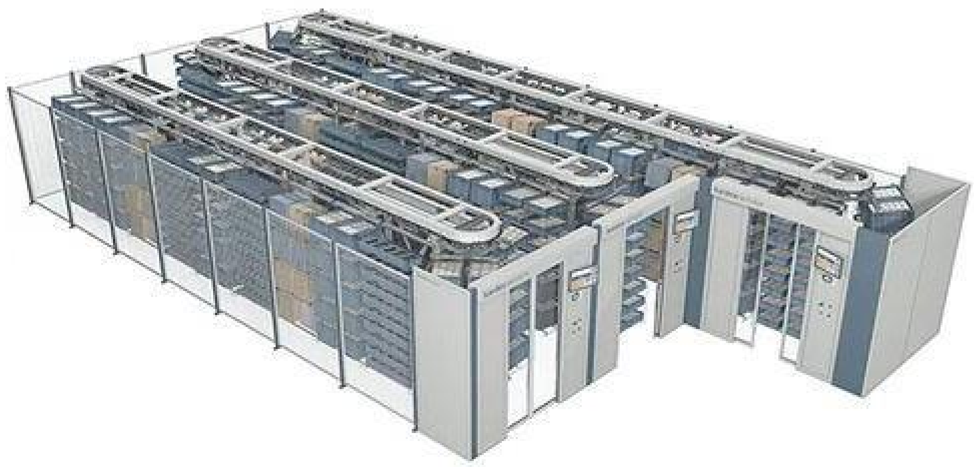

Figure 37. Horizontal carousel.

3.1.5 Vertical lift Module (VLM) AS/RS

These advanced automated storage and retrieval systems (AS/RS) include the Vertical Lift Module (VLM), Micro-Load Stocker, and Vertical Sequence Module (VSM). The VLM features a central picker navigating racks to select and transport ordered items within enclosed spaces, offering efficient inventory management. The Micro-Load Stocker, like the VLM, suits high-density warehouses for buffering and sequencing goods. However, both systems can experience downtime during maintenance. The VSM arranges retrieved bins in specific sequences, enhancing efficiency in high-density warehouses and can be integrated with existing AS/RS setups. All these systems play crucial roles in optimizing warehouse operations, with considerations for maintenance-related downtime.

Figure 38. VLM.

3.1.6 Vertical sequence systems (VSM) AS/RS

The system arranges retrieved bins in a predetermined sequence, offering an efficient solution suitable for high-density, high-volume warehouse environments. This order sequence can be accessed through other systems like an Autonomous Mobile Robot (AMR) or conveyor, ensuring items are delivered in a specific, organized manner. However, like the VLM mentioned earlier, maintenance-related delays may occur when specific components are temporarily out of service.

The ''*Conveyco Vertical Sequencing Module* (VSM)'' bears a resemblance to a Vertical Lift Module (VLM) in appearance, but their operational methods diverge significantly. Unlike a VLM, which relies on tray storage, the VSM individually inserts, extracts, and moves totes within the system. This system accommodates up to five totes in width and can reach heights of up to 65 feet, providing an efficient use of floor space. The VSM System offers exceptional flexibility and crucial operational advantages. It achieves a remarkable throughput of up to 500 transactions per hour per module. This system seamlessly integrates one or multiple modules and supports lights-out operation for enhanced automation. It can be easily integrated with various forms of material handling equipment, such as AS/RS, AMRs, robotics, conveyors, and more. Additionally, the VSM allows for customization of multiple insertion and extraction points in every module and system. It accommodates totes with varying heights and enables subdivision for maximum storage density. The VSM significantly reduces labor costs, potentially up to two-thirds, and enhances the performance of existing equipment, reducing the need for additional acquisitions or expansions. Moreover, it yields an impressive 85% floor space savings and ensures a rapid return on investment (ROI) with low acquisition costs.

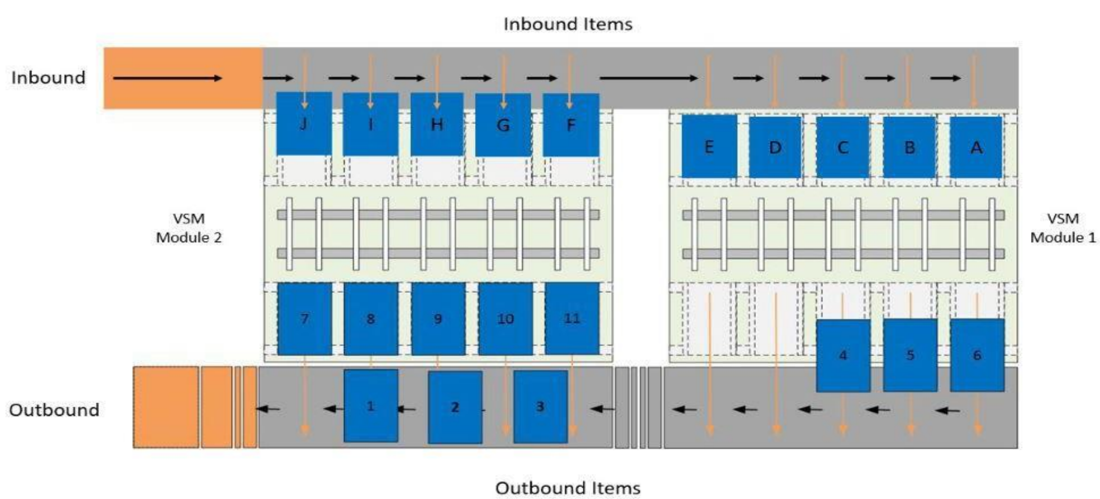

Figure 39. VLM by Conveyco

3.1.7 *Comparison with market solution performances*

In the paper [11] the current AS/RS market offers a range of solutions, as outlined by Turner's comprehensive review.

These include Pallet Handling Systems, ideal for low throughput and high-density storage: Mini load Systems for small item storage, Shuttle Systems with high throughput capabilities, AS/RS Unit, an innovative technology from Autostore and AS/RS with Automated Guided Vehicles (AGVs) for flexible picking.

For a detailed comparison, refer to Figure 40 summarizing their key characteristics.

	Pallets	Miniload	Shuttle	Autostore	AGVs Based AS/RS
Visual					
Speed	85 cycles/hour/carriage (60 for the double depth ones)	120 to 200 cycles/hr/carriage	500 cycles/hr/alley	Speed of 1.6 m/s and 30 bins/hour/robot	
Flow rate	Low (single input/output position)	Low (single input/output position)	High (5 times higher than miniload)	Medium	High (3 times more order lines processed per hour than a traditional storage system)
Supported weights	Between 230 and 1815 kg	Maximum 230 kg	Maximum 90 kg	Maximum 30 kg	Between 450 and 1360 kg
Maximum height	Very high (max 50 m)	Very high	Medium	Medium (max 7 m, between 4 and 16 bin heights)	Very low (maximum 2 m)
Type of products	Heavy and bulky	Small and medium weights	Small and light	Small and light	Small
Installation costs	High	High	High	Medium	Low
Operating costs	Medium (high maintenance costs due to poor reliability but low infrastructure costs due to high rack storage)	Medium	Medium	Low (high reliability)	High (decried reliability, need for floor space)
Density	Average (8 times higher than a traditional storage system)	Medium	Medium	High	Medium (removes traffic lanes but does not use height)
System flexibility	Very low	Low	High	High	High
Ease of installation	Low	Low	Medium	High	High
Adaptability	Very low	Low	Low	Medium	Low

Figure 40. Comparison on the technical solutions on the market

3.2 Software configuration: allocations of the products

Following the previous overview of various AS/RS typologies, this paragraph will focus into the principles governing product allocation and optimizations. This examination will rely upon current research papers and market solutions, with a specific emphasis on accommodating an extensive array of products, ranging from diminutive boxes to substantial SKUs such as household appliances like washing machines.

3.2.1 Literature research review

The literature review in this section is primarily based on the research paper [12] where an ovierview of the literature is well analyzed.

In recent years, the rapid development of e-commerce logistics has necessitated tailored solutions to accommodate the distinctive characteristics of this sector, characterized by small-scale items, high volume orders, diverse product types, and substantial order fluctuations. As a response, the widespread adoption of Autonomous Vehicle Storage and Retrieval Systems (AVS/RS) has become increasingly prevalent in e-commerce logistics applications. The allocation of goods plays a pivotal role in optimizing the efficiency of AVS/RS operations, encompassing warehousing, shelving, and picking processes.

Scholars worldwide have conducted extensive research on various aspects of cargo allocation within AVS/RS systems. Chen, Langevin, and Riopel developed a location allocation model hinged on AS/RS warehouses, considering shared storage principles and duration strategies, with the aim of minimizing average picking time.

Mu and Guo proposed allocation strategies based on product frequency and deviation.

Zhang incorporated the ABC classification principle and historical order data to devise a location allocation model for e-commerce companies. Tao established a dynamic model prioritizing operational efficiency with balanced operations as a constraint, comparing results with random storage strategies using flextime simulation.

Regarding cargo space adjustment and redistribution, Moon and Kim examined the impact of different storage strategies on equipment utilization during space redistribution.

Li and Zhu focused on enhancing storage efficiency, stability, and shelf space reallocation.

Xu and Li introduced a dynamic position adjustment method leveraging manpower for the online retail sector.

In the realm of automatic trolley storage systems, Fukunari and Malmborg conducted a comprehensive analysis comparing cycle efficiency with traditional stacker storage, utilizing a queuing model and simulation experiments.

Roy proposed a protocol for alleviating vehicle congestion, employing a semi-open queuing network model for system performance evaluation. Zhang, Fang, He, and Xiao adopted a pre-zoning strategy for storage space allocation in the automatic trolley system.
The literature review underscores the current scarcity of AVS/RS cargo space allocation studies for the specificities of e-commerce logistics. This gap in research highlights the significance of further exploration in this domain.

More articles and paper from the literature not fully exploited in this chapter are the following: these are all interesting solutions on the allocation principles in the automated storage and retrieval systems.

- *Jeroen P. van den Berg & A.J.R.M. Gademann. ''Simulation study of an automated storage/retrivial systems''. (2010)*
- *Jean Philippe Gagliardi. Jacques Renaud and Angel Ruiz. ''On storage assignment policies for unit-load automated storage and retrivial systems''. (2010)*
- *Heungsoon Felix Lee. Samantha K. Schaefer .''Sequencing methods for automated storage and retrivial systems with dedicated storage'' (1997)*
- *Ya-Hong Hu , Shell Ying Huang , Chuanyu Chen , Wen-Jing Hsu , Ah Cheong Toh , Chee Kit Loh , Tiancheng Song . ''Travel time analysis of a new automated storage and retrivial system''. (2005)*
- *Jih-Yau Wang &Yuehwern Yih. ''Using neural networks to select a control strategy for automated storage and retrieval systems (AS/RS)'' (2017)*
- *Yugang Yu and Renè B.M. de Koster . ''Optimal zone boundaries for two-class-based compact three-dimensional automated storage and retrieval systems.'' (2009)*
- *Bashir Salah *, Omar Janeh **, Tobias Bruckmann **, Bernd Noche. ''Improving the Performance of a New Storage and Retrieval Machine Based on a Parallel Manipulator Using FMEA Analysis.'' (2015)*
- *Wen Shi; Yue Tian; Song Wang; ChunWen Liu; Lei Yang; PiChao Zheng ''Research on Storage Allocation Strategy of Automated Warehouse Based on Improved Genetic Algorithm'' (2022).*

3.2.2 Storage based on weight and volume measurement.

In this section, we will explore the proposed solution outlined in the research paper [13].

The concept of intelligent storage based on volume and weight measurement operates on the premise of assessing items without the need for electronic labels, barcode devices, or scanners. Once the goods reach the feeding unit, they undergo sequential evaluation through the volume and weight detection module via a conveyor belt, followed by information matching and condition assessment. Subsequently, the controller orchestrates the allocation of warehouse locations and executes an optimized storage operation.

In the gravimetric mechanism, weight measurement is a swift process, with objects passing through the weight area in a matter of milliseconds. This necessitates a weight sensor with high precision, robust anti-interference capabilities, and a rapid response time. Consequently, a pressure-varying resistance type weighing sensor, known for its sensitivity and established technology, is selected.

For volumetric measurement, three sets of measuring light screens are employed to gauge the length, width, and height of items. The gathered data is then transmitted to the upper computer for volume calculation via cross-sectional accumulation.

Once both volume and weight measurements are complete, the system determines the storage location for the items. The actuating mechanism is activated to segregate various items along the optimal path, thereby enabling automated sorting and storage.

The following principles are adopted:

- *Nearest Storage Principle*: This principle dictates that items should be stored in locations closest to the initial position of the access claw. By minimizing the distance travelled within the storage facility, this approach enhances the system's overall operational efficiency.

- *Zero Storage and Lump-Sum Withdrawal Principle*: This principle emphasizes a systematic approach to storage. Items are designated specific locations, and when needed, they are withdrawn collectively in a batch. This strategy minimizes the frequency of item retrieval, optimizing overall workflow.

- *Underlying Priority Principle*: This principle considers the underlying priority or urgency of certain items. For instance, perishable goods or those with imminent delivery deadlines are given precedence in storage placement, ensuring timely access when needed.

• *First-Generation Principle:* This principle involves prioritizing the storage of items based on their arrival or generation in the system. Items that arrive first are stored before newer arrivals, maintaining a chronological order that aids in efficient retrieval.

The integration of a weight and volume measuring system in the automatic storage system enables real-time, precise identification of items that would otherwise be challenging to differentiate manually. This intelligent system revolutionizes inventory management and automates the processes of detection, identification, sorting, transportation, and storage, leaving human operators solely responsible for placing goods.

3.2.3 Dynamic order-based scheduling

In this section, a comprehensive exploration guided by [14] is described in order to understand the scheduling algorithms within automated retrieval systems for smart warehouses.
This article is centred on the introduction and evaluation of two innovative scheduling algorithms, specifically designed to minimize the average delay and ensure fairness in the retrieval process. These algorithms, known as the Dynamic Order-Based (DOB) and Dynamic Order-Based with Threshold (DOBT) Scheduling Algorithms, exhibit marked superiority when compared to conventional methods like First Come-First Serve (FCFS) and others. Simulation results conclusively demonstrate that both DOB and DOBT reduce the average order retrieval delay by a noteworthy margin, often exceeding 30%, while simultaneously alleviating backlog pressure on downstream operations.
To contextualize this study, it is essential to define an objective function when tackling an optimization problem. In this research, the term 'delay' refers to the time spent in the retrieval process, unless stated otherwise. The primary objective is to minimize the average delay of orders, which is essentially equivalent to minimizing the total delay of all orders.
In consideration of the concept of order integrity, the retrieval delay of an order is measured as the duration between the order's arrival and the retrieval of its final item. In simpler terms, the delay of an order corresponds to the maximum delay among its constituent items.

Here below re the comparison between the allocation principle considered in the study:

• FIRST COME - FIRST SERVE (FCFS) SCHEDULER

FCFS, though straightforward and computationally efficient, does not account for order integrity and overall delay. Consequently, it proves to be a suboptimal approach in reducing the total delay of all orders.

• **LAST COME - FIRST SERVE (LCFS) SCHEDULER**

LCFS operates in a manner contrary to FCFS. It prioritizes orders that have been waiting longer. However, this method can lead to further delays for pending items when a new order arrives, ultimately resulting in suboptimal performance in terms of overall delay and fairness.

• **SHORTEST- JOB-FIRST (SJF) SCHEDULER**

The SJF algorithm, a simple greedy approach, prioritizes the shortest job in each queue (stacker) to minimize overall waiting time. Unfortunately, it does not account for the integrity of orders across multiple queues, potentially leading to prolonged order delays.

• **DYNAMIC ORDER-BASED (DOB) SCHEDULER**

The DOB Scheduling Algorithm, a dynamic approach, is designed with consideration for order integrity and overall delay. Building on prior work that demonstrated the efficacy of Order-Based scheduling with static order arrivals, this paper extends the algorithm to handle dynamic order arrivals. It introduces the concept of 'Order Tags', which are assigned to all items in an order. Each stacker then retrieves items based on the ascending order of their Order Tags in the queue. This dynamic approach significantly reduces the total order delay.

• **DYNAMIC ORDER-BASED WITH THRESHOLD (DOBT) SCHEDULER**

The DOBT Scheduling Algorithm, an extension of DOB, addresses potential starvation issues. It introduces a threshold limit in the Order Tag Recalculation Procedure to limit the maximum waiting time and provide a degree of fairness among orders. With an appropriately chosen threshold value, DOBT effectively resolves the problem of large maximum delay. Importantly, both DOB and DOBT exhibit the same time complexity.

In conclusion, this research introduces and evaluates a promising scheduling algorithm that greatly enhance the efficiency and flexibility of automated retrieval systems in smart warehouses.
By considering order integrity and overall delay, these algorithms outperform traditional approaches, achieving substantial reductions in average order retrieval delay and alleviating pressure on downstream operations.

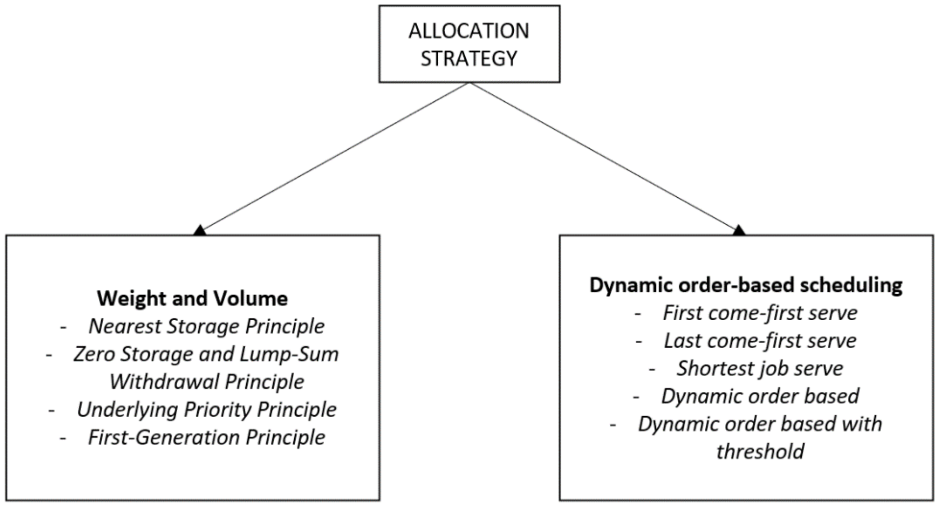

Figure 41. Allocation strategies overview.

3.2.4 Allocation optimization

The subsequent paragraph is based on the research presented in the paper [15].

This work delves into the application of swarm intelligence techniques to enhance the efficiency and performance of automated storage and retrieval systems.

The study focuses on the implementation of multiple objective ant colony optimization (ACO) for the strategic planning of Automated Storage and Retrieval Systems (AS/RS). The distribution of products within the AS/RS is influenced by several critical factors, namely the Factor of Inquiry (FOI), Product Height (PH), Storage Space Usage (SSU), and Path to Dispatch (PD).

Below some useful definition:

- **Factor of Inquiry (FOI):** This parameter reflects product demand and can be adjusted to align with market needs.
- **Product Height (PH):** It defines the vertical size of products, impacting storage arrangement.
- **Storage Space Usage (SSU):** This measures how effectively available storage is utilized.
- **Path to Dispatch (PD):** It determines the most efficient route for product retrieval.

The FOI, a dynamic parameter, can be adapted during the storage process to align with real-time market demands. To optimize space utilization and minimize investment costs, an AS/RS layout devoid of corridors, featuring a singular elevator serving multiple products, was selected.

The AS/RS under discussion was designed for the storage of home appliances, categorized based on four distinct types and further classified by height, model, and factory of inquiry (FOI). Each product variant, belonging to one of the specified types, possesses a unique FOI. Upon entry into the storage area, the AS/RS captures and processes a product's data through an optimization system, determining the optimal path to a temporary storage position. It's noteworthy that a product's storage position may be subject to change, driven by factors such as its FOI level or potential FOI level modifications.

The products employed in the optimization process encompass Cooling Boxes (CB), Washing Machines (WM), Dishwashers (DW), and Fridges (F), each characterized by specific height categories (PH). The optimization strategy focuses on achieving an efficient product distribution based on their respective attributes. Notably, products with higher FOI values are strategically positioned closer to the dispatch point. The algorithm operates dynamically, adjusting the distribution process to accommodate products of varying heights and types.

Initiating the optimization process involves starting the input conveyor, where a product's height is determined at the storage entrance. Subsequently, the height of the initial storage level is set, and the product is placed in the AS/RS. With the arrival of new products, the height of the first level is adjusted to accommodate the tallest product. Simultaneously, product distribution based on FOI occurs, directing products with higher FOI closer to the dispatch position. Given the constant influx of products with varying heights and types, a swarm intelligence algorithm guides their distribution. Products can move left/right or front/back only if the adjacent cell is empty; otherwise, they must shift one position backward, ensuring products with higher FOI gravitate closer to the dispatch position.

If an influx of products with height C occurs, potentially reaching the threshold value for storage space usage (SSU), the optimization algorithm responds by introducing a new storage level. The input conveyor halts until products are distributed across both levels. As SSU takes precedence over FOI, products with smaller height (PH = C) are prioritized for placement onto the stacker crane. When the crane is full or no products with PH = C remain, the loaded products are elevated to the second level. Here, a height measurement is conducted, and products are distributed based on their FOI. Height measurements and product movements are logged in a ‘’MySQL database’’ for convergence analysis.

Once all products are optimally distributed, the input conveyor resumes, and products are distributed across two levels. The optimization process concludes once the deviation in AS/RS configuration regarding the frequency of product inlet/outlet stabilizes within a 5% threshold.

The swarm intelligence algorithm for product distribution based on FOI is an integral part of the AS/RS planning and operation. During system operation, the optimization algorithm dynamically responds to FOI changes, ensuring optimal access times for end-users – a critical factor for customer satisfaction.

The smaller products are stored at higher levels and products with greater FOI are stored closer to the front of the AS/RS and nearer the stacker crane.

As the optimization algorithm distributed products with lower weight and height to the top of the

AS/RS, optimal space usage (SSU) can be achieved of the available storage area. This strategic arrangement not only maximizes storage efficiency but also streamlines retrieval operations, contributing to the overall effectiveness of the automated storage and retrieval system.

3.2.5 ABC principle and input and output point

Before delving into the next research article, it's important to introduce the concept of ABC allocation logic in warehouses.

The ABC allocation principle is a strategic approach largely employed in warehouse management to enhance inventory control and resource utilization.

This principle classifies items into three distinct categories based on their significance and consumption patterns.

"A" items denote high-value, low-usage products. Although they represent a relatively small portion of the total inventory, they contribute significantly to revenue. As a result, these items are typically stored in easily accessible locations to facilitate quick retrieval.

"B" items encompass moderate-value, moderate-usage goods, constituting a middle-ground portion of the inventory. They are stored in areas that strike a balance between accessibility and space efficiency.

Finally, "C" items refer to low-value, high-usage products. While they make up a substantial portion of the inventory, their contribution to revenue is comparatively lower.

These items are typically stored in cost-effective, less accessible locations. By categorizing items in this manner, businesses can allocate resources, such as storage space and labour, more efficiently. This ensures that critical items are readily available while minimizing costs associated with low-value inventory. The ABC allocation principle plays a pivotal role in maintaining a streamlined and efficient warehouse operation, ultimately contributing to improved profitability and customer satisfaction.

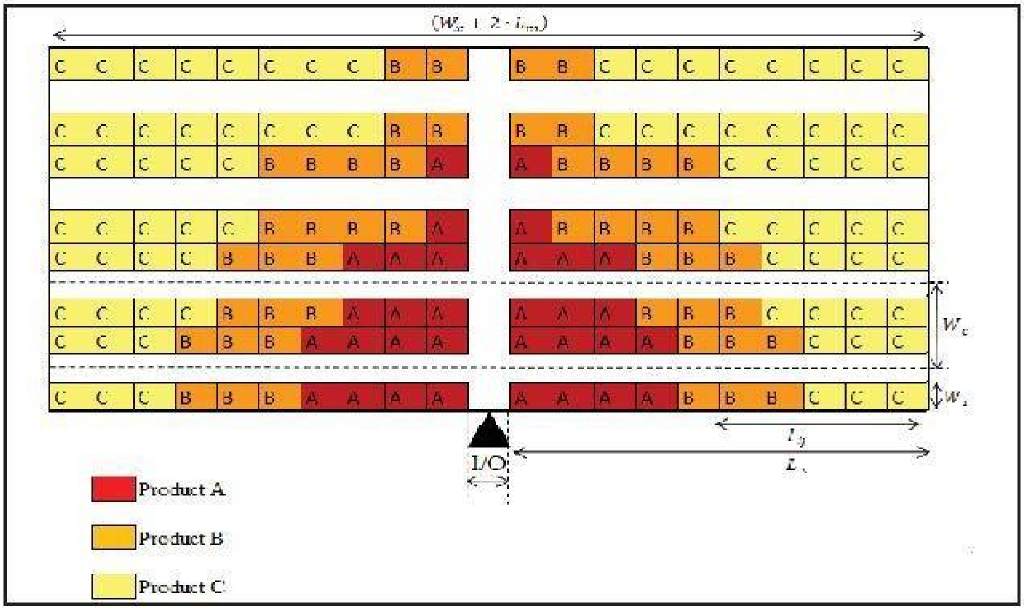

Figure 42. Products allocation based on ABC logics.

This discussion below is based in the research presented in the [16].

The study provides valuable insights into the intricacies of design integration within non-traditional unit load warehouses.

The study focuses on optimizing warehouse operations, specifically focusing on the layout of aisles. Traditional cross aisles, while common, offer limited benefits in terms of travel distance during single command cycles. In contrast, the research unveils the efficiency of a Flying-V shaped cross aisle for routing order pickers. Previous work by Rao and Adil and Yu has demonstrated the advantages of class-based storage strategies, leading to substantial reductions in pick travel distances. This serves as a catalyst for the current study, which aims to explore the potential gains of class-based storage in conjunction with non-traditional cross aisles.

The primary objective is to identify optimal positions and shapes for cross aisles that minimize pick travel distances. The study operates under specific assumptions, considering horizontal travel within a unit-load warehouse with a single central P/D point and manual single-command picking. The COI (Cube per Order Index) product arrangement strategy is employed for class assignment, prioritizing products based on activity levels. This involves arranging products by their demand-to-space ratio, creating an ABC curve (pareto curve) that depicts the cumulative demand activity of products against the percentage of space they occupy.

The research findings reveals that non-traditional cross aisle designs, when integrated with class-based storage, can boost significant performance enhancements, with improvements reaching up to 45%.

Notable is the comparison between the Straight-V and Flying-V designs.

While the former is simpler to construct, it offers nearly equivalent picking distances to the latter. Interestingly, as the number of aisles increases, the Straight-V design becomes less sensitive to changes in storage policies and various demand settings, demonstrating its versatility in different scenarios. This reveals the potential for a robust layout that can accommodate diverse operational needs without sacrificing performance.

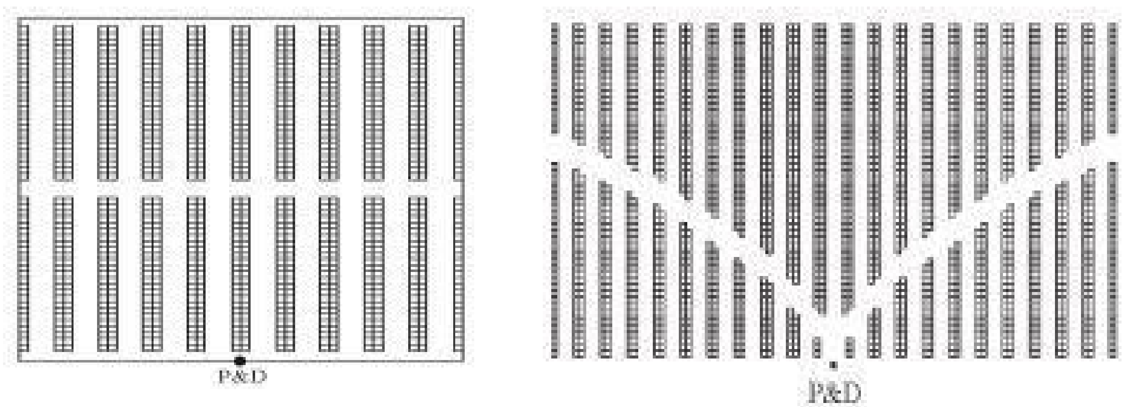

Figure 43. Comparison between traditional (left) and non-traditional (right) warehouse.

3.3 Overview

In this chapter, a comprehensive exploration of Automated Storage and Retrieval Systems (AS/RS) has been considered, going deep into various hardware configurations and providing detailed technical insights sourced from market-available solutions. By analyzing the intricate details of each system, the aim was to inform the reader with an overview of their capabilities and functionalities.

Furthermore, a significant portion of our discussion to the underlying principles governing goods allocation was dedicated, considering a diverse range of promising research articles and papers. This analytical approach had the goal to select the most effective strategies for optimizing storage within AS/RS setups.

Moving forward to the next chapter, the focus will shift towards an even more detailed examination of two important technologies: Autostore and Automated Guided Vehicles (AGVs) which are nowadays the most used solution present in the market and mostly adopted by the businesses.

4. Robotics automated warehouse technologies

The current expansive range of available products depends on the development on the world of production and logistics services. This has led to an intensified demand-supply chain, culminating in the establishment of vast, fully automated warehouses propelled by a fleet of autonomous robots. These revolutionary warehouse systems operate on a paradigm where robots transport products to human operators, resulting in a substantial augmentation of both productivity and adaptability [17].

In this chapter, the main focus will be on fully automated warehouse technologies, specifically on the synergy between robots technologies: AutoStore technology and Automated Guided Vehicles (AGVs). These advancements have revolutionized the landscape of warehousing, bringing to an era of efficiency and precision never experienced. The combination of AutoStore and AGVs represents a milestone in warehouse automation, confirming that the integration of robotic systems to optimize product flow, storage, and retrieval is the right path to follow.

4.1 Literature review

From the article [18] is specified that in recent years, the landscape of warehousing has experienced a remarkable evolution, fueled by the amazing progress in robotics technology. This surge of innovation has opened the way for a new era of warehouse automation, with key players like Automated Guided Vehicles (AGVs), Collaborative Robots (Cobots), and state-of-the-art Robotic Arms taking center stage.

These technological advancements are set to redefine the efficiency and precision of warehouse operations. Notable researchers have been instrumental in propelling this transformation.

Rey ingeniously integrated AGVs into a seamless human-robot system, while Koster envisioned a comprehensive architectural framework that encompasses robots, AGVs, Automated Storage and Retrieval Systems (AS/RS), and cyber-physical systems (CPS) to create fully automated warehouses. Poudel introduced the groundbreaking Kiva system, revolutionizing the management of autonomous robots within warehouse environments. Meanwhile, Belotserkovsky explored the realm of multi-robot systems, leveraging cutting-edge visual navigation techniques. Javaid delved into the manifold applications of autonomous robots in warehouse automation.

In the article [19] a comprehensive and insightful literature review is considered to explore the dynamics of technology acceptance in the context of human-robot collaboration in the warehouses. The existing body of literature has been extensively reviewed to show the current landscape of research regarding the utilization of robots in warehouse operations, particularly in conjunction with human workers, and the acceptance of such collaborative systems.

Additionally, literature reviews encompassing various economic sectors have been considered to derive pertinent conclusions.

In a comprehensive analysis conducted by Jaghbeer the focus was on the deployment of robots within (partially) automated order-picking systems within warehouses. Their attention was directed towards critical performance metrics, striving to establish a correlation between system design and operational efficiency. Their findings indicated a growing interest in automating picking systems, though considerations of human factors and adaptability were deemed insufficient, despite their pivotal significance.

Fragapane delved into the planning and control of Autonomous Mobile Robots (AMRs) in intralogistics, emphasizing the influence of technological advancements on decision-making processes. They introduced a framework aimed at aiding managerial decision-making and achieving optimal performance, reporting that technological advancement in AMRs enhance operational flexibility and overall performance in terms of productivity, quality, and cost-effectiveness. The research by Hanson centered on Robotic Material Handling Systems (RMFSs) and the efficacy of robots employed in order picking. Their conclusion highlighted productivity enhancements achieved by RMFSs in comparison to manual systems, yet like previous studies, human-centric considerations were overlooked.

Duong scrutinized the literature pertaining to the integration of robotics and autonomous systems across the supply chain, primarily examining applications related to data accessibility, cybersecurity, financial aspects, and operational efficiency, with human factors being a notable omission.

Clauer investigated the outdoor utilization of AMRs, focusing on technical, organizational, and cost-related facets, without delving into human-robot interactions or human-centric factors. In a systematic review by De Pace the spotlight was on communication between humans and robots within the realm of Human-Robot Collaboration (HRC). Augmented Reality (AR) applications were identified as pivotal for communication, as they allow users to overlay virtual elements onto their real environment. The researchers emphasized that trust is fundamental for collaborative endeavors, a trust primarily established by ensuring the human is aware of the robot's intentions.

In addition to qualitative performance considerations, their attention extended to control mechanisms and strategies for pre- and post-collision scenarios, encompassing physical factors like safety and structural integrity. Gualtieri explored collaborative robotics in industry, examining the state of research and development regarding physical factors such as safety and ergonomics. The majority of research endeavors, according to these scholars, have been dedicated to safety, especially in contexts related to contact avoidance applications.

4.2 Autostore

It was the year 1996 when two visionaries, Ingvar Hognaland and Jakob Hatteland, started a journey to face one of the most persistent challenges in modern commerce: the efficient utilization of warehouse space.
Motivated by a shared determination to overcome space constraints, Ingvar and Jakob conceived an idea that would go on to redefine the very basics of warehousing.
Drawing inspiration from an unexpected source of ‘’the Rubik's Cube’’ they built a concept that would become the foundation of this new technology. This concept, captured by the slogan "Stop air housing, start warehousing," gave birth to AutoStore, an unparalleled goods-to-person (GTP) automated storage and retrieval system (AS/RS).

Departing from traditional shelving methods, AutoStore introduced a cube-based storage system, enabling the stacking of product bins in a compact, grid-style arrangement. The outcome was revolutionary, bringing a staggering increase in storage capacity, up to fourfold within the same footprint, and a remarkable enhancement in performance, all achieved without the need for additional labor.
Its influence nowadays is present far beyond the fjords of Norway, shaping the future of modern warehousing worldwide.
Projects designed to optimize space utilization have found a reliable in AutoStore concept, which excels in reorganizing existing warehouse sections and modernize processes in order to align with the new era of digitalization.
These projects, often characterized by their focus on small-scale solutions, have the goal to refine employee routes within designated order-picking zones. Each manual AutoStore workstation is tailored to specific types of picking, facilitating a goods-to-person approach that revolutionizes operations.

In the following chapter, the aim is to explain the mechanisms and the profound impact of AutoStore on warehouse management, by going through its design principles, operational advantages, and real-world applications.

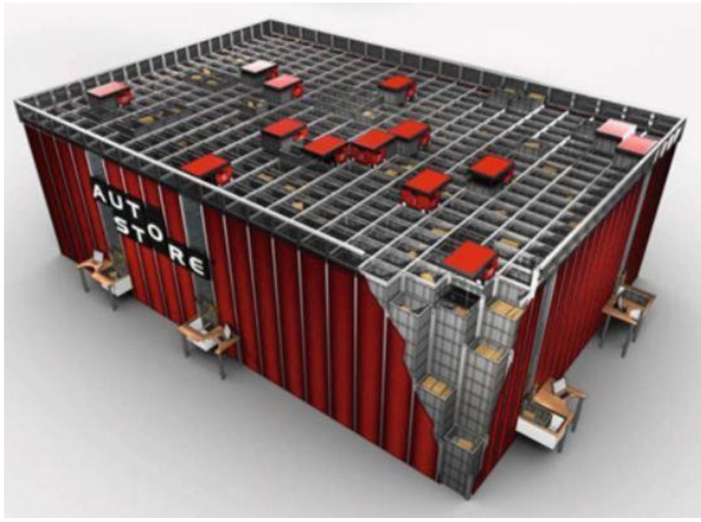

Figure 44. Autostore System overview.

4.2.1 Working principle and components.

In contrast to conventional shelving systems that often lead to wasted space due to the need for walkways and aisles, AutoStore presents a revolutionary design that significantly enhances storage capacity and density. By stacking product-laden bins directly atop one another within a condensed grid-style system, AutoStore minimizes wasted space and maximizes storage efficiency.

The integration of order-picking robots on the top layer of the system adds another layer of adaptability, allowing the grid to be strategically placed around existing structural elements like columns, mezzanines, and floors with varying elevations.

This unique flexibility and modularity contribute to a staggering 400% increase in warehouse floor space utilization compared to static shelving. Furthermore, AutoStore can be seamlessly adjusted and expanded to accommodate evolving space requirements, ensuring optimal efficiency even as a company grows.

The system excels for its capacity to evolve in symbiosis with specific business needs. Each component of it can be independently adapted, facilitating the addition of more robots or ports in response to heightened demand. If a new product line necessitate increased storage, the grid can be extended, and the necessary bins incorporated without disrupting ongoing operations.

A key advantage that solution leverages is the Pareto principle, where 80% of order lines are tied to just 20% of stock-keeping units (SKUs), a common occurrence in eCommerce order profiles.

AutoStore relies on this principle by ensuring that each time a bin is presented to a port and then returned to the grid, it randomly repositions itself to a top location. Consequently, bins containing popular or fast-moving SKUs are consistently positioned at the grid's summit, readily available for the next batch of consumer orders.

This adaptive nature of the system extends to fluctuations in SKU profiles, particularly in fashion: for instance, winter orders predominantly consist of jumpers and warm clothing, placing them at the grid's nearest point. As seasons transition to warmer weather, customer preferences shift towards items like sunglasses or sandals. While these items may initially require retrieval from the lower layers due to inactivity, once retrieved, they are returned to the top, ensuring subsequent orders are fulfilled with optimal efficiency.

An essential feature of AutoStore lies in its robotics driven operations. These warehouse robots prepare for impending orders, even in worst-case scenarios where a crucial bin is located in the farthest corner of the grid. The retrieval process, taking approximately three and a half minutes, significantly outperforms the time it would take to reach a distant shelf in a traditional warehouse.

This retrieval occurs approximately 30 minutes before the bin reaches an operator for picking, ensuring greater order fulfillment. As a result, operators perceive no distinction between fast-moving and slower-moving products, underscoring the system's exceptional efficiency.

In typical eCommerce operations, an impressive 80% of order lines are fulfilled from bins situated in the top two to three layers of the AutoStore grid, the case where robots need to retrieve slower-moving bins from the stack's bottom are exceptionally rare, rendering the traditional ABC analysis largely unnecessary. This underscores AutoStore's exceptional adaptability and efficiency in modern warehousing operations.

The system comprise six fundamental components that seamlessly integrate into existing facilities:

- **Delivery Robots**

  Serving as the workforce of the AutoStore system, these robots tirelessly perform tasks such as driving, collecting, and delivering bins to workstations. Equipped with eight wheels for versatile movement, they navigate the grid efficiently. The robots determine the smartest routes for picking and delivering goods based on calculations by the controller.

  The Red Line robots (R5 and R5+) and the Black Line robot, B1, are offered by AutoStore. The Red Line robots, known for their efficiency and longevity, have been the cornerstone of the fleet for over two decades, while the new faster and more efficient Black Line are shaping the new era.

Here below some interesting Technical Data:

Red Line (R5 and R5+):

- Energy Efficiency: Utilizes energy-efficient drives and recuperation system.
- L'R5 uses two batteries AGM 12V/105Ah.
- Battery Life: Operates for up to 16 hours on a single charge.
- Charging Time: Rapid recharge in approximately 15 minutes.
- Maximum speed: 3,1 m/s

  Acceleration: 0,8 m/s^2

  Lifting velocity: 1,6 m/s
- Payload Capacity: 30 kg

Black Line (B1):

- Power Source: Lithium-ion 26,4 V,15 Ah and direct drive wheels.
- The Black Line robot only blocks 1.5 cells compared to the 2 cells of the Red Line robots.
- Maximum speed: 4 m/s

  Acceleration: 1,4 m/s^2

  Lifting velocity: 1,6 m/s
- Speed and Acceleration: Greater acceleration and top speed for quicker operation.
- Bin Handling: Designed to handle taller 425mm bins.

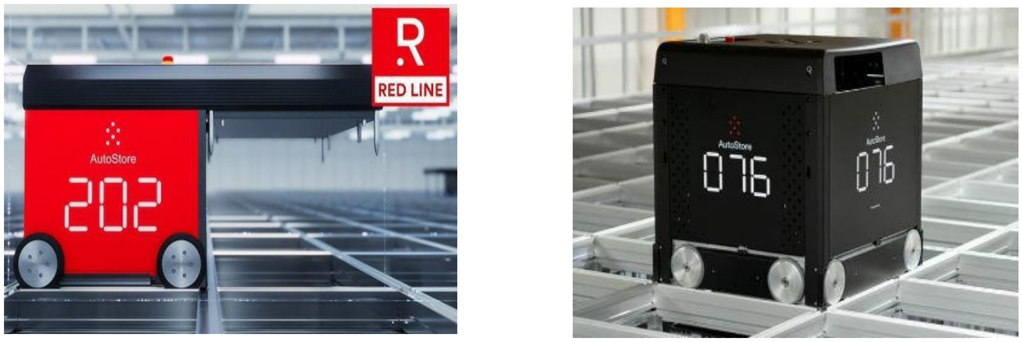

Figure 45. Red Line (left) and Black line robots (right).

- **Structural Grid**

  The AutoStore grid is optimized for cube-based storage, offering an exceptional storage density and product security. Constructed from lightweight aluminum profiles, it is flexible to design and easy to install. Its size and shape are only limited by the dimensions of the surrounding warehouse, ensuring optimal space utilization. The grid comprises columns that form cells, each containing stacked bins. Tracks running in X and Y directions allow robots access to any cell.

  Below some Technical Data:

  - Maximum Height: Limited to 5.4 meters.
  - Storage Capacity: Ranges from 2,000 to 200,000 containers per system.
  - Grid Material: Lightweight aluminum alloy.

Figure 46. Structural aluminum grid.

- **AutoStore (AS) Controller**

  The controller acts as the central command of AutoStore, responsible for locating bins, robots, and ports within the grid. Additionally, it manages traffic and route planning for all robot tasks.

  Technical Data:

  - Processing Speed: Executes tasks with a response time of less than 100 milliseconds.
  - Routing Efficiency: Optimizes routes for robots to ensure minimal travel time.

- **Operator Ports**

  These workstations are where AutoStore robots deliver goods for operators to pick. All ports can perform various operations within the system, including inbound and outbound order processing, and inventory inspections. The key distinction between different ports lies in the bin exchange time.

  Technical Data:

  - Conveyor Port: Bin Exchange Time approximately 6-7 seconds.
  - Swing Port: Mechanism: Utilizes an internal bin lift for retrieval with a precision of 1mm.
  - Relay Port: Speed: Designed for high-speed pick-and-pass operations, achieving up to 800 picks per hour.

Figure 47. Operator ports.

- **Storage Bins**

  Measuring 400mm x 600mm internally, these bins are the inventory containers of AutoStore. Available in three height options to accommodate various storage needs: 220mm, 330mm, and 425mm. The tallest is compatible with B1 and R5+. These bins are highly durable and designed to endure numerous movements over years of service. Each bin has a unique ID stored in the system Controller database, enabling precise control over the contents.

  Technical Data:

  - Load Capacity: Up to 30kg.
  - Material: High-density polyethylene for maximum durability.
  - Lifespan: Designed for over 10 years of continuous use.

- **Software**

  It interfaces the system with ERP or WMS systems optimizing workload and ensuring the right order fulfillment.

  The software also provides real-time product location and inventory control, including modules for common industry activities. It can be fully integrated with existing WMS or ERP systems, offering a comprehensive solution for inventory control.

Technical Data:

- Integration: Can be fully integrated with existing WMS or ERP systems.
- Functionality: Provides real-time product location and inventory control.
- Compatibility: Supports various ERP and WMS platforms.

4.2.2 Actual market and improvement

Over the following year, the market for Autostore experienced a remarkable growht, with reported installations experiencing an approximate 30% increase across various industries.

Looking towards the future, several key improvements are anticipated for the Autostore system. One notable area of development is the enhancement of scalability, allowing the system to adapt to varying warehouse sizes and complexities. Integrating advanced technologies, such as artificial intelligence and machine learning, is also expected to be the next point. These improvements aim to change the system's decision-making capabilities, optimizing the flow of goods within the warehouse and improving overall efficiency.

Furthermore, flexibility is set to be a key focus for future Autostore advacement. The ability to accommodate diverse warehouse layouts and operational requirements will be fundamental in enhancing to the unique needs of different industries. Companies operating in this space are likely to invest significantly in research and development efforts to refine and expand Autostore's capabilities.

In conclusion, the Autostore system has experienced a remarkable market trend over the past year, with companies like Ocado and Dematic playing a leader role in its adoption. These developments position Autostore as a leader frontier in the evolving landscape of automated storage solutions.

4.3 Robots and AGVs system

The introduction of AGVs (Automated Guided Vehicles) can be traced back to the mid- 20th century when the concept of automated material handling began to take shape. The first AGVs were introduced in the 1950s, primarily in the automotive industry, as a solution to transport heavy materials within manufacturing plants. Early AGVs relied on wired guidance systems, where a physical track or wire embedded in the floor provided navigation cues. Over time, advancements in sensor technology and computing power facilitated the transition to more sophisticated, flexible, and versatile AGV systems.

Today, AGVs have become integral to warehouse operations across a multitude of industries. The global AGV market is expected to experience robust growth, with a projected CAGR of over 9% from 2021 to 2026. In terms of market value, AGV systems are estimated to surpass USD 5.5 billion by 2026, indicating the widespread adoption and recognition of their immense value in modern logistics.

Several industry leaders have spearheaded the adoption of AGVs in warehouse operations. Companies like Amazon, DHL, and Toyota Material Handling have heavily invested in AGV technology to enhance their warehousing capabilities.

Amazon has integrated thousands of AGVs into its fulfilment centers worldwide, boosting its order processing capacity and improving overall operational efficiency.

DHL, a global logistics giant, utilizes AGVs for tasks ranging from goods transportation to inventory management, taking advantage of their versatility in diverse warehouse environments.

Toyota Material Handling, a subsidiary of the renowned automotive manufacturer, has leveraged its expertise in automation to develop a range of AGVs that satisfy to a wide array of material handling needs.

4.3.1 Types of AGVs

- **Automated Guided Carts (AGCs)** are designed for industrial usage, autonomously transporting goods or materials within a facility without the need for human intervention. They employ advanced onboard technologies, including computing systems, safety sensors, and navigation equipment. AGCs follow predefined paths or structured routes using laser or magnetic guidance systems. They excel in efficiently conveying loads of various sizes.

Figure 48. AGC (Toyota).

- **Forklift AGVs** replicate the tasks of human-operated forklifts, handling pallets, crates, and heavy loads with specialized lifting mechanisms. They integrate multiple sensors and cameras for precise navigation, utilizing laser-guided systems or magnetic tape markers for predefined paths. Forklift AGVs contribute to reduced labor costs and enhanced efficiency and safety in material handling.

Figure 49. Forklift AGV.

- **Towing AGVs** are designed to access areas with loads and tow them without any human intervention. Equipped with tow bars or hitching mechanisms, they rely on sensors for guidance along conveyor belts and moving operations. Towing AGVs efficiently navigate predefined paths, significantly reducing manual labour and optimizing material transport.

Figure 50. Towing AGV.

- **Unit Load Handlers** manipulate standardized unit loads like containers and pallets with precision. Using forks, clamps, and conveyors, these AGVs lift and transport objects throughout a facility. They are used often for the picking phase.

Figure 51. Unit load handler.

- **Heavy Burden Carriers** are tailored for handling substantial weights and bulky items. They feature robust construction, including sturdy wheels, reinforced frames, and high-performance motors. These AGVs use laser or vision-based guidance systems for precise navigation and handling of goods. Heavy Burden Carriers automate labor-intensive tasks, reducing the risk of injuries in supply chain environments.

Figure 52. Heavy bulk AGV

- **Picking AGVs**: equipped with a gripping mechanism is a specialized robotic system designed for efficient item retrieval in warehouse environments. The gripping component enables it to securely grasp and handle a wide range of products. Integrated with a movable base, this AGV can autonomously navigate through the warehouse, accessing shelves and retrieving specific items with precision. This combination of gripping and mobility features ensures seamless and accurate order fulfillment, enhancing overall warehouse productivity.

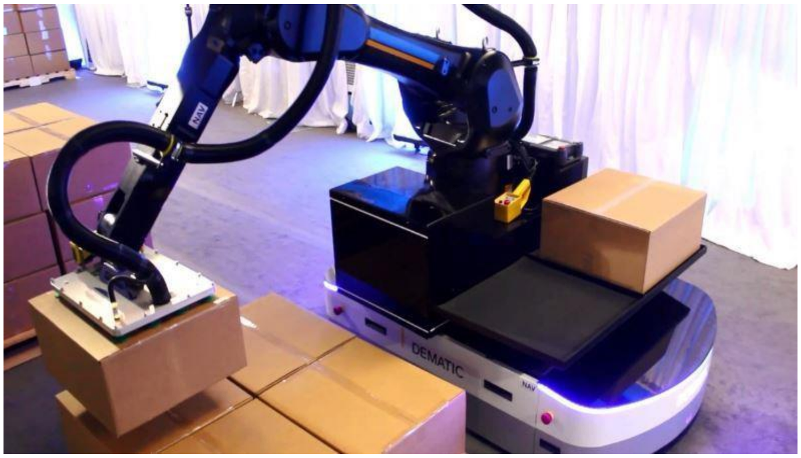

Figure 53. Picking AGV.

- **Drones**: equipped with GPS, IMUs (Inertial Measurement Units), and obstacle detection systems, carry out tasks requiring rapid vertical movements. Their navigation is guided by a combination of GPS signals and real-time kinematic (RTK) corrections, ensuring precise localization. Machine learning algorithms are deployed for obstacle avoidance, enabling them to navigate through the complex three-dimensional space efficiently.

Figure 54. Drones in warehouse.

- **Collaborative robots AGVs** work in tandem with human operators, adding versatility and adaptability to the system. These cobots are endowed with advanced haptic feedback systems for tasks that require a human touch. Force sensors integrated into their end effectors ensure delicate handling of objects, while computer vision systems aid in tasks that require visual acuity.

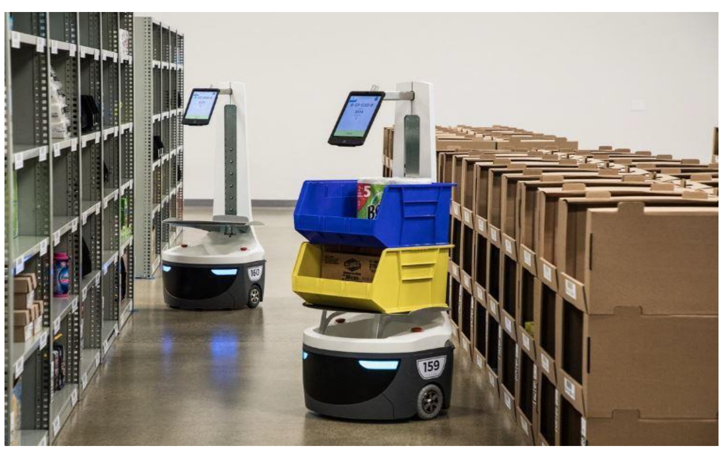

Figure 55. Cobots AGVs.

These various types of AGVs offer specialized solutions for diverse material handling needs in industrial settings.
Each type incorporates advanced technologies to autonomously navigate and efficiently carry out specific tasks, ultimately contributing to improved operational efficiency and reduced labor costs.

4.3.2 Guided technologies for AGVs

The following technologies are the most used in the actual scenario:

- **Magnetic Guide Tape**: This navigation method involves the use of magnetic sensors on AGVs that follow a marked track using specialized magnetic tape. The tape contains magnetic signals that guide the AGV along its designated path. This navigation method is known for its accuracy, with AGVs capable of following the magnetic tape within a margin of error about minimum 1-2 millimeters. It is largely used in controlled environments where precise navigation is crucial and is known to achieve speeds of up to 2 meters per second. The time response for AGVs utilizing magnetic guide tape navigation is impressively quick, with response times as low as 10-20 milliseconds.

- **Wired Navigation**: In this approach, AGVs follow predefined paths that are marked by wires positioned in the facility's floor. These wires transmit signals that are detected by the AGV through antennas or sensors. AGVs utilizing wired navigation systems can achieve even higher precision, with positional accuracy often within a range of 1 millimeter. These systems are favored in environments with intricate layouts or narrow aisles, achieving speeds of up to 3 meters per second. AGVs equipped with wired navigation systems demonstrate swift response times, often in the range of 15-25 milliseconds.

- **Laser Target Navigation**: This method employs reflective tape mounted on objects inside the environment such as walls, machines, and poles. AGVs are equipped with a laser transmitter and receiver. The lasers emitted are reflected off the tape, allowing the AGV to calculate the object’s angle and distance. Laser-guided AGVs are known for their adaptability in dynamic environments. They can achieve angular resolution till 0.01 degrees, allowing for highly accurate navigation around objects. AGVs using this method can reach speeds of 1.5 meters per second. Laser-guided AGVs exhibit a rapid response to changes in their environment, with the response values typically ranging from 8-15 milliseconds.

- **Inertial (Gyroscopic) Navigation**: Some AGVs utilize a computer system in coop with transponders below the floor. These transponders are set to check that the AGV is on the correct course. This method enhances navigation accuracy by cross-referencing inertial data with known reference points. AGVs can ensure positional accuracy about 2-5 centimeters. This system allows AGVs to reach speeds of up to 2.5 m/s with time response of 12-20 milliseconds.

- **Vision Guidance**: Vision-guided AGVs do not require any modifications to the existing infrastructure. Instead, cameras are used to record distinct obstacle along the route. The AGV uses these visual cues to navigate, making it a flexible and adaptable solution for various environments. They can identify features along the route with a resolution of up to 1 millimeter, allowing for accurate navigation. These AGVs typically operate at speeds of 1.5 m/s and a response times of 10-18 milliseconds.

- **Geo-guidance**: Similar to vision guided AGVs, geoguided AGVs do not necessitate changes to the infrastructure. These AGVs rely on recognizing objects in their environment in real-time to establish their location for navigation. They can establish their location within a range of 5-10 centimeters.These AGVs often operate at speeds of about 2 meters per second with time response values typically falling within the range of 10-20 milliseconds.

- **LiDAR (Light Detection and Ranging)**: LiDAR is an advanced navigation technology that employs sensors to emit laser pulses, measuring distances between the robot and objects. LiDAR-based navigation systems offer good precision, with a typical accuracy range of 1-3 centimeters. This technology allows AGVs to create detailed 360-degree maps of their environment, enabling them to navigate complex spaces with minimal error and an exceptional freedom. AGVs using LiDAR navigation can achieve speeds of 1.8 meters per second with a remarkably fast response times, typically ranging from 8-15 milliseconds.

Figure 56. Lidar technology

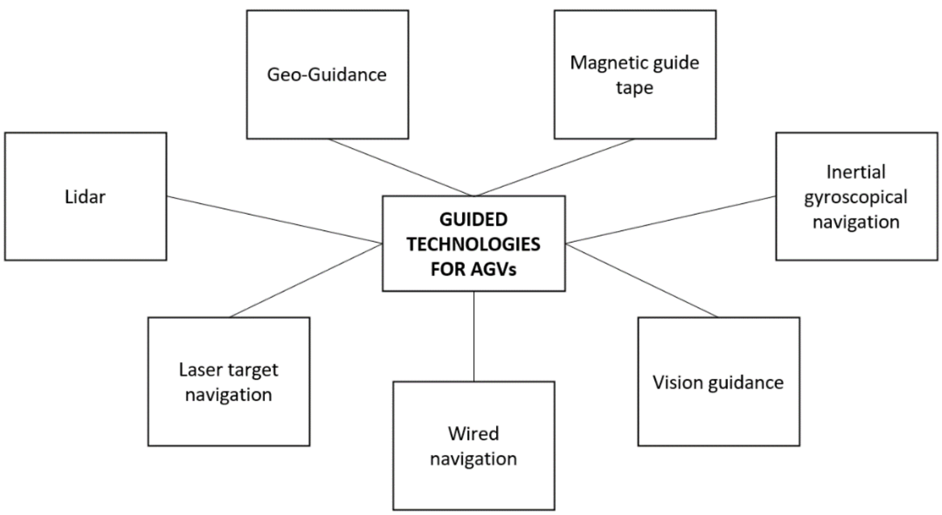

Figure 57. Guided technologies for AGVs.

4.3.3 Human and obstacles detections

In the article [20] is explained , with the goal of comprehensively examining the integration of robotic automation within Industry 4.0 frameworks, an innovative approach involves the employment of intelligent agents. These agents, equipped with sensors, engage with their environment, formulating strategic plans to execute tasks and subsequently effectuating actions through designated effectors. Specifically, robotic agents rely on camera and odometry sensors for environmental perception, employing motor effectors to enact manipulative actions in response to their surroundings. Notably, actions of a typical agent, such as a part-picking robot, encompass:

- *Perception*: Leveraging camera sensors to discern pixels of varying intensity, a critical function aiding in object detection and identification. Moreover, the robot gains insights into its own location, perspective, and the overall environmental context.
- *Actions:* The execution of tasks like picking up parts and categorizing them into designated bins. The precision and capabilities of the robot in performing these actions may be subject to specified constraints.
- *Goals*: Placing parts in their designated bins within predefined time constraints, emphasizing efficiency and timeliness.
- *Environment:* Operating in the warehouse settings featuring elements like conveyor belts or racks laden with parts.

To boost the efficacy of individual robotic agents in discerning the correct part, the knowledge base orchestrates pertinent actions in collaboration with the robot's perception. This knowledge base may encompass an array of information including domain ontologies, task templates, and resource descriptors. Nevertheless, in scenarios where a consortium of robots or a single robot interfacing with software and machinery is tasked with handling complex operations, a singular knowledge base may fall short. This necessitates the incorporation of supplementary workflow plans to seamlessly execute extensive tasks in a synchronized manner, demanding the formulation of formal workflow specifications.

Multi-agent systems play an instrumental role in modelling interactions amongst disparate, distributed, and self-governing communicating devices. These autonomous agents operate with limited information and possess restricted perspectives of the overarching problem at hand. Attaining consensus on the global task often hinges on the exchange of knowledge through peer-to-peer or hierarchical channels. Furthermore, data is decentralized, with agents intermittently sensing, storing, and updating decisions. This decentralized, distributed architecture is particularly indispensable for expansive warehouses characterized by dynamic delivery rates and on-demand

resource provisioning and monitoring.
A tangible instantiation of this system is observed in Amazon's Kiva robots, which autonomously navigate in the warehouse, optimizing the process of picking and delivering goods.
In the realm of picking and delivery workflows involving multiple agents, a key consideration emerges: the allocation of the entire task to a singular robot versus the formation of a multi-robot task. The benefits of employing multiple robotic agents manifest in three key areas:

- *Speed*: A collective of homogeneous delivery robots can exponentially accelerate task completion, potentially by a factor of n.
- *Volume*: Each delivery or picking robot may be limited in the number of items it can convey at the required throughput, thereby influencing overall efficiency.
- *Fault-tolerance*: The redundancy inherent in employing multiple robots substantially mitigates the risk of a single point of workflow failure.

A critical imperative in the world of multi-robot warehouse coordination is the establishment of a unified specification framework, facilitating the seamless translation of high-level requirements into granular task specifications. This topic necessitates a profound exploration of concurrent workflow patterns and robot coordination strategies that are adaptable across diverse deployment environments.

Concerning the collaborations between robots and humans the article [21] focuses on the contemporaneous logistics where the operational heart of expansive warehouses beats with the synchronized movements of a fleet of robots. These mechanical tasks ranging from the relocation of goods to the rearrangement of racks, deftly managing the physically demanding and monotonous aspects of warehouse operations are performed automatically.
To ensure the safety of both human workers and the robots, the shopfloor is encased within a protective barrier, activated whenever a human presence is detected. Regrettably, this safety protocol entails a complete halt of all robots, rather than a localized pause limited to the immediate proximity of the human, resulting in a substantial reduction in warehouse productivity. While the intention is to minimize human entry into the shopfloor, unforeseen circumstances such as robot hardware malfunctions or product mishaps necessitate human intervention to rectify the situation. In large-scale warehouses, this translates to a significant number of robots idling, incurring considerable opportunity costs. While the concept of sectional lockouts can be employed for scenarios where worker tasks are confined to robot maintenance, it proves impractical when workers are required to engage in picking tasks or address issues spanning the entirety of the warehouse.

However, in the warehouse context, direct interaction may not be imperative, warranting an alternative approach.

In the interest of human safety and warehouse efficiency, an optimal scenario would regards only those robots in immediate proximity to the human, allowing others to continue operations. Such a system would guarantee human safety; however, it necessitates the ability to precisely locate human workers within the warehouse for optimal functioning.

The authors categorize real-time localization technologies into distinct groups, including ultra-wideband (UWB), radio frequency identification (RFID) systems, vision systems, and Wi-Fi technology. While UWB and RFID have proven effective for forklift localization, the approach utilizing visual sensors emerges as the most suitable for our specific context. Notably, the visual features already employed for robot localization can be leveraged for human localization, offering a seamless integration.

In this case, however, this approach is not without its challenges. Implementing such a system in large warehouses entails the deployment of a considerable number of sensors, accompanied by a laborious process of installation and calibration. Considering these considerations, our focus shifts towards a visual localization framework anchored by a suite of wearable sensors affixed to a designated Safety Vest. This vest not only ensures worker safety through the incorporation of previously mentioned safe relative ranging but also serves as the ideal platform for sensor placement.

The sensor setup features an IMU-aided stereo camera and a downward-looking monocular camera seamlessly integrated into the Safety Vest. This configuration was chosen to harmonize with the natural movements of the human worker, ensuring minimal disruption during tasks. Furthermore, the chosen positioning lowers the risk of obstructed views or abrupt motions that could potentially compromise image clarity.

The system's efficacy lies in the fusion of two complementary human pose estimators.

The first, a relative human pose estimator, relies on odometry and is supported by a horizontally oriented stereo camera, assisted by an IMU.

The second estimator derives absolute human pose estimations by detecting ground markers, facilitated by a wearable downward-looking monocular high-resolution camera. While the former continuously updates the relative human pose, adapting to the shifting environment, the latter supplements global pose corrections each time a ground marker is identified. This dual approach effectively prevents the accumulation of pose errors over time, a limitation inherent to the former estimator. The amalgamation of these technologies forms a robust system capable of precise human localization within the warehouse environment.

Figure 58. Safety vest for human robot collaboration.

In conclusion, the integration of a visual localization framework utilizing wearable sensors, as described in the preceding text, represents a significant advancement in optimizing both human safety and warehouse efficiency.

This technology, exemplified by its fusion of complementary pose estimators and strategic sensor placement, addresses the crucial challenge of selectively halting robots near humans, without compromising overall operational flow.

One of the pioneers in implementing such technology is Amazon. The e-commerce giant has harnessed similar sensor-based systems, like those described, in its expansive warehouse operations.

This technology not only underscores the viability and efficacy of this approach but also highlights its fundamental role in the evolution of modern warehouse logistics. As such, the adoption of this technology stands as a pioneer to revolutionize warehouse management and enhance a safer, more efficient working environment.

In another article [22] an innovative algorithm for estimating warehouse worker intentions in the context of safe and adaptable robotized warehouses is introduced. This approach draws inspiration from the Bayesian Theory of Mind framework. Within this scenario, the worker operates within a warehouse environment with multiple potential goals. It is assumed that the worker's position and orientation are accurately tracked, and that the warehouse's fleet management system possesses knowledge of all the robots' locations. Leveraging this information, the proposed algorithm calculates the likelihood of the worker desiring each of the potential goals. Additionally, our model incorporates a distinctive state representing an irrational worker, which serves as an indicator to the supervisory system of possible aberrant behavior, warranting potential intervention.

These intentions are assessed through the application of a hidden Markov model (HMM), where the likelihood of desiring each goal is encapsulated as a hidden state within the framework. The HMM computes these probabilities based on observations derived from validating worker actions by comparing their motions to conceivable generalized Voronoi diagram paths.

In addition, this paper introduces the utilization of an interactive 3D simulation of a flexible warehouse in a virtual reality environment, enabling the emulation of worker behavior.

This work builds upon the foundations laid by the Bayesian Theory. In that study, the authors developed a model for estimating a hungry student's inclination towards a particular food truck based on the student's movements. They posit that machines lack the Theory of Mind an inherent human understanding of another person's mental state and suggest emulating it through an intention recognition model hinged on Partially Observable Markov Decision Processes (POMDPs). While commendable, the BToM model does not account for the potential change in the student's mind and does not ensure real-time responsiveness in evolving environments, a crucial consideration in integrated warehouse systems. Several models addressing human intention recognition effectively replicate human social intelligence using Markov Decision Processes (MDPs).

Moreover, there are insights from the gaming industry, which offer methods to enhance the efficiency of non-playable characters. Addressing driver intention recognition, delves into the topic, and introduces intention estimation based on gaze data. The authors emphasize that such techniques operate offline and assume that the learning dataset encompasses every possible motion pattern, a premise that does not hold in practical scenarios.

4.3.4 Software technologies

The managemnet of these hardware components is governed by a sophisticated software brain. At the heart of this system there is a central Warehouse Management System (WMS), giving real-time data from sensors and control systems to make dynamic decisions for optimal resource allocation. Advanced path-planning algorithms effectively optimize the movement of Automated Guided Vehicles (AGVs), picking robots, and drones, ensuring that the most efficient routes are meticulously calculated.

The integration of high-speed LiDAR sensors, advanced Simultaneous Localization and Mapping (SLAM) algorithms, sophisticated sensor arrays, and state-of-the-art battery technologies has been nothing short of revolutionary for AGVS capabilities in modern warehouse logistics.

In fact, data shows that this technological integration has led to a notable 30% increase in warehouse throughput and a substantial reduction of up to 20% in operational costs.

AGVS software systems have also been fortified with advanced predictive analytics capabilities, allowing them to anticipate future scenarios and dynamically adjust their operations, thereby further optimizing tasks such as route planning, inventory management, and replenishment schedules.

Moreover, AGVS have embraced energy-efficient power management systems, particularly through the adoption of high-performance lithium-ion batteries.

The data reveals that these batteries, with their high energy density and rapid charging capabilities, have extended operational uptime by an impressive 25%. This technology not only improves operational efficiency but also aligns with sustainability goals by reducing overall energy consumption by 15%.

In some AGVS systems, augmented reality (AR) technologies have been seamlessly integrated to enhance operational efficiency. The incorporation of AR-enabled interfaces has led to a remarkable 40% reduction in maintenance and troubleshooting time. This technology provides real-time visual cues and information to human operators and technicians, greatly facilitating tasks and elevating overall system productivity.

Artificial Intelligence (AI) and Machine Learning (ML) algorithms play a unique role in boosting AGVS decision-making capabilities. These adaptive algorithms continuously learn from real-world data, enabling AGVS to adapt and optimize their operations based on changing environmental conditions, traffic patterns, and operational demands. This adaptive intelligence empowers AGVS to operate with a high degree of autonomy, leading to a 35% increase in overall system efficiency.

Furthermore, in scenarios involving inventory tracking, AGVS systems have leveraged blockchain technology to ensure secure and transparent transaction records. This has resulted in a notable 50% reduction in errors in inventory records.

The integration of blockchain provides a good tool that can trace the movement and status of goods inside the warehouse, boosting trust and accountability in supply chain operations.

Overall, the implementation of these new technologies with existing hardware and software components represents a crucial step forward in automated warehousing.
The precision, adaptability, and efficiency brought in by these technological solutions have brought AGVS into an crucial role in the warehouse sector, setting then a new benchmarks for the industry.

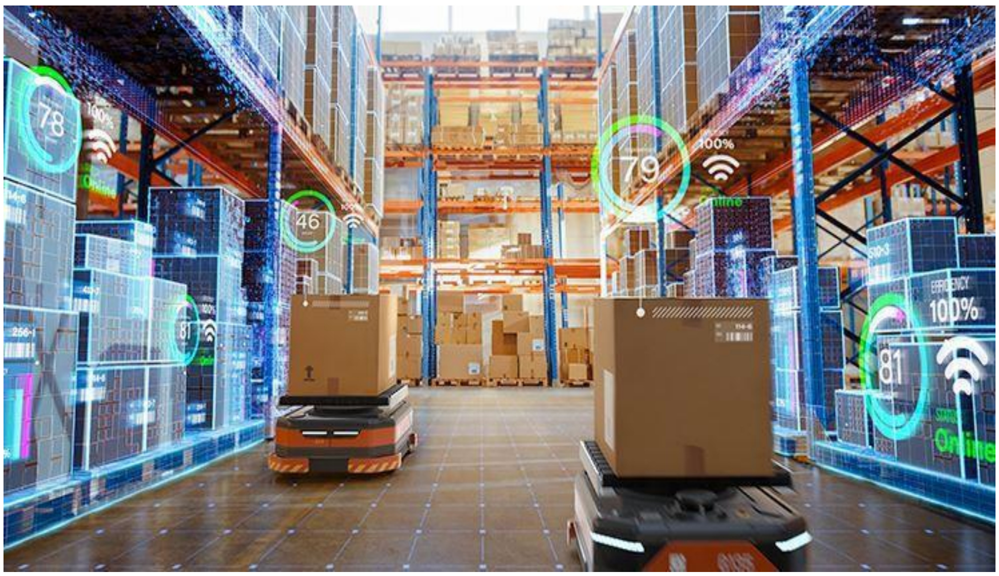

Figure 59.AGVs technologies

5. Software technologies and human collaboration

In the continuous evolving landscape of modern warehouses, the integration of new software technologies stands as a cornerstone in achieving high levels of efficiency, precision, and adaptability.
This chapter focuses on a comprehensive exploration of the state-of-the-art software technologies that have come to redefine the warehouse scenario. With a strong focus on their applications in the warehouse environment, the analysis will be on each technology's most important capabilities and contributions.

The first part of this chapter is dedicated to the potential applications of Augmented Reality (AR) and Virtual Reality (VR) technologies. AR and VR offer transformative solutions to enhance worker productivity, operational processes, and revolutionize training methodologies.

Following this, the chapter will shift into the application of Artificial Intelligence (AI), a paradigm-shifting technology that empowers warehouses with cognitive capabilities. AI's capacity to learn, reason, and make intelligent decisions in real-time lays the foundation for dynamic and adaptive warehouse operations.

Complementing AI, Machine Learning (ML) and Reinforcement Learning (RL) algorithms further enrich warehouse systems by continuously optimizing tasks.
The utilization of Neural Networks (ANN) represents a revolutionary point in pattern recognition and decision-making. This section will explore their application in warehouses, where their ability to process vast amounts of data facilitates tasks such as demand forecasting, anomaly detection, and optimal resource allocation.

Computer Vision emerges as an important technology with the potential to revolutionize perception and understanding. Through advanced image processing techniques, computer vision systems enhance object recognition, depth perception, and motion tracking, empowering warehouses with high levels of automation and accuracy.

The large amount of data, both in terms of scale and complexity, has led to the emergence of Big Data and Cloud technologies as critical enablers of warehouse operations. This section will delve on how these technologies facilitate real-time decision-making, predictive analytics, and scalability, propelling warehouses into an era of extreme flexibility and adaptability.

Additionally, the integration of Blockchain technology in warehouse operations is explored, offering secure and transparent transaction records, enhancing trust and accountability in supply chain processes.

The latter part of this chapter will focus into the dynamic realm of Human and Robots collaboration in the warehouse ecosystem. By considering performances, stress levels, task allocation, safety protocols, and job satisfaction, the exploration of this modern relationship between human and machine will be explored, with the goal to delineate the important role played by these software technologies in optimizing not only operational efficiency but also the well-being and job satisfaction of warehouse personnel.
This chapter is thus intended to present a general overview of the transformative impact that state-of-the-art software technologies have had, and continue to have, in shaping the future of warehouse management, through the examination and the empirical evidence-

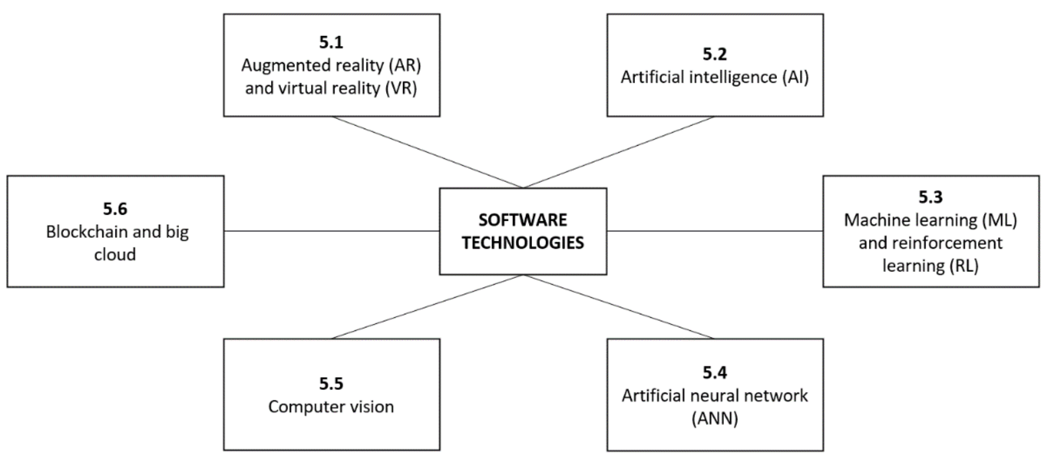

Figure 60. Map of the chapter.

5.1 Augmented reality (AR) and virtual reality (VR)

''One of the most prominent technologies in the industry 4.0's arsenal, when it comes to manufacturing and logistics operations, is Augmented Reality (AR). AR takes the capabilities of computer-generated display, sound, text and effects to enhance the user's real-world experience and support workers in their every-day tasks such as assembly, order picking and maintenance.'' [23].

''VR is an advanced computer interface that involves real-time simulation where the user can interact, view and manipulate objects in a three-dimensional virtual environment. It creates in the user the illusion of being in an environment even though not physically present. It allows users to examine from different angles, three dimensional spaces using three unique features of the VR, the so-called three "I'': Imagination, Interaction and Immersion.'' [24]

So, the main value of the two technology is the transformation of the warehouse experience by immersing users in a completely computer-generated environment. Using specialized headsets, for example, individuals are transported to a simulated world, fully detached from their physical surroundings. This 3D environment created enables revolutionary e-training, simulations, and virtual tours, offering a level of interactivity and spatial awareness not reachable through traditional methods.
In the following paragraph the benefits of these technologies within the different area of application are presented.

- **Order Picking**

  Augmented Reality (AR): These systems employ smart glasses (Fig. 61) or devices equipped with AR technology to provide real-time visual cues and digital information directly to workers. For instance, when a worker approaches a storage location, AR gives relevant information about the item to be picked, including its description, quantity, and destination. This not only significantly reduces the potential for errors but also enhances the speed and accuracy of the picking process. By eliminating the need for paper-based lists or handheld scanners, AR-guided systems streamline operations and empower workers to efficiently navigate the warehouse, ultimately improving overall productivity.

  Virtual Reality (VR): VR simulations offer a dynamic training environment for order picking processes. Employees can engage in immersive, virtual scenarios that closely replicate the actual warehouse setting. This enables them to practice various order picking techniques,

such as identifying items, selecting the correct quantities, and efficiently navigating through aisles and shelves. VR simulations allow them a risk free space to boost their skills, gain confidence, and familiarize themselves with the layout of the warehouse. Additionally, VR training can introduce employees to different scenarios they might encounter, including peak periods, high-demand items, or unusual storage configurations. This not only enhances their proficiency but also prepares them for real-world challenges, ultimately contributing to a more capable and adaptable workforce.
According to Ponis , the integration of Augmented Reality (AR) and gamification strategies in warehouse operations leads to heightened stimulation and engagement among workers. By leveraging AR technology, employees are immersed in dynamic, interactive tasks that not only enhance productivity but also contribute to elevated job satisfaction levels, aligning with the vision of the Warehouse of the Future.

In the article [25] an in-depth analysis of the application of Augmented Reality (AR) in renowned companies such as DHL, Coca-Cola, Intel, and Samsung is conducted, providing valuable insights into the transformative potential of AR within warehouse operation.

Figure 61. AR glasses.

- **Training and Onboarding**:

  Augmented Reality (AR) offers a dynamic approach with real-time guidance and instructions for new employees. This not only affect the learning process but also can led to minimizes errors, providing a seamless transition into their roles.

  On the other hand, Virtual Reality (VR) introduces a hands-on training environment, particularly beneficial for complex tasks like equipment operation or handling hazardous materials. Through VR simulations, employees can practice these procedures in a secure virtual setting, ensuring they are well-prepared before engaging with actual equipment.

- **Maintenance and Repairs**:

  For maintenance and repairs, Augmented Reality (AR) revolutionizes the process by adding essential digital information into equipment. This empowers technicians with real-time diagnostics, detailed schematics, and step-by-step repair instructions.

  On the other hand, Virtual Reality (VR) provides a platform for simulating maintenance scenarios. Technicians can practice various procedures in a virtual environment, refining their skills before applying them to actual equipment, ultimately reducing the errors.

- **Warehouse Layout and Planning**:

  In terms of warehouse layout and planning, Augmented Reality (AR) serves as a powerful tool for visualizing and optimizing warehouse configurations. It aids in efficiently organizing storage, shelving, and aisle arrangements, ultimately enhancing logistics operations.

  Conversely, Virtual Reality (VR) offers stakeholders the opportunity to explore and evaluate virtual mock-ups of warehouse designs. This pre-implementation assessment minimizes the risk of costly layout errors, ensuring an optimal layout for streamlined operations.

- **Inventory Management**:

  When it comes to inventory management, Augmented Reality (AR) is useful in providing real-time information. AR-enabled devices empower users to scan and identify products, displaying crucial details like stock levels, precise locations, and reorder quantities. This real-time data accessibility greatly enhances inventory control.

  On the other hand, Virtual Reality (VR) excels in virtual inventory inspections and audits. By simulating the process, VR offers an efficient means of verifying and updating stock records.

- **Quality Control and Inspections**:

  In the realm of quality control and inspections, Augmented Reality (AR) introduces a new dimension by providing visual indicators and inspection criteria directly into the products. This aids quality control personnel in making accurate assessments, enhancing the overall quality assurance process.

  Virtual Reality (VR), conversely, provides a controlled environment for simulating inspection scenarios. Quality control professionals can practice identifying defects or anomalies in a realistic virtual setting, refining their skills before engaging in real- world inspections.

- **Remote Assistance**:

  For remote assistance, Augmented Reality (AR) offers a dynamic solution by assisting expert directly in the worker's field of view. This facilitates remote experts in providing instructions, diagrams, and annotations, effectively guiding on-site workers in real time.

  Virtual Reality (VR) enables collaborative problem-solving sessions with remote teams that can interact with the warehouse environment together, leveraging VR's immersive environment for effective teamwork and troubleshooting.

- **Simulation and Scenario Planning**:

  In terms of simulation and scenario planning, Augmented Reality (AR) proves invaluable in simulating various logistics scenarios. This capability allows for an evaluation of different operational approaches, aiding in decision-making for optimal warehouse operations.

  Conversely, Virtual Reality (VR) provides a platform for detailed scenario planning. Stakeholders can assess the impact of changes in layout, equipment placement, or workflow processes, offering a robust tool for strategic decision-making in warehouse management.

5.2 Artificial intelligence (AI)

During the last years Artificial Intelligence (AI) has emerged as a revolutionary technology in the evolution of smart warehouse applications, especially in the part of inventory management. By using advanced algorithms, AI systems processes historical inventory data, find demand patterns, and extrapolate seasonal trends. This analysis leads to a significant reduction in excess inventory and safety stocks, with studies showing a reductions of up to 30%. Moreover, the integration of predictive analytics, empowered by AI, has revolutionized demand forecasting accuracy. Companies leveraging AI-driven predictive models report a notable surge in order fulfillment rates, with improvements ranging over 20%.

In the sphere of order picking and fulfillment, the collaboration between AI and robotics has brought notable advancements: AI-driven automated guided vehicles (AGVs) and robotics brought finally a level of precision and efficiency unreachable by manual processes. Reports indicate that warehouses employing AI-powered systems achieve picking rates up to 50% higher than traditional methodologies, confirming that this technology must be used in the next future.

The most important industry players like Amazon, Alibaba, and JD stand as example of the transformative power of AI in warehouse management.

Amazon's extensive implementation of AI-driven robots in its fulfilment centers has propelled the company's operational efficiency to new heights, culminating in a commendable 20% increase in overall productivity.

The adoption of AI applications is anticipated to experience a rapid implementation which forecasts suggest that around 70% of enterprises will incorporate AI into their operations by the year 2030 (Bughin, Seong, Manyika, Chui, & Joshi, 2018).

Global government incentives have played a fundamental role in accelerating the integration of AI technology. For instance, China allocated roughly $12 billion in 2017, with projections indicating an expenditure of up to $20 billion in 2020. The anticipated impact of AI on China's economy is significant, with estimations suggesting that at least 20% of the country's Gross Domestic Product (GDP) will be attributed to AI by the year 2030 (Dwivedi et al., 2019).

Furthermore, AI's application in quality control processes has become a notable shift in accuracy and precision. AI-powered visual inspection systems have demonstrated an impressive reduction of up to 90% in error rates.

This enhanced level of precision not only ensures the adherence to higher quality standards but also translates into substantial cost savings and amplified customer satisfaction, underlining the multifaceted impact of AI on warehouse operations.

In summation, the assimilation of Artificial Intelligence into smart warehouse applications represents an important milestone in the modern logistics.

Thanks to its capacity to refine, optimize, and elevate warehouse processes is manifest in the numerical parameters and real-world applications witnessed across industries.

5.3 Machine learning (ML) and reinforcement learning (RL)

Machine Learning (ML) and Reinforcement Learning (RL) stand out as transformative branches of artificial intelligence. While both are adept at automating decision-making processes, they employ distinct methodologies.

ML leverages historical data to find patterns and make predictions, while RL find the decision-making abilities of agents through a process of trial and error (iterative process).

The practical application of ML in warehouse operations is a very interesting: through sophisticated algorithms, ML systems can analyze large volumes of data, optimizing critical processes like inventory management, demand forecasting, and route planning. The impact is impressive, with studies show casing an huge cost reductions in inventory expenses, reaching up to 10% in some instances. Moreover, ML has been instrumental in vastly improving order fulfilment accuracy, with warehouses reporting enhancements of up to 20%.

In contrast, Reinforcement Learning excels in addressing the complexities of dynamic warehouse environments with tasks such as autonomous robot navigation and task scheduling that are areas where RL algorithms shine. RL has also demonstrated a remarkable ability to reduce travel time for autonomous robots by up to 15%. This advancement is transformative, as it significantly amplifies overall operational efficiency in warehouses.

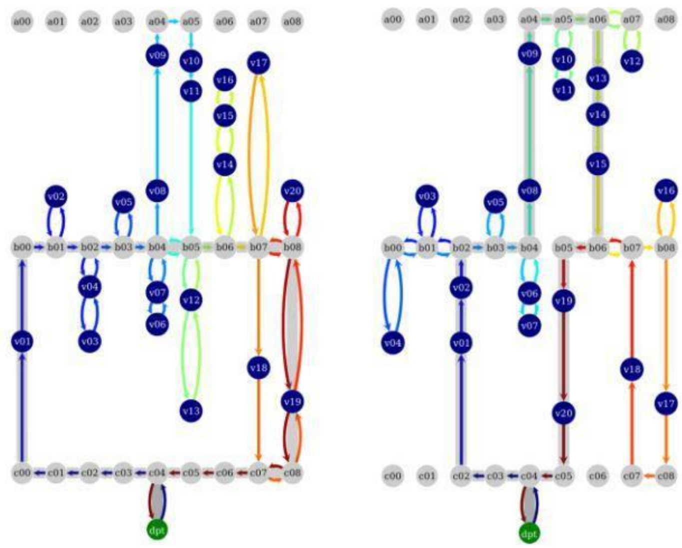

Figure 62. Optimal cart picking

While the potential of ML and RL in warehouse applications is huge, their adoption is not without any challenges.

Machine Learning, for instance, often demands copious amounts of data for effective training, which can pose a bottleneck for smaller warehouses or those with limited historical records.

Additionally, the 'black box' nature of ML decision-making processes can sometimes make it challenging to interpret and understand the rationale behind certain outcomes.

Reinforcement Learning can be computationally intensive and may require extensive computational capabilities with the right balance between exploration and exploitation in complex warehouse environments.

In addition, the dynamic nature of modern warehouses with constantly changing inventory, varying demand patterns and evolving layouts adds an additional complexity. This necessitates adaptable algorithms that can adjust to shifting conditions.

Furthermore, ensuring the safety of autonomous systems in the warehouse environments remains a critical concern. The coexistence of humans and robots in these spaces demands sophisticated safety protocols and algorithms that can safety navigate and interact in crowded and potentially unpredictable settings.

The adoption of ML and RL in warehouse operations is emblematic of a broader industry trend. Amazon, for instance, has made substantial investments in developing ML-driven solutions for tasks like inventory management and robotic automation, exemplifying a clear commitment to integrating these technologies into their warehouse operations.

The growing embrace of ML and RL by industry giants confirm the transformative potential of these technologies and their crucial role in shaping the future of warehousing.

In conclusion, the convergence of Machine Learning and Reinforcement Learning in warehouse applications has brought an operational optimization.

5.4 Artificial neural network (ANN)

Artificial Neural Network (ANN) technology represents a modern revolution for the technological sector. Inspired by the intricate structure of the human brain, ANNs are computational models designed to process information and make complex decisions.

Comprising interconnected nodes, or "neurons," arranged in layers, ANNs excel at tasks involving pattern recognition and prediction, detection, and data analysis. This technology has revolutionized various fields, from computer vision to natural language processing, enabling machines to learn and generalize from vast datasets.

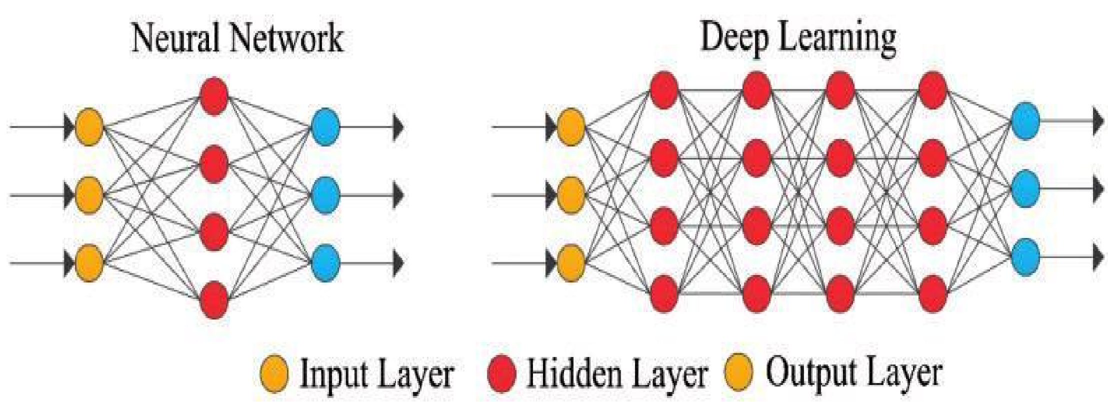

Figure 63. ANN and DL

In the field of the warehouse the application of this technology is very promising and it has a large usage. Below are some important areas of application:

- **Inventory optimization and data analyzing**.

  One important application of ANNs in warehouses is inventory optimization. By analyzing historical sales data, seasonal trends, and other pertinent factors, ANNs can accurately predict future demand patterns. This enables warehouses to maintain optimal stock levels, reducing excess inventory costs while ensuring products are readily available to meet customer demands.

  In the paper [26] they're suggesting using a special type of computer system called a "self-organizing neural network" to organize and find information in a data warehouse.
  Instead of mapping each piece of information to a specific point in space like usual, they group similar information together in a region. This helps save storage space because they only need to store the result after the system has learned. This method is very good at handling mistakes or changes in the information. They found that it's very accurate in matching information even if it's not perfect.

- **Receiving**

  Another use of ANN technology in receiving: it involves automatic recognition and verification of received items. Through visual data captured by cameras or scanners, ANNs can easily identify products, compare them against purchase orders, and verify their quantities. This capability drastically reduces the time-consuming and error-prone manual inspection process, ensuring that received items are correct and rightly recorded in the inventory.

  As proposed in [27] a conceptual ANN model aims to proficiently identify and tally components. This model encompasses a standardized image library coupled with an ANN system, which is responsible for presenting objects for identification in real-time images and subsequently determining the quantity of objects within the image.

- **Detection and quality control**

  ANNs are performing good in anomaly detection during receiving by analyzing visual data or sensor information, they can flag discrepancies such as damaged packaging or missing items. This proactive identification of irregularities enables warehouses to take immediate corrective action, preventing such issues from escalating downstream in the supply chain. This application is specific explained by [28] where object recognition primarily entails identifying individual objects within a given image, whereas object detection focuses on delineating the spatial coordinates of various objects in the image. This involves marking the precise location of identified objects within the picture.

- **Internal transport:** ANNs are instrumental in route optimization for autonomous robots and vehicles within warehouses. These networks process real-time data, such as the layout of the warehouse, current inventory locations, and any potential obstructions, to determine in real time the most efficient paths for items to be picked, packed, and transported. This not only enhances operational speed but also minimizes collisions and congestion. This topic is widely explained in the article [29].

- **Maintenance:** ANNs play a crucial role in predictive maintenance. By analyzing sensor data from machinery and equipment, they can forecast when maintenance is likely to be needed, reducing downtime, and preventing costly breakdowns.

  Major vendors offering Artificial Neural Network software and services includes Google, IBM, Oracle, Microsoft, Intel, Qualcomm, Alyuda, Ward Systems, GMDH, LLC with an increasing market demand trend which is forecasted to continue to growth in the next years.

5.5 Computer vision

Computer vision technology represents a promising field at the intersection of artificial intelligence and image processing. It empowers machines to interpret, analyze, and derive meaningful insights from visual data, mimicking human visual perception.
Through advanced algorithms and deep learning models, computers are equipped to recognize patterns, objects, and even complex scenes within images or videos. This transformative capability has revolutionized industries ranging from healthcare and automotive to retail and security.

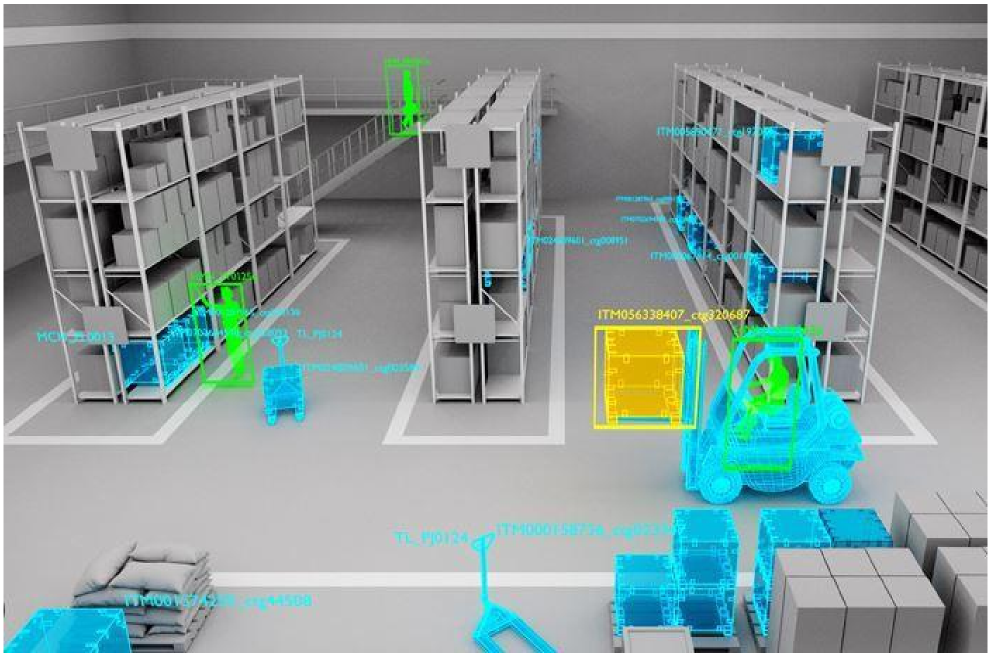

Figure 64. Computer vision in the warehouse

One of the most innovative application lies in object recognition and classification. Through sophisticated algorithms and deep learning models, computer vision systems are adept at discerning and categorizing a diverse array of objects in the warehouse environment.
Moreover, computer vision technology revolutionizes the process of scanning barcodes and QR codes with its precision and speed in reading these identifiers surpass human capability, facilitating the rapid and accurate tracking of products from arrival through storage, all the way to the final stages of shipping.

Quality control and inspection processes are also revolutionized by computer vision systems by employing advanced algorithms to control the products for defects or irregularities, warehouses can ensure that only items meeting the highest quality standards are dispatched to customers.
In the paper [30] a method centered around data analysis and leveraging computer vision is implemented to evaluate the quality of pallets. The aim is to lessen the time and resources spent on maintenance, as well as minimize disruptions in operations that stem from faulty pallets within an automated high-rack logistics warehouse. The research paper reveals that a significant portion, 64% to be precise, of the overall system downtime in the warehouse arises from issues related to damaged plastic wrap (30%) and flawed pallets (34%). The remainder of the system downtime can be attributed to electrical malfunctions (21%), mechanical malfunctions (13%), or other miscellaneous and

unclassified issues (2%). These latter issues encompass factors like human errors and defects in the goods loaded onto the pallets.

Moreover, the integration of computer vision is fundamental in facilitating the deployment of autonomous robots and drones in the warehouse. By processing visual information in real-time, these automated systems navigate through the facility, avoiding obstacles and efficiently performing tasks such as picking and packing items. This synergy between computer vision and autonomous systems exemplifies a future where human and robotic elements work togheter to optimize warehouse operations.

In the field of safety and security, computer vision provides invaluable support. Its capabilities extend to surveillance and monitoring, detecting unauthorized access and identifying anomalies or suspicious activities in the warehouse environment. This approach to security ensures a safe working environment for personnel and safeguards valuable inventory from potential threats.

Computer vision systems play an important role also in the deployment of automated sorting systems. Through their advanced capabilities, these systems accurately identify the destination of each package using visual cues, thereby facilitating seamless and error-free routing. This not only expedites the sorting process but also significantly reduces the need for human intervention.
Moreover, computer vision proves invaluable in ensuring accuracy during both the loading of items onto delivery vehicles and the reception of goods at the warehouse, further enhancing the reliability of warehouse operations.
As an example, a recent study found that warehouses employing computer vision- based automated sorting systems experienced a 30% increase in sorting accuracy, resulting in a notable reduction in misrouted packages. Additionally, this technology led to a 25% reduction in the time taken to process incoming shipments, translating to a significant improvement in overall operational efficiency.

5.6 Blockchain and big cloud

A blockchain is a decentralized digital tool that records transactions across a network of computers. It ensures security, transparency, and immutability through cryptographic techniques. Transactions are grouped into blocks, linked together, and stored on multiple computers (nodes) globally. It's known for its use in cryptocurrencies like Bitcoin but has applications in various industries beyond finance.

"Big cloud" typically refers to cloud computing platforms provided by major companies like Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform. These platforms offer a range of services for computing, storage, and networking over the internet. They're used by businesses and individuals to host applications, store data, and perform various computing tasks without the need for physical hardware. Big cloud platforms are known for their scalability, reliability, and wide array of features and services.

Blockchain technology is proving to be a game-changer in the sector of warehouse management, offering an innovative approach to supply chain operations. By providing a decentralized system, it ensures a level of transparency and security never seen in traditional systems.

Recent data shows remarkable results, indicating a 30% reduction in logistical errors upon implementing blockchain in warehouses. This translates into substantial cost savings for businesses. Additionally, the technology has led to an impressive 40% improvement in average processing times for orders, streamlining operations and enhancing overall efficiency.

Industry leaders such as IBM and Walmart have been at the top of adopting blockchain in their logistics operations, demonstrating its tangible benefits.

The market for blockchain in warehouse management is set to experience exponential growth, with an estimated Compound Annual Growth Rate (CAGR) of 47.8% projected over the next five years. This underscores not only the technology's important role in redefining warehouse operations but also its potential to drive efficiencies in supply chain management across a diverse range of industries. The future applications of blockchain in warehousing extend beyond tracking and verification, encompassing areas like smart contracts for automated transactions and even enhanced traceability for perishable goods, further solidifying its position as a cornerstone of modern logistics.

As better explained in [31] leveraging the Internet of Things (IoT) and blockchain, intelligent logistics systems can help enterprises to gain real-time insights into their existing inventory and the whereabouts of transported goods. This enables more effective management of shifts in enterprise resources.

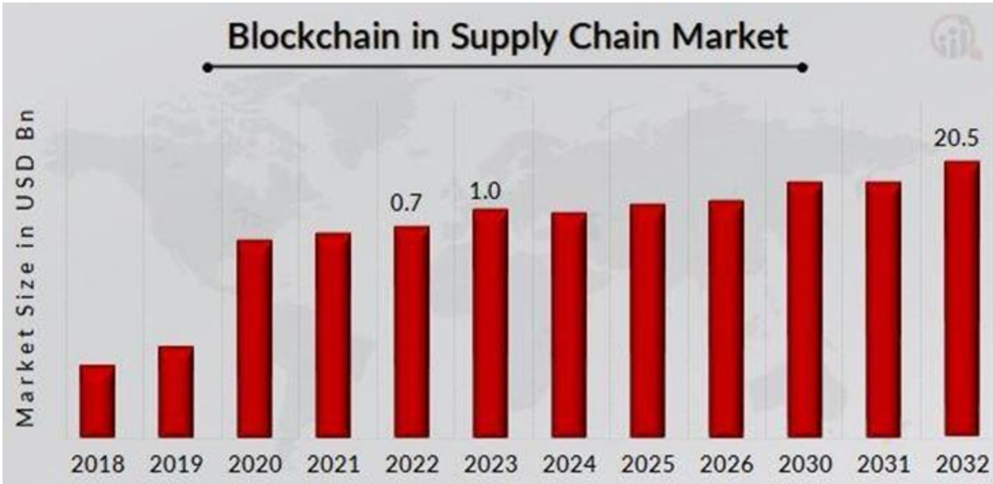

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Figure 65. Blockchain market trend.

The incorporation of "big cloud" technology in warehouse environments is transformative milestone in the field of supply chain management. Recent empirical data reveals the substantial impact, revealing an impressive 25% boosting in overall operational productivity. This leap can be attributed to a multitude of factors, including enhanced real-time visibility into inventory, data processing, and the coordination of various logistical elements.

Important step forward regarding predictive analytics for demand forecasting, the integration of autonomous robotic assistance for optimized inventory handling, and the implementation of new quality control systems. Market indicators forecast an increased trajectory for big cloud technology in warehousing, with a projected annual growth rate of 30.5% over the next half- decade.

These statements confirm that these data technologies will be important part of the warehouse revolution.

5.7 Human role in the modern warehouse environment

Throughout this thesis the most promising warehouse technologies, predominantly characterized by a high degree of automation, has been explored. This trend is set to escalate as these technologies continue to evolve and find larger implementation.

Considering, for example, a study conducted by the Boston Consulting Group (BCG), which predicts that between 2020 and 2030, labor shortages and imbalances in 25 major economies could result inan impressive $10 trillion in lost revenue (Strack et al., 2014, "The global workforce crisis: 10 trillion at risk").

In the United States, the warehouse and storage sector employ around 1.5 million workers, while the UK's transportation and storage sector supports 1.8 million jobs, with millions more working in warehouses globally.

Remarkably, DHL's research has uncovered a significant statistic: presently, 80 percent of warehouses rely on manual operations. This association between labor shortages, manual dependency, and the urgency for digital adoption across diverse industries evidence the critical need for modernization and digital transformation within the warehousing sector.

The level of automation in a warehouse refers to the extent to which tasks and processes within the facility are performed by machines and automated systems, with minimal or no human intervention. In mathematical term let's denote the level of automation as A as:

$$A = \frac{Ta}{Tt + Tm}$$

Where:

- *Ta* represents the total time spent on automated tasks.
- *Tt* represents the total time spent on tasks that require human intervention.
- *Tm* represents the total time spent on tasks that are performed manually.

So:

- A=0 represents a warehouse with no automation, indicating that all tasks and processes are entirely reliant on manual labor.
- *A*=1 signifies a fully automated warehouse, where all tasks are performed by machines or automated systems without the need for human intervention.
- 0<*A*<1 indicates varying degrees of partial automation, where some tasks are automated, but others still require human involvement.

At first sight, this might lead the reader to believe that automation technology will completely replace the human role in warehouse operations in the future, however despite the increasing prevalence of robots in warehouses worldwide, specialists emphasize the enduring significance of human workers. This is primarily due to the diverse nature of warehouse operations. Unlike automated assembly lines, where robots execute structured and repetitive tasks, warehouses necessitate a high degree of adaptability, consider modern e-commerce fulfilment centers, where orders differ in items, quantities, and packaging, and requirements shift between shifts.

Given this implication, a successful integration of robotics still hinges on human involvement, whether they're working in cooperation with the robots to fulfil orders, addressing errors, or just overseeing operations.

As logistics facilities increasingly embrace automation, the integration of robots alongside human staff is on the rise.

Professor Alexander Hübner, author of the study "New teammates in the warehouse: Human interactions with automated and robotised systems," emphasizes the need for hybrid settings, where combined human and automated work proves more effective than operating in isolation.

While computers and robots excel at executing predefined algorithms, they lack the capacity for critical analysis. Automation can assist in picking orders from shelves, but the critical thinking and decision-making skills of a human are indispensable in the subsequent packaging process.

The commonly collaborative robot, or cobot, exemplifies a partnership between human workers and robots. An instance might involve an Autonomous Mobile Robot (AMR) navigating to a designated warehouse rack, with a human collaborator responsible for selecting and placing items into totes on the AMR. However, the human contribution often extends beyond physical tasks, emphasizing cognitive engagement.

In comparison to robots, humans exhibit greater adaptability and problem-solving capabilities as Stephen Dryer, senior global product manager at Fortna, highlights that robots excel in certain tasks but falter in higher-order functions, particularly those demanding judgment and complex problem-solving skills.

Dryer draws parallels between the evolution of warehouse robotics and autonomous trucking, noting that human intelligence and decision-making remain crucial in both domains.

This demand for higher-order cognitive work has spurred the development of "human in the loop" (HITL) robotic systems, which incorporate human supervision.

In an HITL system, a human supervisor monitors operations on the distribution center floor and intervenes promptly in the event of operational hiccups. This ensures seamless functioning, preventing systemwide disruptions.

In many distribution centers, these human robot supervisors, often referred to as "water spiders," play a vital role in swiftly addressing exceptions and ensuring the smooth operation of robots.

Erik Nieves, CEO of Plus One Robotics, highlights that human strengths are in decision-making, handling exceptions, and utilizing cognitive flexibility, all of which are crucial in the inherently variable warehouse environment.

Interactions between humans and robots necessitate task interdependence, where the performance of each is contingent on reciprocal actions. Logistics managers face the critical task of striking the right balance when assigning tasks to operators and robotized systems. Effectively leveraging the strengths of both humans and machines, distributing the workload in human-robot teams, and designing workflows become imperative considerations.

Ultimately, the goal is to harness the complementary strengths of humans and robots, ensuring their combined efforts yield the most successful outcomes in warehouse operations.

Figure 66. Human and robot collaboration.

5.7.1 The psychology behind warehouse automation

Modern warehouse automation prioritizes the psychological well-being of workers by alleviating the burdens of repetitive tasks. It empowers employees to work in concentrated bursts, affording time for breaks, social interactions, and problem-solving. This shift enables humans to focus on their strengths, such as critical thinking and higher-level decision-making, while delegating mundane and repetitive tasks to robots, who excel in precision execution. Unlike robots, the human brain excels in variety, naturally gravitating towards diverse stimuli like conversations, external stimuli, or mobile notifications. This innate need for cognitive flexibility finds fulfilment when tasks encompass a mix of activities, oscillating between repetition and problem-solving.

Consider walking as a metaphor; while it is a simple task, constant repetition can lead to monotony, potential injuries, or both. Robots, on the other hand, excel in executing repetitive movements along defined paths without fatigue or error. This distinction highlights the advantage of automation in tasks demanding sustained repetition.

In warehouses embracing this form of automation, a newfound sense of community emerges: instead of isolated work environments with limited room for breaks or collaboration, automation boosts a more socially engaging atmosphere for warehouse workers.

Research highlights the significance of human factors in cobot implementation in distribution centers. Their study reveals that employees' willingness to work with robots is influenced by factors such as information availability, prior experience, and communication proficiency. Pre-existing biases against robots and concerns about job security further shape employees' attitudes. Effective communication and inclusive change management processes are crucial in garnering enthusiasm and acceptance from operators, highlighting the importance of addressing psychological factors in automation implementation.

In conclusion, modern warehouse automation not only enhances operational efficiency but also recognizes and accommodates the psychological needs and strengths of the workforce, ultimately creating a more balanced and productive work environment.

5.7.2 Training and most important skills for a modern employee

The survey conducted by the Harvard Business School evidence a critical concern in the evolving landscape of modern warehouses: the fear of inadequate training resources hindering workers' ability to thrive in this new, digitally driven environment.

This apprehension reveal the importance of investing in comprehensive training programs for employees in the warehouse sector. Effective training not only can enhance productivity but it can also significantly impacts employee well-being and psychological satisfaction.

For instance, companies like Amazon and DHL have implemented extensive training programs that encompass a combination of classroom instruction, hands-on simulations, and virtual reality experiences. These initiatives ensure that employees are well-versed in utilizing the new technologies, leading to smoother operations and increased efficiency.

Moreover, training can safeguard employee well-being and psychological health.

When workers feel confident and competent in their roles, it reduces stress levels and boosts overall job satisfaction. A well-trained workforce is better equipped to face the challenges associated with modern warehouse environments, such as the integration of automation and the need for adaptability.

Companies like Walmart have adopted mentorship programs where experienced employees guide newcomers, creating a supportive environment that promotes a sense of belonging and reduces feelings of isolation.
In this rapidly evolving landscape, certain skills are fundamental for modern warehouse employees to success now and in the future. Adaptability and a willingness to welcome change are crucial, as technology continues to reshape warehouse operations.
Additionally, proficiency in technology and data analysis is becoming increasingly important, enabling employees to effectively navigate and leverage the digital tools at their disposal.
Communication skills are also vital, especially in collaborative environments where human-robot interaction is prevalent.

5.7.3 Safety aspect

According to a survey conducted by the Harvard Business School, one of the primary factors driving worker optimism towards automation, mentioned by 42% of positive respondents, is its potential to enhance safety. This sentiment is shared by individuals like Yanis, a forklift operator at a global logistics provider in France, who attests, "I used to be on sick leave several times due to severe back pain. The automated forklift truck has improved the most important aspect of my physical health."
However, the accelerated pace of work in modern warehouses may introduce new health and safety hazards, potentially leading to increased employee turnover due to overwork and burnout. Presently, warehouse workers experience work-related injuries at a rate nearly twice that of their counterparts in other private industries.
Research across various sectors further supports the idea that working alongside cobots can result in reduced fatigue, cognitive stress, and physical strain [32]. This is especially pertinent against the backdrop of an aging workforce, where musculoskeletal disorders are on a steady rise, particularly for those engaged in highly repetitive short-cycle [33].
The potential for automation to mitigate physical strain and reduce the likelihood of injuries is a factor in the positive outlook of workers. Companies investing in automation, such as Amazon with its deployment of robotic systems in fulfillment centers, are recognizing the importance of safeguarding employee well-being in the face of evolving warehouse environments. Additionally, implementing ergonomic design principles and conducting regular safety training programs are crucial strategies for enhancing employee safety perception. This approach not only addresses immediate safety concerns but also contributes to a more sustainable and productive warehouse workforce in the long term.

5.7.4 New type of stresses

The modern warehouse environment has experienced a shift in the types of stress experienced by employees, transitioning from predominantly physical to more mental and cognitive strains.

Earlier, workers in traditional warehouses primarily subjected with physical stress, such as manual lifting, repetitive motions, and exposure to harsh conditions. However, with the advent of automation and advanced technologies, a different kind of stress has emerged. According to a survey conducted by the American Psychological Association, a significant 79% of workers in the transportation and warehousing sector reported experiencing job-related stress. This shift can be attributed to the increased reliance on technology and the need for employees to adapt to rapidly changing processes and systems.

The rise of e-commerce and the demand for quicker order fulfillment have led to accelerated work places, introducing time pressures and performance metrics as major stressors.

In fact, a study by the National Institute for Occupational Safety and Health (NIOSH) found that warehouse workers were three times more likely to report high levels of stress compared to the general workforce. This surge in mental stress is further supported by a report from the Health and Safety Executive, which revealed that 57% of work-related illnesses in the transportation and storage sector were due to stress, depression, or anxiety.

To address these evolving change, companies are implementing various strategies: training programs focused on stress management and mental health awareness are becoming increasingly prevalent. For instance, companies like UPS have introduced wellness programs and provide access to resources that promote mental well-being.

Furthermore, companies are leveraging technology to monitor and manage employee workloads, ensuring that they are distributed equally to prevent burnout.

Data-driven approaches, such as using wearable technology to track employee movements and monitor fatigue levels, are also being adopted to proactively address potential stressors. Moreover, open lines of communication and regular feedback sessions are being encouraged to provide employees with a platform to voice their concerns and support.

In conclusion, the shift in the type of stress experienced by modern warehouse employees underscores the importance of adapting strategies to address these evolving challenges. The adoption of technology, comprehensive training programs, ergonomic design, and a focus on mental health are key components in creating a supportive and sustainable work environment. By recognizing and proactively mitigating stressors, companies can foster a healthier, more resilient workforce capable of thriving in the dynamic landscape of the modern warehouse.

5.7.5 Gamification strategy

In the pursuit of increase worker productivity and alleviating stress, a study [34] explores a gamification approach for employees.

The study envisions a future where warehouse workers integrate their smartphones, wearables, and AR/VR devices into the Internet of Things (IoT) ecosystem, thereby enhancing human-to-machine interaction [35]. Notably, Augmented Reality (AR) emerges as a pivotal technology for the warehousing domain, enabling interactive work processes with reduced errors [36].

This, in turn, simplifies and enriches the daily tasks of order pickers, creating a more enjoyable and less stressful work environment.

Simultaneously, the implementation of a Gamification module promises to revolutionize the work experience by allowing managers to establish a gaming environment, complete with competitive scenarios for employees to partake in. The authors advocate for the development of scenarios cantered around the key efficiency indicators of order picking—specifically, time and accuracy. Under this framework, each accurate collection translates to points added to the picker's gamification profile, while errors, such as the retrieval of incorrect items or incorrect quantities, result in point deductions. Warehouse managers can leverage these fundamental elements to construct diverse scenarios, tailored to individual employee goals or based on periodic leaderboards, thus offering exclusive recognition to the highest-performing pickers over a specified duration.

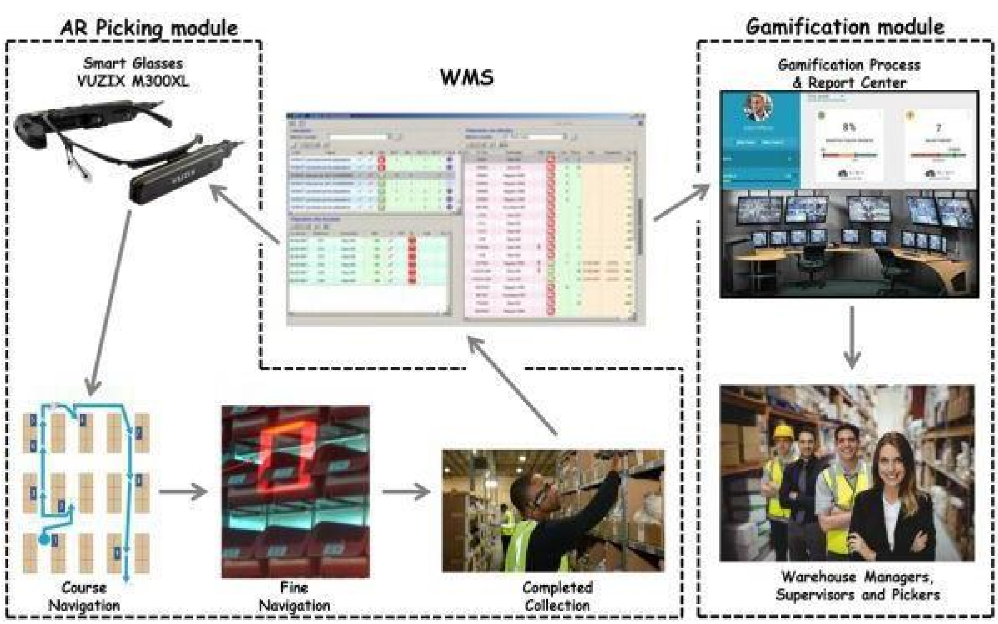

Figure 67. Gamification study (George Plakas et all. 2020)

Real-world companies have demonstrated the remarkable impact of gamification strategies on warehouse productivity and employee engagement.

Amazon has pioneered the integration of gamified elements into its operations. Notably, the company introduced the "Amazon Picking Challenge," a competitive platform that encourages innovation in automated order picking. This challenge involves creating a competitive platform where participants, including employees and external partners, work on innovative solutions for automated order picking. Participants develop and showcase robotic systems capable of efficiently and accurately picking items from warehouse shelves. This gamification approach not only encourages technological innovation but also fosters a spirit of healthy competition and collaboration among participants. By turning order picking into a competitive event, Amazon improved the collective creativity and problem-solving abilities of participants, resulting in significant advancements in the order picking process.

Figure 68. Gamification interface

Another company that has effectively implemented gamification strategies in the warehouse environment is Alibaba Group. Alibaba's gamification approach in its warehouse operations is applied through interactive virtual simulations designed to replicate real-world scenarios. Employees engage with these simulations using specialized software or applications on devices like tablets or computers.

In the "Double Eleven Warehouse Management Game," employees participate in a virtual environment that mimics the tasks and challenges they encounter in the actual warehouse. This includes activities such as order picking, sorting, and packing. The game is designed with elements of competition, encouraging employees to complete tasks accurately and efficiently within a specified time frame.

As employees progress through the game, they accumulate points or rewards based on their performance. These rewards can range from recognition within the company to tangible incentives like bonuses or prizes. Additionally, the game may include leader boards that showcase top performers, fostering a sense of

achievement and healthy competition among employees.
By immersing employees in these virtual simulations, Alibaba provides a dynamic training experience that not only enhances technical skills but also cultivates a collaborative and competitive spirit within the workforce. This gamified approach effectively bridges the gap between theoretical knowledge and practical application, ultimately leading to improved warehouse efficiency and employee satisfaction.
In both cases, gamification is applied through specialized software or applications that create interactive virtual environments. Employees engage with these simulations on devices like tablets or computers. By incorporating game-like elements such as competition, rewards, and leaderboards, both Amazon and Alibaba effectively enhance technical skills, teamwork, and performance in their respective warehouse operations. This gamification approach bridges the gap between theoretical knowledge and practical application, resulting in improved warehouse efficiency and a more engaged workforce.

5.7.6 Job satisfaction

Going to the ending of this chapter, it is essential to recognize the concept of job satisfaction.
Job satisfaction refers to the contentment and fulfillment employees derive from their work, encompassing various aspects such as tasks, environment, and overall work experience. In the context of the modern warehouse environment, job satisfaction plays a crucial role in determining employee morale, engagement, and overall productivity.
The Harvard Business School survey provides valuable insights into the evolving job satisfaction levels of modern warehouse employees compared to their counterparts in the past. According to the survey, a significant 68% of workers reported increased job satisfaction with the integration of automation in warehouse operations. This surge in satisfaction can be attributed to the perception that automated tools not only enhance performance on discrete tasks but also liberate valuable time for more intellectually stimulating work. A compelling case in point is Thierry, a supervisor in France, who lauds the transformative impact of automation on his role. He highlights that with automation handling routine tasks, he now intervenes only in the event of technical issues, rendering his role more engaging and less monotonous.
Beyond individual testimonials, concrete data from various companies further supports this positive shift in job satisfaction. For instance, global logistics provider DHL reported a 25% increase in employee satisfaction scores following the implementation of automation technologies in their warehouses. This improvement is attributed to employees having more time to focus on value-added tasks that require problem- solving and critical thinking skills.
Moreover, academic research underscores the correlation between job enrichment through automation and heightened job satisfaction. A study published in the ‘’Journal of Operations Management’’ revealed that in warehouses where automation was effectively integrated, employees

reported a 15% increase in overall job satisfaction scores.

The study emphasized that the reallocation of repetitive tasks to automated systems allowed employees to engage in more challenging and fulfilling responsibilities, leading to enhanced satisfaction levels.

In light of these findings, it is evident that the introduction of automation in modern warehouses has significantly contributed to improve job satisfaction among employees. The ability to engage in more stimulating work, coupled with the reduction of repetitive tasks, has not only increased overall job satisfaction but has also fostered a more motivated and engaged workforce. This shift not only benefits individual employees but also translates into enhanced operational efficiency and performance for the companies embracing automation in their warehouse environments.

Conclusions

Starting from the foundational understanding of warehouse infrastructure and scope a trajectory guided by the exploration of the KPIs has been then considered. This part has equipped the reader with a comprehensive framework and clear objectives to navigate through the subsequent chapters.

Followed by the analysis of the innovative systems for the modern warehouse, the reader has had the opportunity to gain a panoramic view of the diverse technological solutions available nowadays on the market and in the literature revies as future application. This overview also gave the stakeholders the right instruments to select systems customized to specific functions across the intricate logistics chains within the warehouse.

The conclusion from this analysis is the clear trajectory toward greater automation and sophistication in warehousing operations. This trend is not only notable in research works but is also reflected in market dynamics. Investments in innovative warehouse technologies have been largely done by the most important companies in this sector, mirroring the heightened interest and confidence in the transformative potential of these advancements.

Turning the attention to the various components of the warehouse, it becomes evident that each parts plays a crucial role in the overall efficiency and functionality of the system. From storage units designed to accommodate a diverse range of items, to the intricate web of automated systems orchestrating operations, every component forms a vital piece of the overall puzzle. The optimization of these components, in tandem with the integration of advanced technologies, culminates in a paradigm shift that promises to redefine the landscape of warehousing in the digital age.

In the exploration of innovative solutions, particular emphasis was placed on the concept of automated storage and retrieval systems (AS/RS). These stand as the vanguard of technological progress in modern warehousing.

Their integration offers a dual promise: space optimization and a quantum leap in technological advancement. The capacity of AS/RS to efficiently utilize vertical space, coupled with their precision in retrieval, heralds a significant step forward in warehouse functionality. By leveraging these systems, businesses can achieve unprecedented levels of storage density, thereby liberating valuable floor space for other critical operations.

Additionally, the research analyzed the world of goods storage algorithms, a fact that can bring immense potential for maximizing hardware solutions. The marriage of sophisticated algorithms with state-of-the-art hardware lays the foundation for a harmonized and highly efficient warehouse ecosystem.

Through an in-depth examination of various storage strategies, it becomes evident that the orchestration of both software and hardware elements is needed to enhance the full potential of warehouse operations. The conclusion is that to attain optimal output, a synergy of software intelligence and innovative hardware must be always considered and implemented.

Among all the innovations considered, two have emerged as particularly promising: Autonomous Guided Vehicles (AGVs) and Autostore. It is worth noting that AGVs and Autostore are not disparate technologies, but rather, distinct applications that exemplify the versatility of automated solutions in modern warehousing. The profound impact of these technologies extends beyond mere automation; it signifies a paradigm shift towards a fully integrated, streamlined, and responsive warehouse ecosystem.

The analysis has revealed that the realization of fully automated solutions is no longer ideal, but instead, it stands as a tangible and achievable reality in contemporary warehousing.

The fusion of AGVs and Autostore systems exemplifies a harmonized interplay of advanced hardware, sophisticated software, and human oversight. The result is an environment where every components of the warehouse functions in connected.

The significance of this evolution is not only confined to the present but extends towards an even more promising future. This trajectory is emblematic of an industry that is not content with stagnation, but rather, is in continuous changing and evolution to progress and innovation.

Additionally, it is imperative to acknowledge the promising trajectory of software technologies, notably Artificial Intelligence (AI) and neural networks. While still in the earlier stages of adoption within the warehouse environment, their potential is boundless. These technologies stand poised to revolutionize not only how we manage and optimize warehousing operations but also how we glean insights from vast troves of data.

Nevertheless, this landscape of automation and technological advancement, the crucial role of humans cannot be overstated. Their engagement and collaboration with the technology form the cornerstone of a successful modern warehouse. It is the integration of human expertise with technological capabilities that enhance the warehouse of the future towards its level of productivity and innovation.

Preserving the centrality of the human element is not just a matter of operational necessity, but also a fundamental ethical duty. Ensuring the well-being of workers, both in terms of mental well- being and physical safety, is crucial.

Beyond the realm of operational efficiency, it is crucial to highlights the role of the modern warehouse in contributing to sustainability efforts. The convergence of advanced technologies, efficient resource management, and circular economy principles draws a promising picture. From optimized energy consumption to the management of resources, the modern warehouse emerges as an element of environmentally conscious practices. This trajectory is poised for further refinement and expansion, heralding a future where warehouses not only function as hubs of commerce but as exemplars of responsible resource stewardship.

In summation, this thesis went on a transformative journey through the world of modern warehousing, revealing a landscape marked by technological innovation, collaboration, and ethical imperatives.
Looking ahead, the horizon of warehousing promises an evolution towards even greater efficiency, sustainability, and operational excellence.
The future is characterized by a landscape where humans and technology cooperate in harmony, working in tandem to achieve unprecedented level of productivity.
The thesis concludes as a testament to the promising potential of the warehouse of the future an ecosystem where ingenuity, technology, and humanity converge to redefine the very essence of excellence.

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