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Master Thesis

A New Decision Making Tool for Automated Industrial Storage Systems Selection

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Abstract

Rising customer expectations asking for highly customized products and short delivery lead times is putting under great pressure production and logistic systems, which are forced to become more flexible and reactive to demand requirements. On the market a wide range of options is present and new solutions are continuously introduced. This work thesis is divided in two main steps. First, after a general academic introduction on warehousing and storage systems, a thorough analysis of all the existing storage technologies for both pallet unit loads and small unit loads is conducted, in order to gain insights into the alternatives currently available and to highlight their strengths and weaknesses. Especially as far as light loads are concerned a big variety of possibilities are present, but, despite the key role that the appropriate storage and retrieval system plays in determining warehouse performance, academic research on storage system selection is scarce and a large gap exists between academic literature and the practice of warehouse design. This thesis aims at filling such a gap by providing warehouse and distribution center managers a practical tool assisting them in the decision making process of selecting the most appropriate small loads automated storage and retrieval system through the Analytic Hierarchy Process (AHP). Seven evaluation criteria (throughput, picking accuracy, scalability, storage and retrieval interference, flexibility in product dimensions, space utilization, picking ergonomics) are used to prioritize eight different automated storage systems for small-sized unit loads (miniload AS/RS, horizontal carousel, vertical carousel, vertical lift module, automated vehicle S/RS, robot-based compact S/RS, robotic mobile fulfillment system and A-frame). Providing that the classification of alternatives with respect to each evaluation criterion is conclusive, decision makers only attribute the weight to each criterion according to their specific requirements. The developed multi-criterion decision aiding (MCDA) tool returns a ranking of the analyzed systems indicating their degree of appreciation. Such result can be used by the decision-maker as a starting point in the best storage system selection process.

Keyword: warehousing; warehouse automation; automated order picking systems; automated storage and retrieval system; Decision making; AHP analysis;

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Introduction

Background

Before the 1950s, logistics was only intended in military terms. It was about procurement, maintenance, and transportation of military facilities, materiel, and personnel. First researches on logistics only emerged in the 1960 as a consequence of the prolonged economic growth following World War 2. In those years, logistics costs were extremely high, to the extent that physical distribution was considered one of the "most sadly neglected and promising areas of American business" (Ballou et al. 2007).

One of the most critical activities within logistic is warehousing. According to Hompel and Schmidt warehousing is defined as a planned process to bridge distance and time between production and consumption, seeking for logistic optimization (Hompel and Schmidt, 2007).Nowadays the relentless inflation of e-commerce sales volume (Statista, 2020 [1]), forces companies to store millions of unique items and handle large and variable daily order volumes. On the other hand, walking around the warehouse looking for items to retrieve is the most laborious and expensive process, and it is repetitive, often suffers from poor ergonomics, and requires high-quality labor willing to work in shifts, often difficult to get. In addition, the land available for warehouses (which should preferably be close to the demand points) has become scarce, and many warehouses have to operate 24/7 (Azadeh et al., 2019A). Furthermore, online retailers are facing new needs and rising expectations of customers especially in terms of tight delivery schedules and large assortment and product range (Boysen et al., 2019). Together, these factors have given an enormous boost to storage and retrieval automation. To cope with this challenging situation the trend is to outsource complex logistic services and large parts of the logistic operations to Third Party Logistics (3PL) provider. Quoting X. Guo and S. Wu. “Third part logistic is the best way to reduce the cost and enhance the core competence of manufacturing enterprises. It is called the “third profits headspring" (Guo and Wu, 2014).

Warehousing, if properly managed, highly affects all other logistic operations, and can become source of competitive advantage (Richards, 2018). It is for this exact reason that warehouse automation is becoming increasingly popular, because it allows to achieve increased service levels, reduced operational costs, improved picking accuracy and the ability to cope with future business growth.

Purpose

This thesis work wants to express the added value that automatic storage systems can offer to different businesses regardless if they are performing warehouse, distribution or manufacturing operations. After presenting the available automatic storage systems offered today and their working principle, focus is on the selection process, how to choose the most suitable option for a specific application. In fact, selection of appropriate storage systems has an incredible impact on operating costs and performance throughout the whole lifespan of a warehouse (Shah & Khanzode, 2015). Thompson claims that material handling activities account for up to half of the total operating expenses and up to 95% of order processing time (Thompkins, 2010). Despite its importance, the problem of storage system selection is little to not considered at all in the literature and in paragraph 1.7 such research gap is thoroughly illustrated.

For this reason on the one hand the present thesis provides a complete and detailed overview of the automated storage systems today available, and on the other hand it fills the research gap offering a practical tool for the selection of the most appropriate small load automated storage system depending on the specific application. Such selection and evaluation process is performed using the Analytic Hierarchy Process method (AHP). Finally, it applies the developed decision making tool by analyzing a real case study and comparing the results coming from the tool with the actual storage solutions which were implemented.

Thesis outline

Chapter 1 starts with introducing the basic concept of warehousing and providing an outline of the typical activities and flows of a warehouse. Before dwelling specifically on automatic storage systems, picking systems in general are presented and a rigorous classification is reported. Focus then shifts to automatic storage systems, core of the thesis, analyzing the main types one by one. After a literature review on the topic, the last paragraph is dedicated to the identification of the research gap.

After discussing the characteristics and working principles of the most popular automated storage systems, in Chapter 2 the various products offered by the main material handling and storage system suppliers are analyzed and compared.

Chapter 3 deals with the Analytic Hierarchic Process (AHP) method which is used to actually aid the warehouse manager in decision making process of selecting the appropriate automated storage system for small unit loads. After an introduction on this multi criteria decision making process, its working principle is illustrated. The seven criteria considered most influential for the selection of the automatic storage system are outlined. Then, in order to quantify the relative importance of the different criteria, reference was made to a real case study, namely the recent development by Dematic of a new Shimano warehouse in the metropolitan city of Sydney. Finally, the results of the AHP analysis are presented and the reliability of the software is confirmed by the consistency of the results with the system actually implemented by Dematic. This thesis therefore contributes to the existing literature in the warehouse automation stream by providing a simple analytical aid to the decision making process.

1. Warehouses and Storage Systems

This chapter gives the theoretical foundations of the present master thesis, starting with a presentation of warehouses and analyzing its benefits, typical activities and material flows. Then the recent trend towards deeper automation is examined. In addition, given the actuality of the COVID-19 pandemic and the radical changes that have become necessary to cope with it affecting every aspect of our lives, possible implications of COVID-19 on warehouse activities are outlined. Next, automated storage systems are introduced along with a classification of all the alternatives currently available on the market. Finally, a review of the literature helps to clearly define the research gap that will be addressed in the thesis and consequently the purpose of the entire work is outlined.

1.1 The concept of warehousing

Warehouses are the physical link between producers and consumers. Although term warehousing easily takes on a negative connotation, because of non-value-adding activity, time waste and high costs, in practice there are several reasons compelling companies to store some amount of their goods and implement a warehouse (Hompel and Schmidt, 2007):

- *Optimizing the logistic performance*: first customer concern is promptness of delivery. Since the exact timing and quantity of orders entry can only be estimated, for the vast majority of goods the unique solution is keep a minimum number of pieces in stock, ensuring the readiness to deliver. This process is even more legitimate in case of large distances between the site of production and consumption.

- *Ensuring the productivity*: Production chains designed for JIT delivery, thus managing minimum stocks, are highly sensitive to disturbances, stock keeping helps ensuring a continuous flow along the whole supply chain.

- *Providing additional services*: Due to the constant increase in the product range, one solution to achieve low costs is to finish the possible variants at the last moment available.

- *Reducing transport costs*: Stock keeping offers the advantage of reducing transportation cost by optimally exploiting the loading capacity. Typically, it is much more convenient to handle a small number of big loads rather than a big number of small loads.

- *Balancing required and delivered quantities*: Global market has clearly shifted to a demand-driven production (pull system), but still many industries have to produce in advance appropriate lot sizes, in order to face events like seasonal fluctuations or to avoid idle times between one workstation and the following.
- *Warehousing as a process step*: For some products or processes warehousing represents an elementary value-adding process (e.g., by maturing of speculative intent) and thus becomes part of the production process.

Very often warehouses have evolved to become distribution centers. The latter are not simply the last point in the supply chain before reaching the customer, but they can operate as *cross-docking points*. Supply-chain distribution centers can offer *value-added services* (e.g. packaging, pricing, labelling cross docking), can ensure that all goods entering the warehouse leave on the same day, without occupying shelf space (especially useful in case of fresh goods or goods with rapid perishability) , or finally they can operate as *management points for the post-production phase* , as points for return management (management of defective or end-of-life product return lines).

Distribution centers are today under great pressure to comply with cost and service requirements. To introduce some figures from *LogisticsIQ*, it is record that in terms of costs, distribution centers represent about 20% of the total cost of logistics, while in terms of services, they are crucial to achieving customer satisfaction (Dhooma and Baker, 2012).

1.2 Warehouse activities and flows

Inn today economy, warehousing is crucial to support the success of a company's supply chain. In a general warehouse, the process of getting goods in and out, requires several functional areas and five main activities can be highlighted. Figure 1.1schematically illustrates the order in which operations are generally performed, namely *receiving*, *put-away and storage*, *order picking, sortating and accumulation* and finally *packaging and shipping* (Hompel et al., 2007).

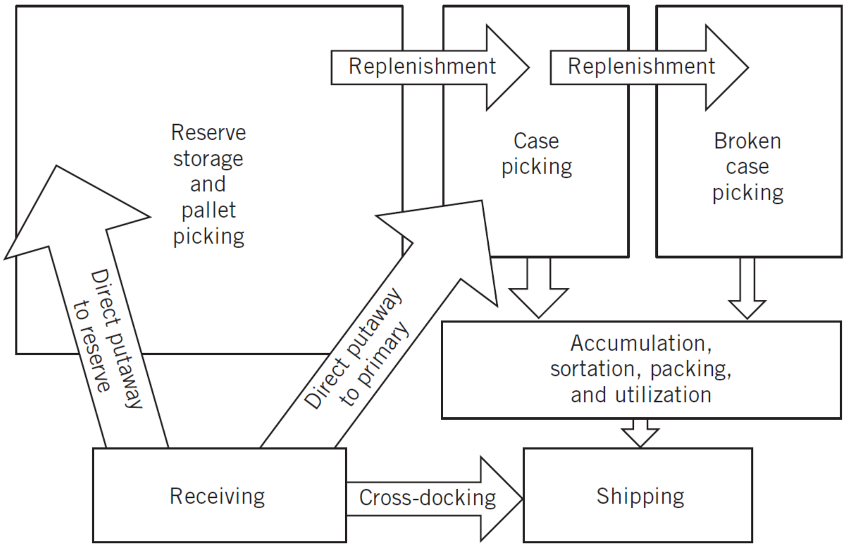

Figure 1.1 Typical warehouse functions and flows (Tompkins et al., 2010)

Receiving is the first activity performed, it starts with the arrival and unloading of goods incoming from the supplier. Afterwards, it is usually required an inspection and quality control, to assure the quantity and quality of materials are as requested, simultaneously the inventory records are updated. Another activity that can be considered as an extension of the receiving process is repackaging. Especially when products from a supplier come in bulk, it is often convenient to pack them singly before storing to facilitate later retrieval (break bulk mode). The next operation is materials storage or delivery to other departments within the firm that need them.

Put-away is the next step, it involves material handling and placement and implies the transfer and placing of goods in the correct storage location. During this phase the most important decision is where and how to store materials, because it heavily impacts on the next activities, such as order picking.

Order picking is regarded as the most essential operation and for this reason it will be carefully discussed later in this chapter (section 1.4). Here order picking can be simply described as the process of retrieving items from storage to meet a specific customer order (Manzini, 2012).

Depending on the picking strategy employed, orders consisting of more than one item usually require *sorting and/or accumulating* items into individual orders. In case of batch picking for example the picked units have to be grouped by customer order, upon completion of the picking process.

Final step is *packaging and shipping*, which other than goods physically leaving the warehouse, may involve a few additional activities such as checking for order completeness, packaging in appropriate parcels or containers, preparing shipping documents and eventually loading the trucks (in many instances, this is a carrier's responsibility).

1.3 Storage assignment policies

Deciding where to store which product is not a simple task, and thorough evaluation of all the different possibilities is vital in order to guarantee satisfactory warehouse performances. The set of rules that define a product storage location, is called *storage assignment policy*. It must take into consideration many factors volumes, routing policy, number of Stock Keeping Unit (SKU) per pick route, and the warehouse size with available locations (de Koster et al., 2007). Special attention must be directed to routing policies. the set of rules that governs the travel paths within the warehouse during the order picking process. These policies determine the picking sequence of the SKU and their optimization is of paramount importance since a reduction in travel distance leads to a reduction in costs and time of the order picking process.

As far as storage assignments methods are concerned a first classification divides them between dedicated and dynamics. In dedicated storage assignment policy, each product is stored in a fixed location. Such a solution offers two main advantages, products can be grouped and placed according to a logical criterion, for example by putting heavier products at lower height and concurrently it helps the order picker to become familiar with product positioning. On the other side each location is reserved even for products that are out of stock and for every single product enough room must be secured so that the maximum inventory level can be stored, thus resulting in the poorest space utilization among all storage assignment policies. In dynamic storage assignment policy, as the name suggests, storage locations are defined dynamically according to one of several methods, from completely random assignment or closest open location assignment, under the closest open location rule, the closest available location to the input/output point is selected for storage. which minimize space requirements, to more complex methods like full turnover and class-based assignment, which considerably improve picking productivity. If implemented correctly, a dynamic storage assignment policy could significantly increase the space utilization and picking productivity (Manzini, 2012).

1.4 Order picking systems

Stoking goods for later use is one goal of automated storage and retrieval systems and it affects many factors including space utilization, storage capacity, product flexibility and selectivity. Automated storage and retrieval systems however accomplish another crucial operation that of order picking, the process of retrieving a small number of products from a storage area to satisfy a number of independent costumer orders (Chackelson et al, 2013). Order picking is the most straightforward way for reducing the picking cycle time while at the same time maximizing the throughput of the system (Manzini, 2012). It is the most labor-intensive operation in the warehouse, in particular order collection covers more than 50% of all warehouse operating costs and has a major impact on the service level (Quader and Castillo-Villar 2018).

Simplest way to perform such operation is to pick one order per picking tour, in other words to process each order individually (Manzini, 2012).

As an alternative to single order picking, it is possible to divide the picking area in zones. Each order picker is assigned to a specific zone and he is asked to pick the part of the order that is in his own zone of responsibility. Zoning offers the advantage that each order picker only moves inside a small area (i.e. the zone he is assigned to) thereby reducing maximum travel distance per pick and traffic congestion. Additionally, order picker can get familiar with items location, thus further accelerating the picking process (de Koster et al., 2007 and Manzini, 2012)

Another organizational policy that is often used when order sizes are small is called batching. It is used when dealing with orders that do not require to be picked individually, in fact whenever orders are small it is possible to reduce travel times by picking a set of orders in a single picking tour. Order batching consists of grouping a set of orders into a number of sub-sets that can be picked together. Batching strategy can be applied following two different criteria namely proximity of picking locations and time windows. In proximity batching, orders are grouped considering the distance between parts. In time window batching orders are grouped considering the time at which they arrived, those orders that arrive in the same time window are batched and then processed simultaneously (de Koster et al., 2007).

Scientific literature provides several distinct methods to classify order picking systems (e.g. de Koster et al., 2007; Van den Berg, 1999). In this thesis the adopted classification suggested by Dallari (Dallari et al. 2009), because the most spread. It is based on four drivers allowing to distinguish between five system categories as depicted in Figure 1.2. The drivers are (i) who is in charge of picking goods (humans or machines), (ii) who moves within the picking area (pickers or goods), (iii) use of conveyors to exchange goods between picking zones, and (iv) picking policy. The five categories that emerge from the classification are picker-to-parts, parts-to-picker, pick-to-box, pick-and-sort, and completely automated picking, ordered with increasing level of automation.

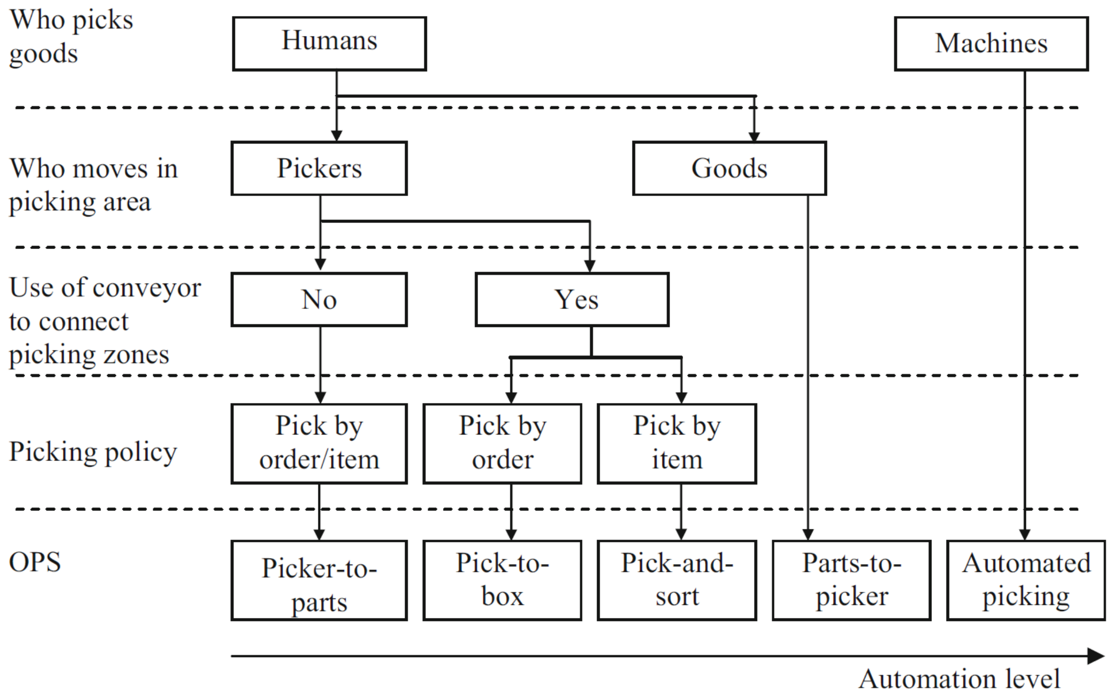

Figure 1.2 The classification of order picking system categories (Dallari et al., 2009)

Picker-to-parts systems are characterized by no automation and they represent the vast majority of warehouse picking systems (Sowinski, 2013; Lahmar, 2008). In such systems the picker walks or drives to the picking location and manually retrieves the item. It is possible to distinguish two types of picker-to-parts systems: low- and high-level picking. In low-level systems, goods are stored in racks easily accessible by the picker while travelling along the aisle. In high-level systems, also called man-on-board order picking systems, items are stored on high storage racks and the picker moves along the aisle on board of an order-pick truck or crane. The crane automatically stops in front of the desired item allowing the picker to manually retrieve it. The mission when designing zones in picker-to-stock systems is to minimize picker travel time.

In *Pick-to-box systems*, the picking area is divided in zones connected by means of conveyors and each area is assigned to one or more pickers. Each customer order corresponds to one picking box and orders are picked sequentially by zone. As soon as all required items from the current zone are collected, the picking box is placed on the conveyor and passed to the next zone. As already mentioned with zoning the criticality lies in properly balancing the workload among the different zones (Dallari et al., 2009). Pick- to-box-systems are to be preferred when dealing with high number of small sized items, medium-sized flows and small order size (Marchet et al., 2014). Bigger orders size result in an excessive number of boxes to be handled and a proper balancing of workload among zones may become very difficult to achieve.

In *pick-and-sort systems* such as the one shown in Figure 1.3, operators retrieve each different item in the amount resulting from the batching of multiple orders and place them on a conveyor connecting the picking area with the sorting area. Once on the conveyor, a computerized system determines the destination bay for each item. Pick-and-sort systems usually work with “pick wave”, meaning that all orders in a given batch must be sorted completely before starting a new one. With respect to picker-to-parts systems, batch size is consistently high (higher than 20 customer orders per pick wave) (Dallari et al., 2009) and this results in picking locations visited less frequently, thus reducing picker travel time and increasing productivity. These systems are to be preferred when dealing with high overlapping of order lines (different orders with many equal items), high picking volume and absence of brittle products.

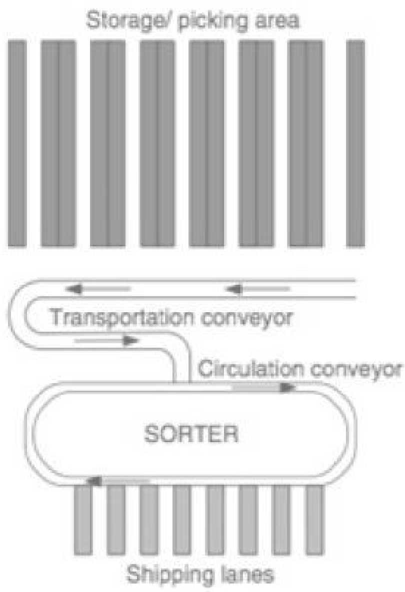

Figure 1.3 Advanced sorting system with circulation conveyor (Koster et al., 2007)

In *parts-to-picker systems*, as the name suggests, an automated machine brings the good from the storage area to the operator who waits in the picking station. The operator is only in charge of selecting the right amount of each item. Afterwards the unit load is brought back by the machine to the storage area. The obvious advantage of these kind of systems derives from the reduction in cost, both in the labor hours component and in the space required, in fact space between aisle can be minimized since only machines are performing picking operations. Parts-to-picker systems are to be preferred when dealing with a large number of items and a small picking volume. Inside this category are those automated systems that can be regarded as the cornerstone of this master thesis, carousels, vertical lift modules (VLM), mini-loads, and automated storage and retrieval systems (AS/RS), automated vehicle storage and retrieval systems and autonomous robotic unit load systems which will be presented in section 1.6.

Last and most technologically advanced category is *fully automated picking systems*. Here the most popular example is the A-frame analyzed in depth in section 1.6.7. In such a system, products are picked automatically, while the storage process is carried out manually, meaning that human operators have to place items one by one in the proper storage location (Azadeh et al., 2019A).

1.5 Automation of storage systems

Before the actual classification of automated storage systems presented in section1.6, this chapter provides an overview on the trend that warehouse automation is following also referring to the COVID-19 pandemic that has certainly imposed new challenges. Afterwards the advantages of warehouse automation are illustrated.

1.5.1 Overview on warehouse automation

Recent fiercer competition and the understanding of warehousing as a source of competitive advantage, put warehouse efficiency under new light. On the one side, warehouses and distribution centers have to comply with Just in Time (JIT) production, meaning that both raw materials and intermediate components must be available at the right place in the right amount at the right moment. On the other side, thanks to the unprecedented increase in adoption of e-commerce, customers require complex product varieties with short lead times and with highly variable demand (Custodio and Machado, 2020 and Boysen at al., 2019).

Warehousing is in general a highly labor-intensive activity so increasing demand asks for new resources, manpower at first, but also equipment and space. Problem is that mature economy countries such as Europe or U.S. need to adjust to an aging workforce with declining technical skills. Furthermore, growing concern for workers' safety and more stringent ergonomics assessments, make it more challenging to rely only on increased workforce to cope with the increased demands on warehousing operations (Thompkins, 2010).

These challenges require more efficient, flexible and agile warehousing management systems and push the logistic industry to move towards innovative technologies. (Azadeh et al., 2019A). LogisticsIQ market research study [3], estimates that the global Warehouse Automation Market will grow more than 2x from $13 Billion in 2018 to $27 billion by 2025, at a Compound annual growth rate (CAGR) of 11.7% between 2019 and 2025, as depicted in Figure 1.4. Furthermore, with increasing focus of retailers to improve the shopping experience of its customers, technology associated with retail is progressing. In particular, the retail industry is expected to grow at the highest CAGR during the forecast period.

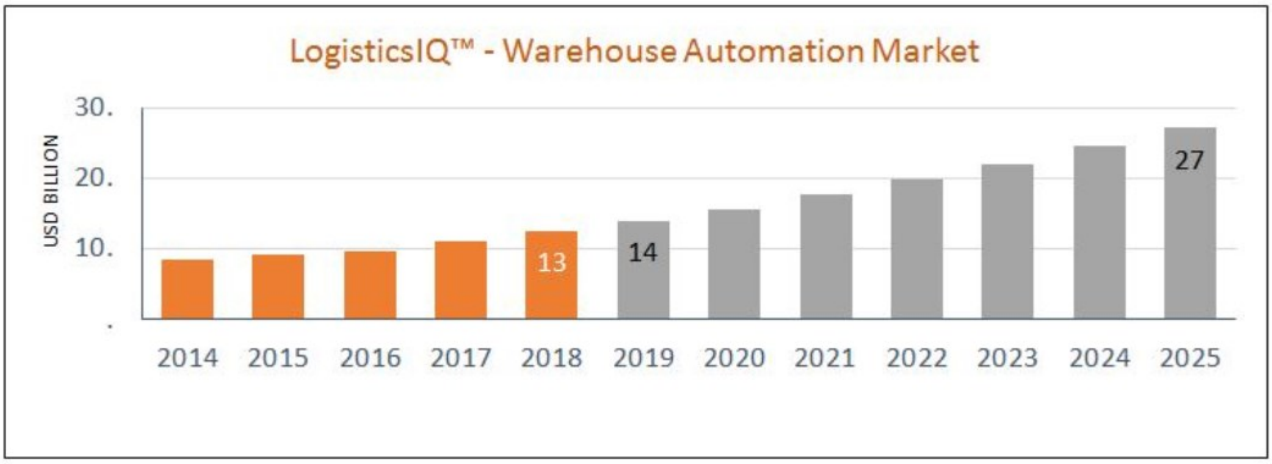

Figure 1.4 Warehouse Automation Market by LogisticsIQ [3]

Despite a generally slowing global economy, the warehouse automation market remains fairly resilient to the macro conditions due to the underlying structural drivers; the phenomenal rise in e-commerce – especially within APAC (Asia-Pacific), the consumer demand for ever shorter delivery times and the on-going labor shortages [4].

Prior to COVID-19 pandemic, McKinsey estimated up to 30% of jobs in the US will be automated and "automation and AI will lift productivity and economic growth, but millions of people worldwide may need to switch occupations or upgrade skills" [5].

A few months after the outbreak, as COVID-19 forces an unprecedented number of workers to stay home, most of the companies have the only choice to turn to automation in order to keep their business running. Thanks to the acceleration triggered by COVID-19, Bain & Company estimates the number of companies scaling up automation technologies will more than double in the next two years [6].

We have yet to see how the global pandemic will impact jobs in the long term and how demand for logistic automation companies might evolve, as well as the timing and pace of their recovery, but it's reasonable to assume that wherever automation is able to ensure both workers and consumers safety, it will undergo a further acceleration.

For sake of completeness, Table 1.1 lists, the key players in logistics automation market by turnover in 2018.

2018 Rank	2017 Rank	Company	Worldwide 2017 revenue (million USD)	Worldwide 2018 revenue (million USD)	Percent change '17-'18	Three-year change	HQ
1	1	Daifuku Co.	3659	4167	13.9%	53%	Osaka, Japan
2	2	Schaefer Holding	3060	3217	5.1%	24%	Neunkirchen, Germany
3	3	Dematic	2267	2350	3.7%	18%	Atlanta, Ga.
4	6	Honeywell Intelligrated	1000	1700	70.0%	124%	Mason, Ohio
5	4	Vanderlande Industries B.V.	1538	1538*	0%	56%	Veghel, The Netherlands
6	5	Murata Machinery, Ltd.	1287	1287*	0%	3%	Kyoto, Japan
7	11	Knapp AG	643	1050	63.3%	64%	Hart bei Graz, Austria
8	8	Beumer Group	900	1000	11.1%	27%	Beckum, Germany
9	10	Swisslog AG	915	923	0.9%	34%	Buchs, Switzerland
10	N/A	Material Handling Systems	N/A	860	N/A	N/A	Mount Washington, Ky.
11	7	TGW Logistics	742	817	10.1%	56%	Wels, Austria
12	12	Witron Logistik	635	637	0.3%	59%	Parkstein, Germany
13	14	Kardex AG	425	478	12.5%	26%	Zurich, Switzerland
14	16	Bastian Solutions, LLC	233	316	35.6%	62%	Indianapolis, Ind.
15	15	Elettric 80	261	272	4.2%	131%	Viano, RE, Italy
16	20	System Logistics	185	225	21.6%	45%	Fiorano, MO, Italy
17	17	DMW&H	225	214	-4.9%	61%	Fairfield, N.J.
18	19	viastore systems Inc.	152	197	29.6%	41%	Stuttgart, Germany
19	N/A	Lödige Industries	188	188	0%	N/A	Scherfede, Germany
20	18	Stöcklin Logistik AG	153	148	-3.3%	N/A	Aesch, Switzerland

Table 1.1 Top 20 worldwide materials handling system suppliers [7]

1.5.2 Benefits and drawbacks

To further stress the benefits coming from automation, Figure 1.5 shows the time components in a typical picker-to-parts warehouse, and it is clearly observable that travel is the most time-consuming activity and it is not simply a waste of time, travel is a non-value added activity, so it leads to unnecessary cost increase as well (Bartholdi and Hackman, 2019).

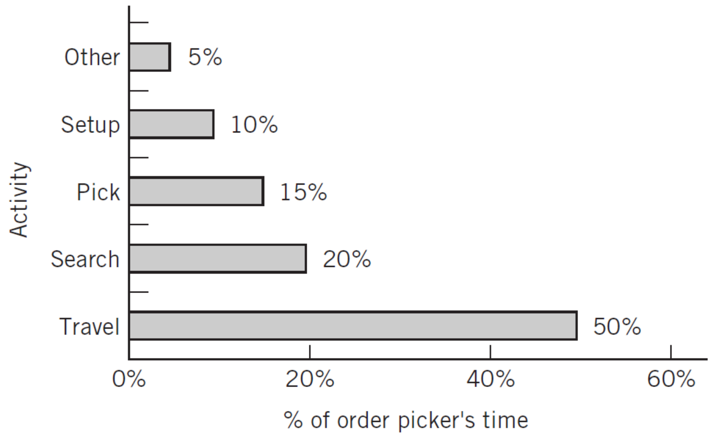

Figure 1.5 Typical distribution of an order picker's time (Thompkins, 2010)

The growing trend towards the introduction of automated systems inside the warehouse lies at first in the need to maximize the service level subject to resource constraints. Service level is a complex parameter made of different factors, order delivery time, order integrity and accuracy, it measures the level, in percentage, to which prefixed goals are achieved (de Koster et al., 2007).

The introduction of an automated storage system in an existing warehouse is expected to lead to numerous benefits. Generally, these benefits are divided into efficiency and effectiveness improvements (Marchet et al., 2014). The most evident *efficiency* improvements are space savings and lower operational costs. Space saving is obtained thorough denser storage and better space utilization, while reduced operational costs result from savings in human labor and better ergonomics (Marchet et al., 2014; Baker and Halim, 2007; de Koster et al., 2007). Improvements on *effectiveness* are enhanced storage and picking accuracy and quicker process times, which result in improved service levels (Baker and Halim, 2007; Marchet et al., 2014). One main goal is that of maximizing picking speed, because the faster an item is picked, the sooner it can be shipped. Faster picking also allows for greater flexibility in handling late changes which is unquestionably source of competitive advantage (de Koster et al., 2007).

Even with a low level of automation it is possible to achieve great benefits, but it is evident that as the automation level increases so do the benefits. Decreasing human involvement, the automatic system becomes less prone to errors and more accurate (Dukic et al., 2015; Hamberg and Verriet, 2012; Koster et al., 2007), concurrently the less workers are involved the safer will be the workplace because unlike humans machines are highly predictable and risk of accidents declines (Baudin, 2005). Baudin (2005) stresses one more advantage associated to warehouse automation, that automated systems do not require as much labelling, scanning and administrative work as manual systems do. Advantages of automation cannot all be catalogued in efficiency and effectiveness, De Koster (2007) claims that automated systems tend to improve constantly, for example by applying dynamic storage, they can rearrange goods overnight.

Despite the compelling list of advantages, automated systems also present drawbacks. The main problem is certainly related to the high investment required before even starting the business, and the second big barrier is the lack of flexibility especially in terms of product variability and peak demand due to their cognitive and motor skills (Grosse et al 2017). Additionally, the area of application of these systems can hardly be comparable to that of manual systems where the operator can easily change tasks from one day to the next, handling different volumes and different types of SKUs. The combination of these two factors becomes a real barrier and therefore many plant managers continue to favor manual storage systems (Baudin, 2004; Marchet et al., 2014).

Finally, another factor that makes the adoption of an automated warehouse complicated is the risk of failure. In the event of failure the system cannot run automatically, nor it can be operated manually, so the whole plant comes to a halt. In case the automated system is installed retrospectively, then the concern is that the plant needs to stop for the whole time of installation of the new equipment (Marchet et al., 2014).

1.6 Classification of automated storage systems

In the broadest sense, automated storage systems can be defined as a combination of equipment and controls which automatically handle, store and retrieve materials with great speed and accuracy, without direct handling by a human worker (Linn and Wysk 1990; Manzini et al. 2006; Lee et al. 1996).

More specifically these systems store and retrieve full unit loads from the storage area and bring them to the picking stations, being them usually of the parts-to-picker category, where pickers extract the required amount of each item. Subsequently, the unit loads are conveyed back to the storage area before the next load is retrieved. Since the operator does not need to retrieve the items, the picking time can be shortened and the ergonomics for the picker improved and same thing applies for storing operations. (Arnold et al., 2008).

Figure 1.6 categorize the major automated storage systems available on today market.

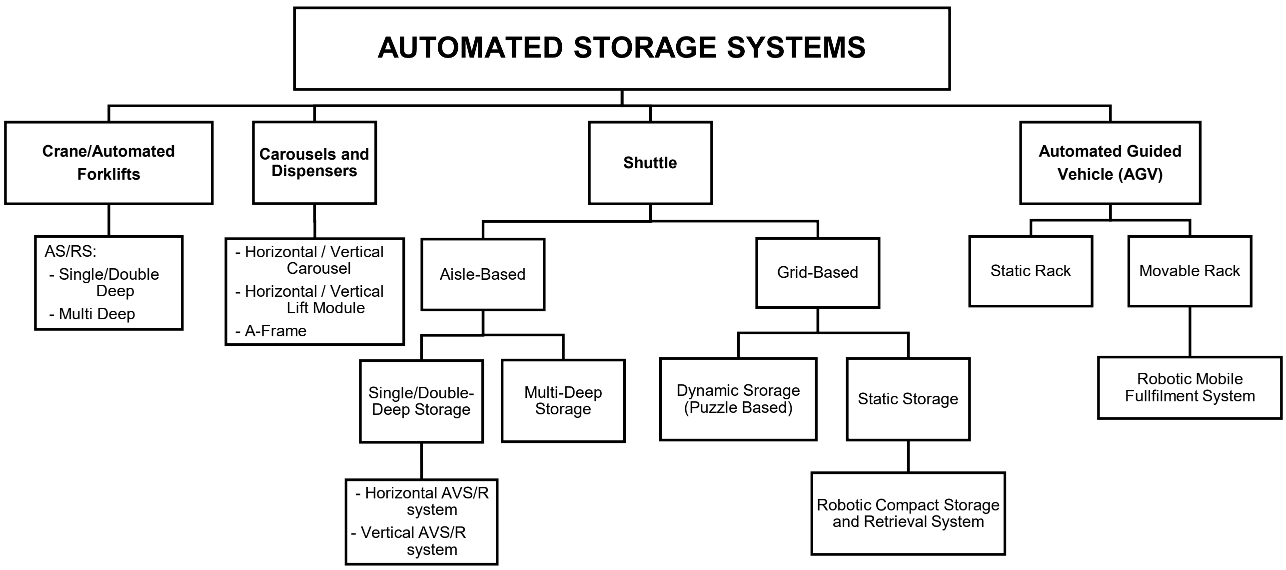

Figure 1.6 Classification of Automated Storage Systems (Modified after Azadeh et al., 2019A)

1.6.1 Automated Storage and Retrieval Systems (AS/RS) and Miniload Systems

The term automated storage and retrieval system can cover a huge variety of systems with varying degrees of complexity and size, so that some scientific papers (Manzini, 2012), the Material Handling Industry of America [2] and most material handling equipment suppliers' [8,9], use AS/RS as synonym of parts to picker system. In academic literature however, AS/RS has come to mean a single type of system, a storage system that uses fixed-path storage and retrieval machines running on one or more rails between fixed arrays of storage racks (Material Handling Institute of America) [2].

The main components of an AS/RS are racks, cranes, aisles, I/O-points, and pick positions are shown in Figure 1.7. Racks are typically metal structures with shelves on which loads (usually pallets) can be stored. Aisles are defined as the empty space in between two racks, where cranes can move. Cranes are fully automated machines, equipped with forklifts or other forms of piking device, able to travel along the aisle both in horizontal and vertical direction to store or retrieve loads. Finally, an input/output point (I/O-point) is the location connecting the storage area and the incoming/outgoing materials area, it is where retrieved loads are dropped off and where incoming materials are picked for storage. (Roodbergen et al., 2009)

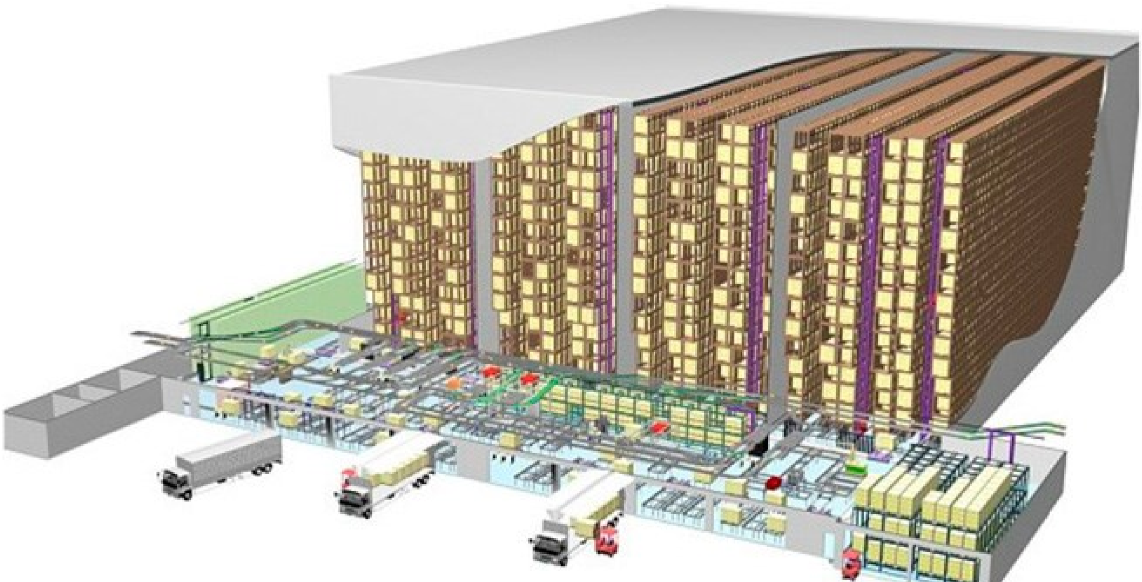

Figure 1.7 Automated High-Bay Warehouse for Pallets with Aisle-Captive Cranes (De Koster 2015)

To perform a storage operation, a crane picks up a load, usually from a conveyor, and stores it in the 30- to 40-m-high racks. Driving and lifting in the aisle take place simultaneously. The process sequence is reversed for a retrieval operation. (Azadeh et al., 2019A)

Roodbergen et al. (2009) provides the most exhaustive analysis on AS/RS and they state that the usage of AS/RSs has several advantages over non-automated systems. Examples are savings in labor costs and floor space, increased reliability, reduced error rates and improved product security for premium inventory. Most evident disadvantages are high investments costs (approximately $634,000 for a single aisle AS/RS, Zollinger, 1999), reduced flexibility and higher investments in control systems (about $103,000, Zollinger, 1999).

Several types of the AS/RS can be distinguished and as depicted in Figure 1.8 three drivers are needed for this purpose crane motion, picking methods and rack motion.

The simplest version of an AS/RS has cranes which are not able to move from one aisle to the other (*aisle captive*) so that there must be one crane per aisle, and each crane can only transport one unit-load at a time (*single shuttle*). In this basic version racks are stationary and single-deep, meaning that each unit load is directly accessible. This type of AS/RS is known as single unit-load aisle-captive AS/RS.

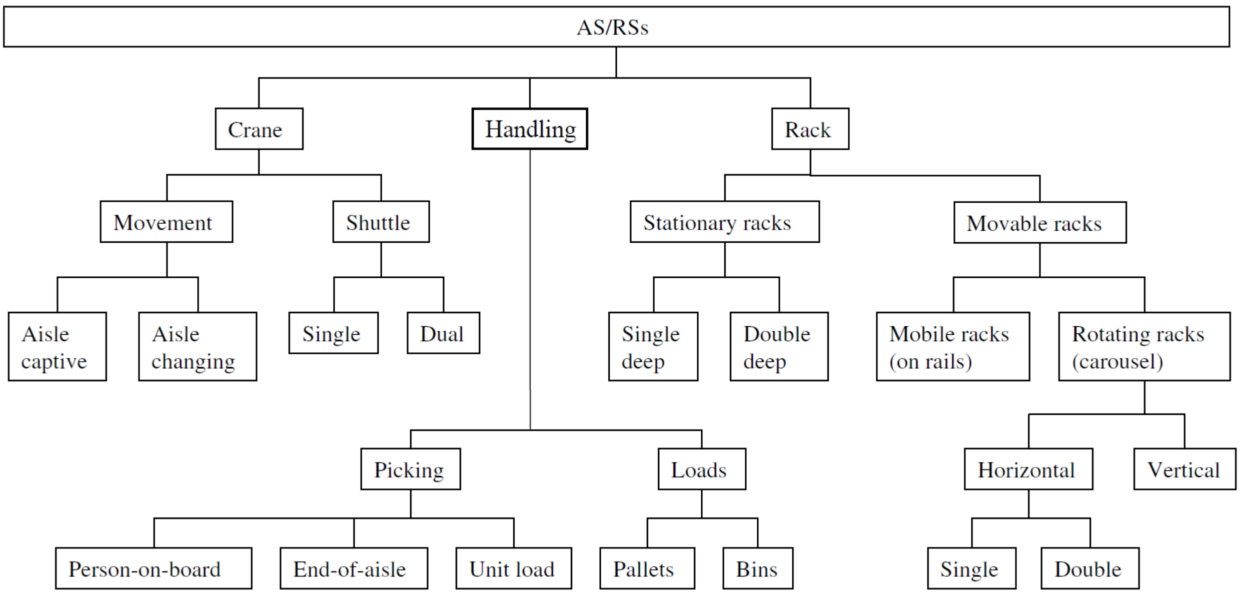

Figure 1.8 Classification of various AS/RS system options (Roodbergen et al., 2009)

In case cranes are able to move among different aisles (*aisle changing*) their number can be inferior to the number of aisles allowing for an investment reduction. To overcome the restriction of the crane's unit-load capacity, *multi-shuttle crane* may be adopted, such cranes can transport two or more loads at a time. The machine picks up a load at the I/O point, travels loaded to an empty location, deposits the load, travels empty to the location of the desired retrieval, picks up the load, travels loaded to the I/O point, and deposits the load.

In many cases, however, only part of the unit-load may be needed to fulfill a customer's order. This can be solved by having a separate picking area in the warehouse; in such a case the AS/RS serves to replenish the picking area. An alternative solution is that of integrating the picking operation with the AS/RS. For example, the most popular solution to integrate item picking is the crane picking the whole loads and bringing it to the workstation where the picker manually takes the correct number of items, the crane then brings back to the storage location the load with the remaining items. This system is called end-of-the-aisle. An alternative is a crane that allows an operator to ride along (person-onboard), this way the operator picks the correct number of items without even moving the load from its location.

If dealing with small items suitable to be stored in small plastic bins, totes or trays then the system is called a *Miniload AS/RS* (Figure 1.9). In those systems racks can typically be very high up to 25 meters and aisles extremely narrow, often marginally wider than the Miniload itself, they usually range between 850 and 1500 mm (Bartholdi and Hackman, 2019).

Figure 1.9 Miniload System (Dematic RapidStore ML on the left [12], Daifuku MiniLoad on the right [11])

When the variety of loads stored in the system is relatively low, throughput requirements are moderate to high, and the number of loads to be stored is high, it is often beneficial to store loads more than one deep in the rack (*Double-Deep* or *Multi-Deep*). In a double-deep rack, each rack location has space for two unit-loads; one load is stored in front of the other load. A load can only be put into or retrieved from the second position if there is no load in the first position.

The AS/RSs are typically used in applications where volume of loads moved in and out is high, space constraints make storage density a critical factor, no value adding activity is present in this process, and whenever the accuracy is crucial in order to prevent potentially costly damages to the loads (Manzini, 2012). Under such circumstances, most applications of AS/RS technology have been associated with warehousing and distribution operations, but AS/RS can also be used to store raw material and WIP in manufacturing.

1.6.2 Carousel

A carousel is made of a single I/O point and a series of carriers or racks attached to a chain drive and moved by a motor unit (Bartholdi and Hackman, 2019). When an item is requested, the chain rotates until the appropriate rack is presented in front of the operator waiting, usually to speed up operations in modern systems an integrated lighter will indicate to the picker which item to pick (*pick-to-light systems*). To reduce the retrieving time the chain can rotate in both directions (Vickson, 1996). In order not to waste time when the carousel is rotating and preparing the rack with the next item, each piker is usually assigned from 2 to 4 different carousels grouped together and called pods (Bartholdi and Hackman, 2019).

For specific demand patterns carousels can provide very high pick rates, in fact a carousel moves entire racks thus presenting to the picker a set of different items, if those items were stored correctly several order lines can be completed without any changeover (Arnold et al., 2008). Carousels also ensure high storage density (Manzini, 2012), since there is no relative motion among shelves and no picking machine is required, as in the case of the crane for AS/RS, all the space within the closed system is exploited for storage. With respect to the Miniload systems presented in section1.6.1, carousels are generally cheaper and more flexible in product dimensions (Manzini, 2012). Flexibility is assured by the rack shelves that can be divided into various size compartments according to need (Vickson, 1996).

The main limitation of carousel systems is that, being single I/O point, in case of high and unpredictable demand they perform poorly because it is not possible to speed extraction by assigning additional workers to a carousel. Furthermore, as more product is picked from a carousel, it becomes necessary to restock it more frequently and both tasks must be done by the same worker. This interleaving of picks and restocks can retard the rate of picking and reduces the ability of the warehouse to respond to surges in demand (Bartholdi and Hackman, 2019). A second limitation is again related to the low flexibility in case of varying demand, because it is not possible to increase nor reduce the number of racks (Arnold et al., 2008). Carousels systems are suitable if dealing with low to medium weight goods, high number of SKUs and continuous demand with low variations (Arnold et al., 2008).

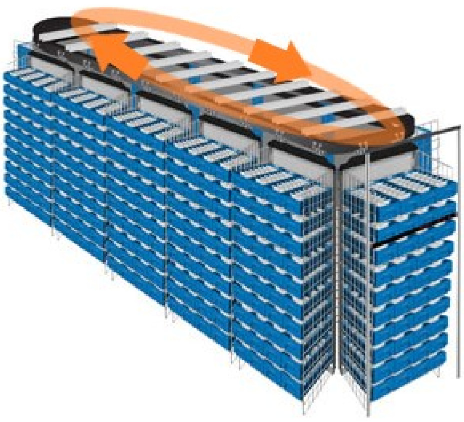

Figure 1.10 Comparison of a vertical and a horizontal carousel [2]

Mainly two types of carousels are available depending on the direction of rotation, horizontal and vertical as illustrated in Figure 1.10.

In horizontal carousel, each carrier is made of bins arranged one on top of the other and the rotation allowed by the chain or belt on top of the system takes place horizontally, around an axis perpendicular to the floor. Their height rarely exceeds 7m due to the need of the picker to access all the items, regarding the length the longer the carousel the more time, on average, is required to retrieved a desired item and it generally ranges from 4 m up to 30 m. (Thompkins, 2010).

Vertical carousel rotates vertically around an axis parallel to the ground. Motion is provided by rotating chain or belt on one or both side of the carousel module. This kind of system offers the big advantage of always presenting items at the optimal height (i.e. picker waist level) and this results in reduced cycle time and improved accuracy with respect to the horizontal counterpart. On the other hand, since vertical carousels move against gravity, they generally rotate slower (indicative carousel rotational speed values range from 8 meters per minute up to 25 meters per minute) and are more expensive due to the extra power required. (Thompkins, 2010)

One final concern related to vertical carousels is weight distribution, if not taken into account the system may become imbalanced as shown in Figure 1.11.

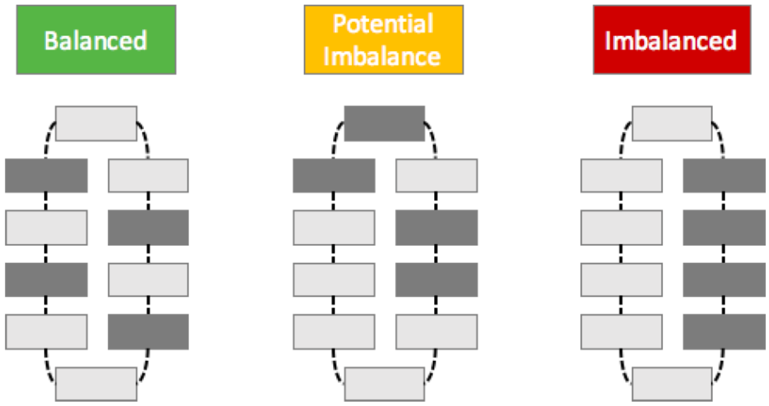

Figure 1.11 Weight imbalances in a carousel, ranging from balanced to highly imbalanced (based on Industore, 2016).

1.6.3 Vertical Lift Module

Vertical Lift Module (VLM) can be seen as an upgrade to vertical carrousel, here items are stored vertically on trays (Dukic et al., 2015). As shown in Figure 1.12 a VLM consists of two columns of trays with a lift mounted inserter/extractor in the center. When an item needs to be retrieved (Figure 1.13), the inserter/extractor moves in front of the tray in which the desired item is located and moves the whole tray in front of the picker, who is waiting at the I/O port like in carousel systems (Azadeh et al., 2019A). Once the operator has performed the picking/replenishing operation, the inserter/extractor returns the tray to an empty position (Dukic et al., 2015).

Figure 1.12 Vertical Lift Module (Azadeh et al., 2019A)

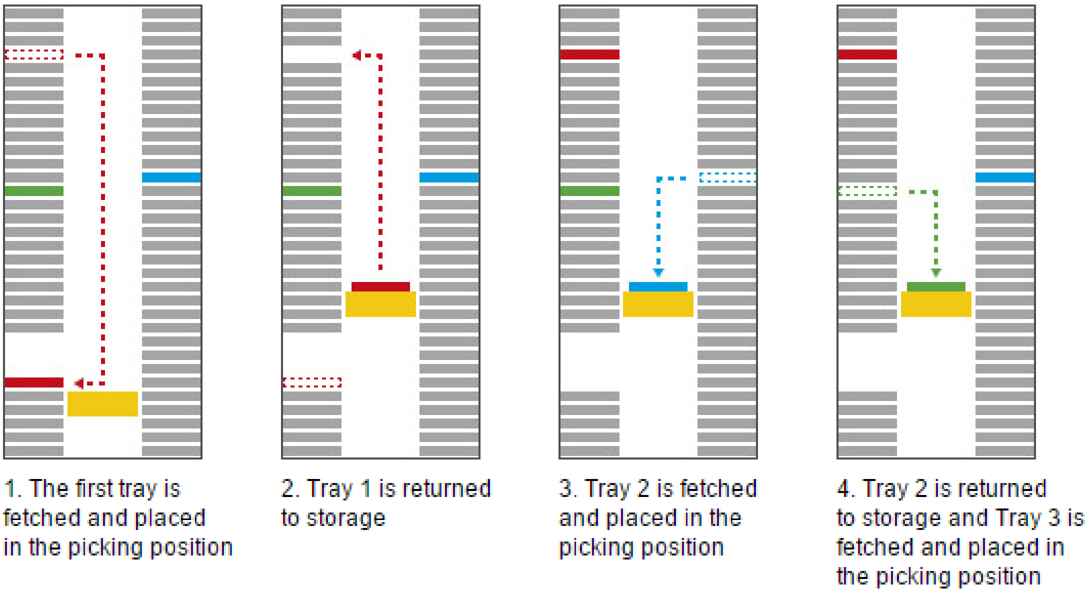

Figure 1.13 Vertical Lift Module operation principle, as seen from the side [2]

VLMs still maintain the strong points of vertical carousels, ergonomic picking height and flexibility in item dimensions. To further increase picking productivity, the dual tray mechanism depicted in Figure 1.14 can be exploited. While the operator is working on a tray, the inserter/extractor retrieves the following one and place it just above or below (depending on the VLM model) the I/O point, so that as soon as the operator is done with a tray the next is already waiting in front of him. (Dukic et al., 2015)

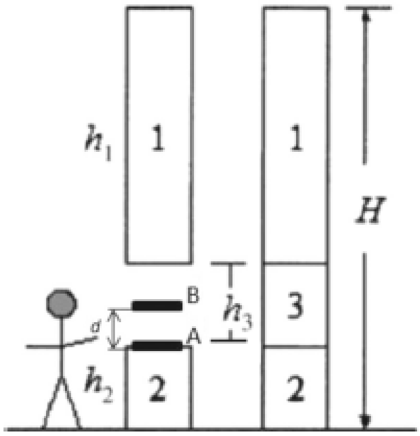

Figure 1.14 Side view of VLM with typical sections (Dukic at al., 2015).

1.6.4 Automated Vehicle Storage and Retrieval Systems (AVS/RS)

In AS/RSs all loads within an aisle are handled by one machine no matter the storage location tier. Automated vehicle storage and retrieval systems (AVS/RS) were introduced to overcome such throughput limit by allowing to add more machines per each aisle (Azadeh et al., 2019A). AVS/R systems were initially adopted only to handle small loads as an alternative to Miniload, but they are now available also for heavy loads. AVSR/RS are becoming increasingly popular thanks their adjustable throughput rate but also because they require an initial investment similar to that of AS/RS and offer much more flexibility in capacity (Azadeh et al., 2019A)

The most common AVS/R system is made of shuttle carriers, lifts and multitier storage rack shown in Figure 1.15. There is usually one shuttle in each tier of the storage rack (tier-captive system) and shuttles can drive in the x direction (i.e. along aisle) and y direction (i.e. from one aisle to another) only, and rely on lifts for loads vertical displacement, hence these systems are categorized as horizontal systems. In case of horizontal systems retrieval operation consists of the shuttle moving to the load storage location, then the shuttle pulls on board the load (usually exploiting the telescopic forks it is equipped with) and finally transports it to the lift for the vertical travel. Then the shuttle either hands the tote to the lift (tier-captive system; Heragu et al. 2008) or uses the lift to move the load to a lower level (tier-to-tier system; Heragu et al. 2008) where it is transferred to the pick station by conveyor belt. Once picking operation is concluded, the load is carried back to the storage location in the reverse way. (Azadeh et al., 2019A).

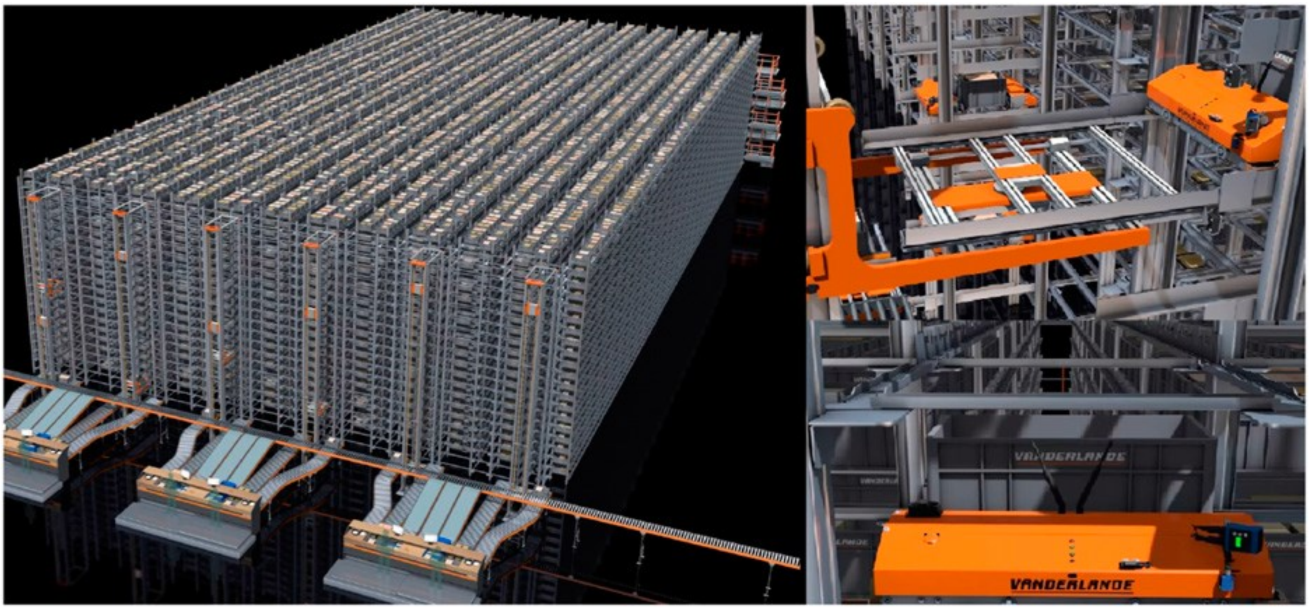

Figure 1.15 Example of AVS/R system source Vanderlande [10]

Typically, in horizontal systems throughput capacity is limited by the number of lifts (Azadeh et al., 2019B and Lerher et al., 2015). More recent solutions addressed such constraint by introducing shuttles (called robots) able to move not only horizontally but also vertically, thus eliminating the need for elevators.

In vertical systems each single robot can move in all three directions, independently and autonomously roaming the storage racks. Similar to traditional shuttles, these robots retrieve the standardized totes by means of telescopic platform and then navigate down the rack and on the floor towards any of the order picking workstations. Such single-touch retrieval process results in increased flexibility other than higher throughput capacity (Azadeh et al., 2019B). In vertical systems optimal throughput can be achieved just by adding or removing robots to the system, while in horizontal system systems throughput rate highly depends on the number of lifts which cannot be easily modified. Furthermore, in a horizontal system, failure of an exchange point may lead to system shutdown, while failure of a robot in vertical system is a minor concern since it can be replaced without affecting operations (Azadeh et al., 2019B).

1.6.5 Robot-based Compact Storage and Retrieval Systems (RCS/RS)

Robot-based Compact Storage and Retrieval Systems, RCS/R system, is another type of shuttle based automated picking system like the AVS/R, but this time falling in the category of Grid-based systems (see Figure 1.6).

In RCS/R systems goods are stored in bins all of the same size usually made of plastics, which are stacked one on top of the other and laid out forming a grid of columns and rows (Azadeh et al., 2019A). The aluminum grid ensures the correct positioning of bins and serves as rail for the robots moving on top of it. The goal with this kind of system is to maximize the use of available space (Beckschafer et al., 2017). In Figure 1.16 a sample system with several robots and four workstations is presented. Robots store and retrieve bins by roaming on top of the storage rack, once they are above the desired bin, they are able to lift and extract the bin from the storage position and then transport it to the workstation (Zou et al., 2016).

Figure 1.16 Representation of AutoStore^{TM}, i.e. Grid Based Storage System [15]

All bins have same external size, but internally they can be divided in smaller compartments to accommodate different items. Workstations are situated at floor level, next to the storage racks and can be seen as empty stacks on the perimeter of the frame. When the picker is done processing a certain bin, a robot transports it from the working station to a free storage location. Generally, all robots have same features, however warehousing software generally distinguish robots between sorting and transportation. Whenever the requested item is not in a top-level position the sorting robot must extract a number of bins and move them to nearby free locations until the desired item is accessible by the transportation robot (Beckschafer et al., 2017). The most well-known robot-based compact storage and retrieval systems is AutoStore developed by Hatteland and further discussed in chapter 2.2.6.

In order for the picker not to waste time while waiting for the next bin, ports usually have a buffer, moreover ports can be added retrospectively to cope with faster picking requirements. In the same way, also robots can be added or removed to the system to adjust for varying throughput demand and even the size of the grid can be scaled iteratively without interrupting operations (Beckschafer et al., 2017).

1.6.6 Robotic Mobile Fulfillment Systems (Amazon Robotics)

Robotic mobile fulfillment (RMF system consists of several robots able to lift and transport to the picker entire racks (called pods). The picker can then manually take the needed items from the shelves and when he is done, a robot brings back the pod to a free location (Azadeh et al., 2019A).

There are three main components in RMF system, as illustrated in Figure 1.17, robotic drive units, inventory pods and workstations. Robotic drive units are computer-controlled machine electrically powered. Inventory pods are nothing more than simple racks containing the stored products. Finally, workstation is the ergonomically designed environment in which human workers can perform picking and replenishment operations (Azadeh et al., 2019A).

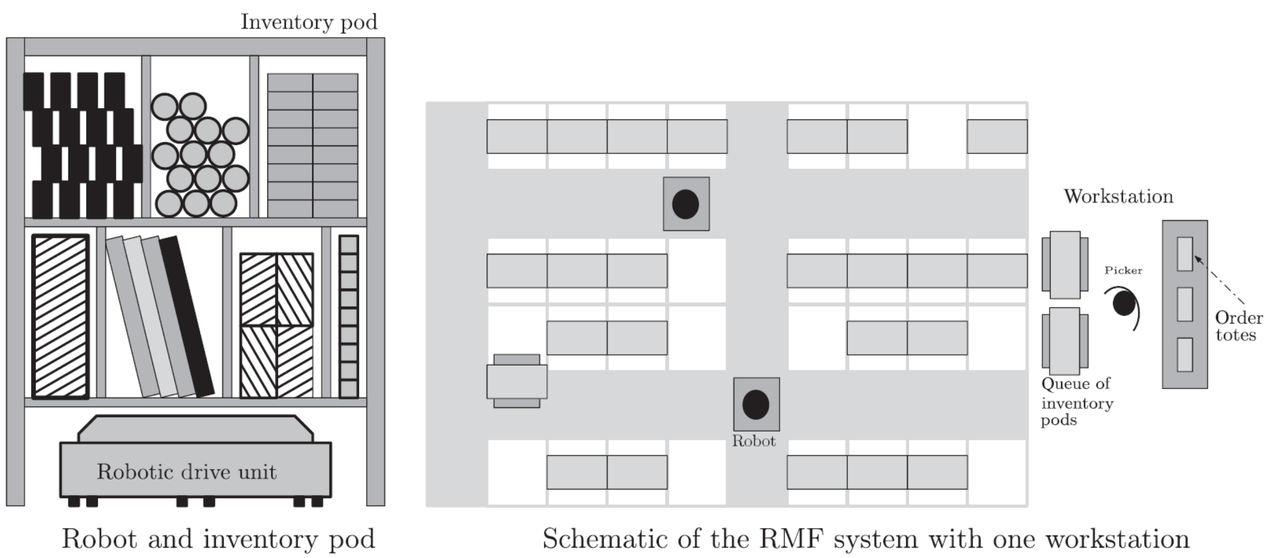

Figure 1.17 Major elements and sample layout of the RMF Systems (Azadeh et al., 2019A).

When an order arrives, the software assigns the requested item first to a workstation then to a robot. The robot starts moving from its dwell position, exploiting the electromagnetic grid underneath the floor. When travelling towards the rack (i.e. without loads on top), it can drive under the standing pods in order to leave highways available for robots moving pods. When the pod is reached, the robot goes underneath it and lift it. The robot can then bring the rack to the assigned workstation and enters a buffer area where it waits for the operator to be ready to process the pod. After the worker ends his task the robot returns the rack to a given storage position depending on the items remaining on the pods and on their request frequency (Azadeh et al., 2019A). Therefore, the policy for storage locations is fully dynamic and it can be adjusted according to products and order characteristics (D'Andrea, & Mountz 2008; Enright & Wurman 2011). As far as robot orientation is concerned, different solutions are available on the market, but the most popular one (KIVA system) is dividing warehouse floor in a grid and each square is labeled with a barcode, robots navigate themselves by reading the barcodes with a camera (Boysen at al., 2019).

Such a solution is extremely flexible both in product dimension, since shelf space can be arranged according to item size and in throughput capacity, since more robots and pods can be added or removed at any time without affecting operations. This characteristic makes the system particularly suitable for businesses experiencing high product variability and seeking for cost efficiency and at the same time ensuring good service level [8].

1.6.7 A-Frame

A-Frame the last automated storage system analyzed in this work. It is the only one in featuring fully automated picking. Generally an A-frame such as the on in Figure 1.18 is composed of four integrated modules (a) storage module, (b) picking module, (c) order collection module and (d) control module. The storage module (a) consists of a series of vertical channels positioned in an "A" shape to store the individual items of various sizes and shapes ready to be dispensed. The picking modules (b) are usually positioned at the bottom of each storage modules to pick the quantity of a line items in a defined order, more specifically there is an automated dispenser pushing one or more bottommost items towards the conveyor whenever required by a passing order (Boywitz et al., 2019). The order collection module (c) can be a tote or conveyor belt running through the center of the A-Frame system to collect and transport picked items. Finally, one or more control modules (d) are required, these controls are capable of interfacing with a wide range of Host systems to receive orders and upload post picked information (Material Handling Industry of America [2]).

A-Frame picking occurs when a microprocessor in a pick module receives picking instructions from a control module. Order lines are processed by automatically dispensing the required products in a virtual window on the conveyor belt or directly collected into a tote, each time window or tote corresponds to a different order (Azadeh et al.,2019A). A-Frame systems can dispense multiple orders at one time enabling it to pick at rates of 250 to 4,000 orders per hour. Items picked to the belt are conveyed to the end of the A-Frame and are deposited into a waiting tote or shipping carton. Orders picked directly into a tote and those deposited into a waiting tote or shipping carton (depending on the system configuration) are then conveyed to an order packing station where they are checked, packaged, labeled, and then conveyed directly to shipping (Material Handling Industry of America [2]). Such solution is designed to process a high volume of less than full case orders at a low operating cost, making it most suitable for high-speed retrieval activities (Dallari et al., 2009) and special cases with high volumes of small and uniform items (de Koster et al., 2007). Examples can, for instance, be found in the pharmaceutical, cosmetics and tobacco industry (Boywitz et al., 2019).

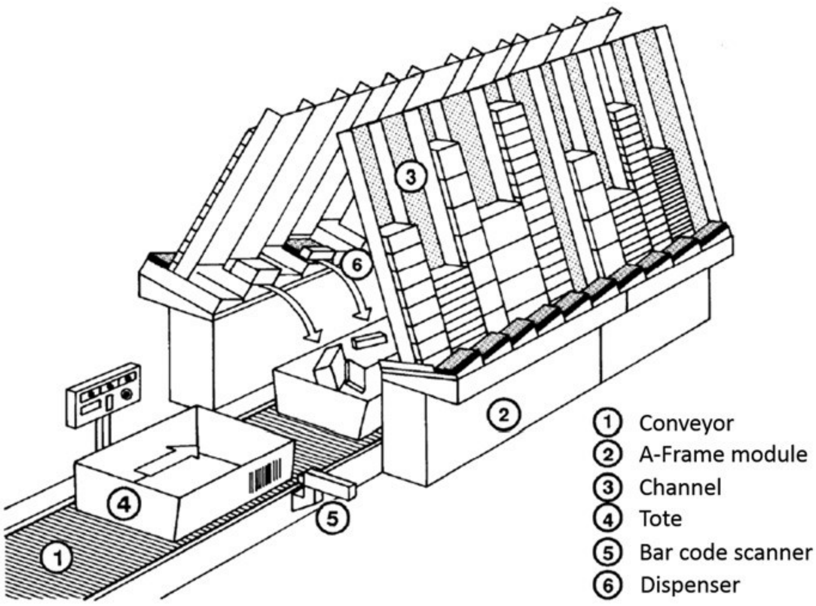

Figure 1.18 Example of A-Frame system (Boywitz et al., 2019)

1.7 Literature Review and Research Gap

Despite the increasing amount of research on warehouse, the problem of best storage system selection is still not sufficiently investigated, so that a proper research gap can be identified. Most recent papers in the warehousing literature focus either on best routing policies in a given context (see for instance the literature review by Masae et al., 2020) or on specific design issues and new technologies performance analysis (make reference to Azadeh et al., 2019A). Specifically to performance analysis of new systems, shuttle-based S/RS was first investigated by Malborg (2020). He was able to develop a state equation model to estimate the vehicle utilization and cycle time. Starting from these premises, Kuo et al., 2007 and Fukunari and Malmborg (2008) extended the application field of the model developed in 2003 by Malborg and especially they made it more efficient from a computational point of view to solve large scale problems. Successive studies on this topic have focused on the research of queuing approximations able to improve the accuracy of transaction waiting time estimates (Roy et al., 2017), (Ekren et al., 2014). The studies of Roy et al. suggest that, in case of a system with lift in the middle, a warehouse layout configuration with depth-to-width ratio equal to 2 provide best system performance. Ekren et al. provide a simulation-based regression analysis for the rack configuration of the system.

The limited existing scientific literature focuses on very specific topics and an overall design procedure with a systematic approach allowing the decision maker to compare various automated storage systems and choose the most suitable to their need is still lacking (Custodio et al., 2020; Rupasighe et al., 2019; Azadeh et al., 2019A).

Zaerpour at al., 2019, claims that academic research on storage system selection is scarce and that a large gap exists between academic literature and the practice of warehouse design. They wanted to bridge this gap by comparing various manual and automated storage systems based on the investment and operational costs, stressing that their paper was the first addressing such a topic. Zaerpour's results show that the choice of automated or manual storage system and the associated costs depends on the required capacity and throughput. When the storage capacity and throughput are low, the manual pallet racks are the preferred storage system and incur the lowest costs. As the storage capacity and throughput increase, there is a need for more compact storage systems that can store more loads in a smaller footprint. Thus, for medium to high capacity levels, double-deep AS/RS and deep-lane compact storage systems are the ones with the lowest investment and operational costs. The results for tote storage show that the investment and operational costs increase rapidly with an increase of the throughput. In particular, the increase is noticeable for operational costs of the shelf rack system and the investment cost of the Miniload system where the storage capacity and throughput level are high.

Azadeh 2019 states that questions about system comparison, how do different systems compare to each other on performance, space utilization, operational costs have still no answer, or at least have not all storage systems. Nowadays the wide range of options available on the market and the rapid introduction of new technologies oblige distribution center managers to take decisions which are crucial to the future of the warehouse without the possibility to rely on a structured approach for storage system comparison and evaluation (Azadeh et al., 2019A).

According to Azadeh 2019A the only published paper addressing the storage system selection problem is Pazour and Meller 2014, however it is evident that more research is needed at least to include more recent automated systems.

Pazour et al. by analyzing the seven factors that mostly influence the storage and retrieval system selection problem, developed a systematic framework which jointly selects the types of technologies (automated dispensing, stock-to-picker or picker-to-stock system), and the assignment of SKUs to the selected technologies. These seven factors are number of SKU, number of order lines processed per day, average number of pieces per order line, demand curve, number of shifts, yearly labor rate and peak demand factor. They conducted two Analysis of variance ANOVA. The first analysis has the scope of finding interactions between distribution center characteristics and SKU and line automation and result is that the number of SKUs, number of lines, number of shifts, and labor rate statistically impact both SKU and line automation. A second ANOVA aimed at understanding if interactions between distribution center characteristics influence the levels of automation and they figyre out that in general automation is most attractive when the number of SKUs is low, the number of lines is high, the demand curve is skewed, the number of shifts is high, and the labor rate is high. Finally, they analyzed SKU characteristics that lead to the selection of the three different types of order-fulfillment technologies.

(i) Automated dispensing systems tend to have a low cost per line picked and a high cost per SKU location because automated dispensing systems are used to fulfill high-moving SKUs that have a high lines-per-SKU ratio.

(ii) Slow-moving SKU make up a large number of total SKUs, consequently, slow moving items consume large amounts of space and if fulfilled via a picker-to-stock system will require large travel distances. For this reason, automated stock-to-picker systems tends to be used for the many slow-moving SKU.

(iii) Picker-to-stock strategy is suggested for the remaining medium-moving SKUs.

According to Custosio et al., 2020 and Rouwenhorst et al. (2000), such a research gap is due to the vast set of available alternatives and their very different operating principles, which make it difficult to perform a complete comparison and evaluation. To deal with the current needs imposed by the market, innovative technologies are appearing, and they provide new solutions and new research opportunities. De Koster states that not all storage systems have yet been studied in detail and still there is a research gap between practice and academic when it comes to storage system selection (de Koster et al., 2007).

Due to the lack of decision aids, facility designers tend to solve the order-fulfillment technology selection problem based on their own experiences or rely on the experiences of technology providers (Custodio at al., 2020; Zaerpour et al., 2019; Azadeh et al., 2019A; Pazour et al., 2014; Gu et al., 2010).

The present thesis work aims at filling this gap by providing a complete overview of the systems available today, highlighting their working principles, advantaged and weaknesses. Secondly, it wants to assist warehouse managers in the crucial issue of selecting the most suitable small unit load automated storage system, by offering a decision making tool which is easy to interpret and whose priority ranking can be adjusted to meet to the different needs of each business. Such tool is based on the Analytic hierarchy process AHP method and evaluates the eight tote storage systems analyzed throughout the thesis, namely miniload crane, horizontal and vertical carousel, vertical lift module, shuttle-based storage and retrieval system, robot-based compact storage and retrieval system, robotic mobile fulfillment and A-frame based on nine evaluation criteria which are considered the most relevant for the selection.

2. Current state of the art of storage systems for small and large unit loads

This chapter presents automated storage systems actually marketed by major companies operating in the field of logistics and warehouse automation (Table 1.1 Top 20 worldwide materials handling system suppliers [7]). Most up-to-date configurations and technical solutions are here described and compared. Reported data were collected either by suppliers' web pages, internet available materials (technical specifications and datasheets and brochures) or by directly contacting the company via e-mail. It is to be highlighted that the technical specifications mentioned in this chapter may vary depending on individual systems, what is reported in the thesis are standard configurations, but very often customized modifications are available to better suit the exact application.

	AS/RS	AVS/RS
Daifuku	Unitload AS/RS	
Dematic	Rapid Store UL	
Ferretto Group	Stacker Cranes	
Mecalux	MT-	
SSI Schaefer	Exyz + Lift&Run	
SwissLog	Vectura	PowerStore
Systems Logistics	Stacker Cranes	

Table 2.1 Overview of analyzed Automated Storage systems for heavy loads

	MiniLoad	Horizontal Carousel	Vertical Carousel	Vertical Lift	Automated Vehicle S/RS	Robot-Based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
Amazon Robotics							Amazon Robots	
Daifuku					Shuttle rack			
Dematic	RapidStore ML				MultiShuttle			
Ferretto Group	Miniload crane		Eurot	Vertimag				
Inther								A-frame
Jungheinrich	MiniLoad Crane		Paternoster	LRK				
Kardex Remstar		Horizontal	Megamat RS	Shuttle XP				
KNAPP					OSR Shuttle			
Mecalux	ML							
SSI Schaefer	MiniLoad Crane			Logimat	Flexi + Navette			A-frame
SwissLog	Tornado				CycloneCarrier	AutoStore	CarryPick	
Systems Logistics	Miniload crane							

Table 2.2 Overview of considered Automated Storage systems for light loads

The topic is examined distinguishing between storage systems dedicated to pallet handling and systems dedicated to handling smaller unit loads, i.e. boxes, cartons, crates and trays. Table 2.1 and Table 2.2 provides an overview of the analyzed systems for heavy and light loads respectively.

2.1 Solution for Pallets and Heavy Loads

In this paragraph the two most popular solutions for handling bulky materials are analyzed, unlike what happens for smaller loads, in this case the analysis is quite straightforward because there are basically only two alternatives available on the market, unit load storage and retrieval systems (AS/RS) which is by far the most spread solution and shuttle based automated storage and retrieval systems, which is more of a niche solution and very few suppliers are marketing it.

2.1.1 Unit Load Storage and Retrieval Systems (AS/RS)

A wide range of alternatives is present on the Unit Load AS/RS market and from an academic point of view their main differences can be summarized with two parameters crane movement and load storage density, same characteristics that were used in the automated storage system classification (Figure 1.8 Classification of various AS/RS system options (Roodbergen et al., 2009)). Crane movement refers to the ability of a crane to move in different aisles (aisle-changing) or to a crane only allowed to operate within one aisle (aisle-captive). Load storage density refers to the rack design that is, how deep loads can be stored inside the rack, we talk about single deep storage density when only one unit load is placed on each side of the rack (i.e. all unit loads are directly accessible) and multi deep storage density when several unit loads are stored one behind the other (in each line same product codes are usually stored so that it is never needed to move the first pallet to access the one further back).

In practice however, during state of the art analysis, it appeared that the majority of manufacturers offer aisle captive multi deep AS/RS, probably because such system represents to the user the best tradeoff, between performances, investment cost and space utilization. In fact, crane movement and load storage density are not distinctive factors and during the systems overview focus must be shifted to other aspects that are often overlooked in the scientific literature such as minimum aisle width, maximum height of the rack, maximum payload, crane speed and acceleration, operating temperature range.

Below are reported and described the systems offered by the major suppliers listed in alphabetical order (table 2.1). In the Appendix, table 5.1 synthetically summarizes the technical parameters that characterize the analyzed systems.

Daifuku, Unit Load AS/RS

Daifuku is the leader in logistic automation market and especially its Unit Load AS/RS is claimed to be the best-selling automated storage and retrieval system in the world [11]. Daifuku offers a variety of stacker cranes to fit specific load profile and weight, building dimensions, and operating environment. Daifuku, Unit Load AS/RS, shown in Figure 2.1, comes in both single-deep and double-deep storage density, meaning that one stacker crane has access to four rack rows (two on each side), suitable for high-density storage of low/medium throughput. In both cases (single-deep and double-deep) it is possible to have aisle-changing cranes which use a traverser to change aisles and access multiple rack rows.

Figure 2.1 Daifuku, Unit Load AS/RS [11]

Load weight capacity ranges from 500 kg up to 3,000 kg and machine height from 3 to 36 m can be reached. Crane horizontal speed, often called travelling speed, ranges 1.05 to 4.17 m/sec, crane vertical speed, often referred to as hoisting speed, ranges from 0.17 to 1.67 m/sec. Load extraction is performed by means of shuttles capable of moving at a speed of 0.33 m/s ÷ 1.33 m/s. Daifuku, Unit Load AS/RS is also ideal for freezer applications (operating temperature can be as low as -50 °C) and low-noise applications.

Finally, Daifuku being founded in Japan where earthquakes are extremely common, has accumulated strong expertise in earthquake risk management, additional stopper, special racking and other more sophisticated countermeasures (Figure 2.2) such as seismically isolated rack are offered to minimize earthquake damage.

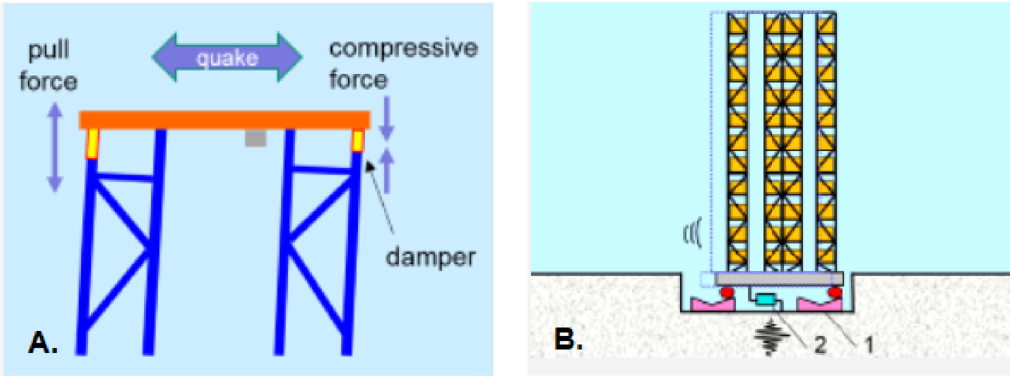

Figure 2.2 (A.) Dampers installed at the top of AS/RS racks reduce energy of seismic activity by up to 50%, reducing the potential for loads to fall of the racks during earthquakes. (B.) A seismically isolated AS/RS base severs AS/RS from direct influence of earthquake tremors, 1 is a bearing isolator while 2 is a hydraulic damper [11]

Dematic, RapidStore

Dematic offers the widest range of unit load AS/RS called RapidStore UL that can be tailored to clients' exact storage and handling requirements irrespective of load type, weight or throughput requirements. The feature Dematic is most proud of is the limited aisle width required, thanks to an optimal crane design, aisles can be only 200 mm wider than the load.

Dematic's RapidStore offerings can be designed to handle loads of up to 1,800 kg and the racking structure can be as high as 45 m, achieving throughput rates of 60 double cycles per hour (depending on load weight, system height and aisle length). As far as speeds and acceleration are concerned the heavier the load to be handled the lower maximum speed and acceleration will be, in particular the fastest configuration is the RapidStore UL1200 (i.e. capable of handling unit loads up to 1200 kg) depicted in Figure 2.3. The lightweight configuration ensured by the single mast design allows maximum travel speed (x-direction) of 4.0 m/s and hoist speed (y-direction) of 1.4 m/s, while travel acceleration is 0.78 m/s^2 and hoist acceleration is 1.3 m/s^2. The highest weight-carrying configuration is RapidStore UL 1800 with a 2200kg capacity featuring travel speed and acceleration of 3.6 m/s and 0.7 m/s^2 respectively while hoist speed and acceleration are 1.3 m/s and 0.7 m/s^2.

The extracting mechanism exploits either standard forks allowing for single deep storage, or shuttles allowing to achieve double or even multi-deep storage thus improving space utilization. In this latter case throughput reduction can be minimized by ensuring that all product codes are always directly accessible.

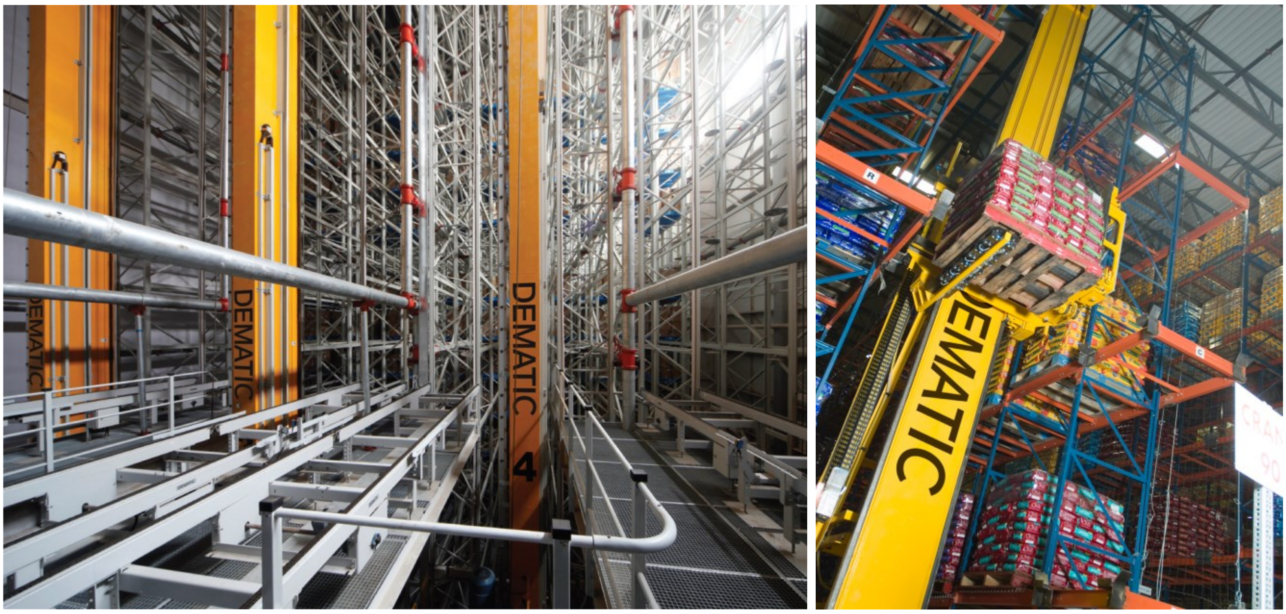

Figure 2.3 Dematic RapidStore UL 1200 [12]

Ferretto Group, AS/RS

Unlike the two solutions previously discussed, the Italian company, Ferretto Group offers both single mast stacker crane (depicted in Figure 2.4) and double-mast stacker cranes, depending on the requirements of the system. Ferretto group AS/RS are equipped with telescopic fork gripping systems for picking or storing goods in single or double deep density. Both systems can handle a maximum payload of 1500kg, but with respect to single mast, double mast configuration can reach greater heights (40 meters with respect to the 25 m of single mast) at the expense of speed and acceleration. Double mast indeed reaches a maximum speed V_x of 3.5 m/s and V_y 0.8 m/s while single mast features V_x of 3.5 m/s and V_y 1 m/s.

Other than traditional stacker cranes for storing goods in single or double shelving depth, as already seen for Dematic, also Ferretto Group offers solutions allowing higher storage density (multi deep storage). In fact, exploiting shuttles instead of forks it is possible to store units loads deeper in the rack. Such solution is to be preferred when space utilization is critical and throughput requirements are not excessive.

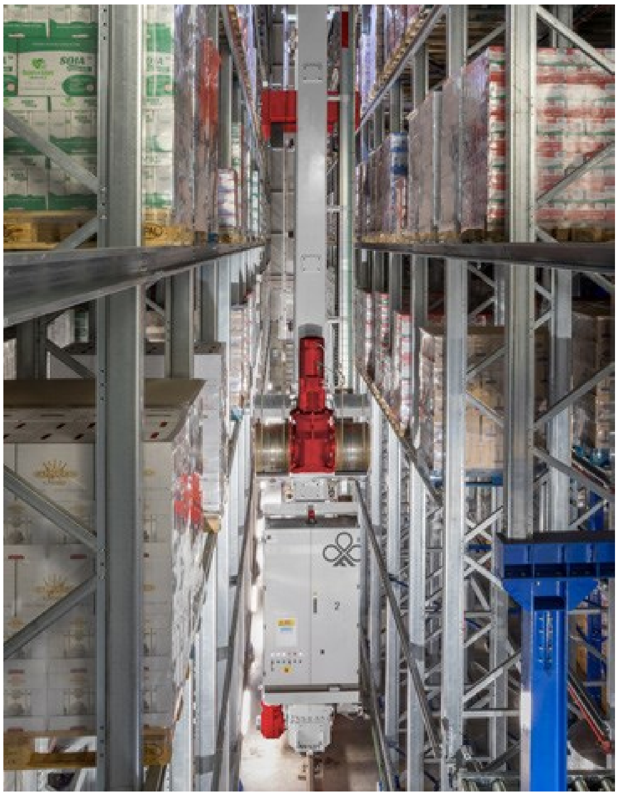

Figure 2.4 Ferretto Group, AS/RS with single mast stacker crane on the left (dairy sector) and AS/RS with double mast on the right [22]

Mecalux, MT

The offerings from Mecalux is again extremely rich. The simplest system is Single-mast stacker crane MT-0 suitable for small plants, its peculiarity is that it does not need a top rail (Figure 2.5), it is guided and stabilized exclusively by the rail at the floor level. For this reason, maximum height is limited to 15 m and maximum weight to 1200 kg.

More complex plant requires more sophisticated solutions and Mecalux offers six different single-mast configurations and seven-double mast configurations. Independently from the number of mast, they can all be equipped with telescopic forks reaching single, double or triple-deep storage density and they all show equal dynamic features Vx 3 m/s, ax 0.45 m/s^2, Vy 1m/s and ay 0.8 m/s^2. Differences lie uniquely on maximum admissible load (1000 kg ÷ 1500 kg) and maximum height (18 m ÷ 45 m).

When the rotation of stored goods is relatively low, but the storage capacity must be high, it is not necessary for a stacker crane to be installed in every aisle. In such a case, a system is put in place to allow the stacker crane to move from one aisle to another (aisle-changing crane) either by exploiting curved tracks or transfer bridges (i.e. a dedicated machine that moves stacker cranes from one aisle to another).

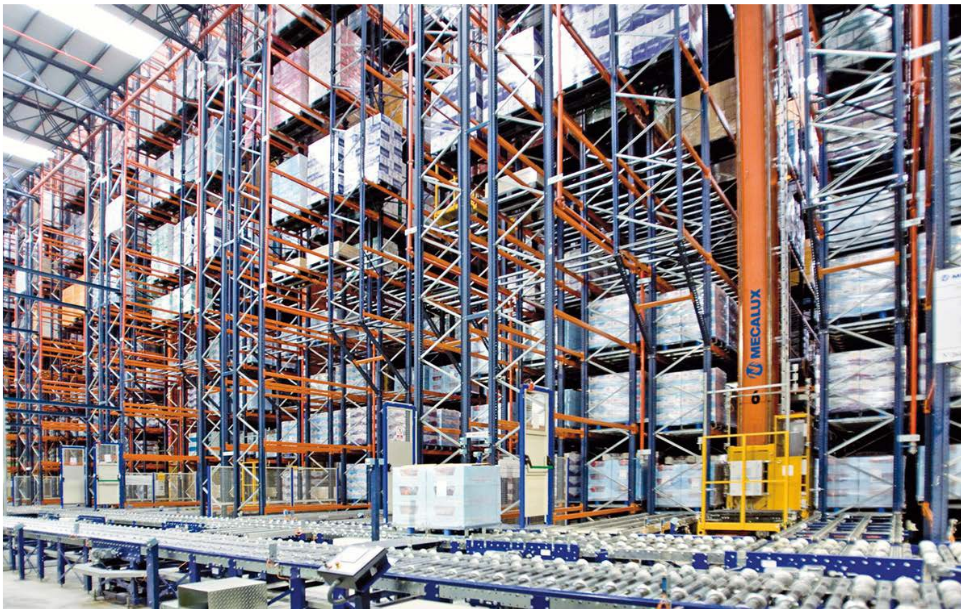

Figure 2.5 Mecalux. (A) On the left MT0: single mast stacker cranes for pallets without top rail guide; (B) on the right complete view of Mecalux AS/RS, MT [13]

SSI Schaefer, Exyz and Lift&Run

SSI Schaefer Storage and Retrieval Machines called Exyz are available in a one or two mast design for single, double or multifold deep storage. Rack heights of more than 45 m, travelling speed up to 4 m/s and hoisting speed up to 1.5 m/s make Exyz one of the best performing systems on the market. Additionally, thanks to the use of state-of-the-art control technologies, SSI Schaefer AS/RS requires minimum spatial reserves and the interlocking design of the floor supports, pallet truck, and mast further enhance this benefit. Moving counterweights integrated into the mast are fitted and compensate for up to two thirds of the pallet truck’s own weight improving performances while also decreasing energy consumption. As a result, it is claimed to achieve energy savings of up to 25% in comparison to conventional machines with the lifting alone [14].

SSI Schaefer other than Exyz offers another product for handling unit load called Lift&Run (Figure 2.6). It still falls in the category of automated storage and retrieval machines and it is equipped with a double mast crane, but differently from conventional AS/RS, it runs on two rails situated at floor level and does not need an upper guide rail. A shuttle is in charge of load handling and multi deep storage is possible. Such system is targeted for highly dynamic pallet handling. Due to its design, maximum height is quite low, 9 m, but the peculiarity is that using multiple devices, one on top of the other, allows the creation of high bay warehouses with heights of up to 45 meters.

Figure 2.6 SSI Schaefer Lift&Run [14]

SwissLog, Vectura

SwissLog Vectura (Figure 2.7), depending on storage density and throughput requirements, can handle one, two or more loads at each cycle in single to multi-deep layouts. It is equipped with telescoping forklifts able to lift up to 3500 kg at heights up to 45m, achieving maximum throughput rates of 45 double cycles per hour [15]. Dynamic performances are the highest recorded, horizontal speed 5m/s and vertical speed 1.5 m/s.

Figure 2.7 SwissLog, Vectura [15]

A distinctive feature is the mechanical strength, all chassis undergo heat treatment after assembling (i.e. welding), which removes stress from the material reducing the pressure and ensuring longer lifetime. A second peculiarity is that the crane during lift and horizontal movements benefits from regenerative energy from one drive directly to the other. This means that the crane uses its own movements to generate more energy.

System Logistics, Stacker Crane

System Logistics produces multiple versions of stacker cranes such as the one shown in Figure 2.8. Depending on the client's specific needs, they vary in loading unit type and capacity, height (up to 40 m), number of columns, horizontal speed (up to 4m/s), load lifting devices with single or double-depth telescopic forks, multi-depth satellite vehicles and temperature (room temperature, controlled temperature or cold storage)..

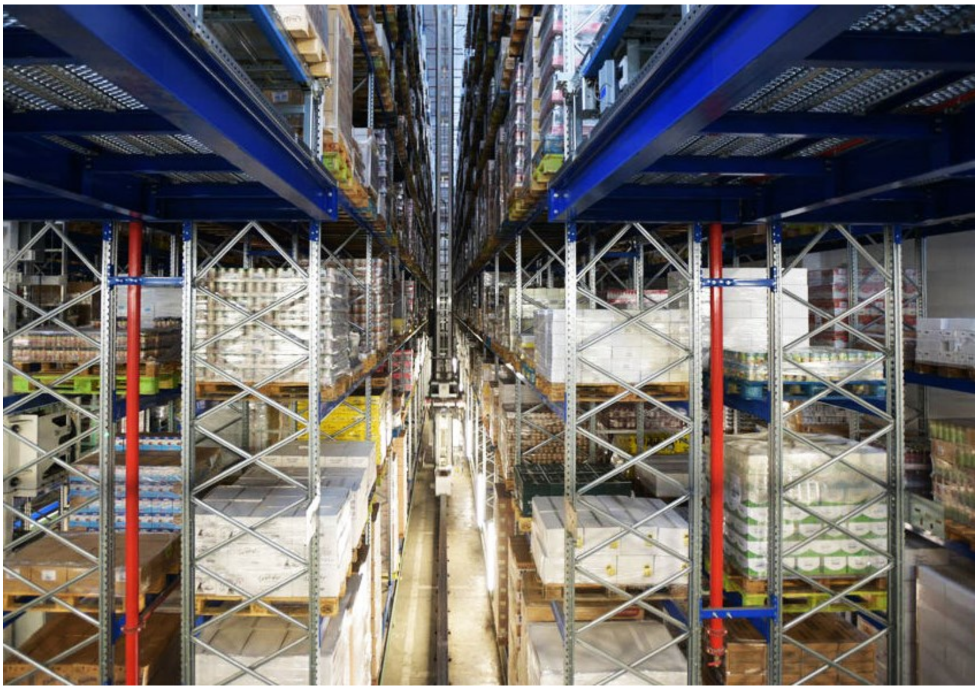

Figure 2.8 System Logistics, Stacker Crane [23]

2.1.2 Shuttle Based Automated Storage and Retrieval Systems

SwissLog, PowerStore

PowerStore by SwissLog is quite unique in its genre since all other manufacturers limit their unit load product offering to different configurations of AS/RS, PowerStore instead belongs to the category of Automated Vehicle storage and retrieval systems (AVS/RS) described in paragraph 1.6.4nd very popular for handling small loads.

Figure 2.9 SwissLog, PowerStore [15]

Such a system, represented in Figure 2.9, consists of lifts and shuttles. Vertical lifts with single fixed mast are in number equal to the number of aisles. Shuttles (here called aisle carrier) are in charge of moving in front of the rack row where the desired pallet is located. Extracting operations are not performed by the shuttles which are not equipped with forks and never enter the rack, insisted all unit loads within the rack are placed on belt conveyors which move the load to the shuttle. Shuttles have conveyor belt as well, so that the load slide from its position inside the rack, no matter the depth, to the top of the shuttle. Once the pallet is loaded on top of the shuttle, it starts moving horizontally along the aisle towards the lift. Finally, the pallet is transported to the workstation at floor level by means of the vertical lift. The system supports storage depth up to 20x and beyond per channel within a rack design and each rack can have ten or more levels. The simultaneous use of automated storage and retrieval devices, along with independent lifts allows for easy addition of extra shuttles whenever throughput demand requires so. Most significant technical specifications are reported below in Table 2.3.

Load weight per transport unit	up to 1,500 kg
Transport units	CHEP, EURO, BLOCKPALLET, STRINGER, AS
AisleCarrier vehicle speed	up to 5.0 m/s
Conveyor speed	up to 3.0 m/s
Vertical Lift speed	up to 2.0 m/s
Throughput	up to 200 pallets per hour per module
Temperature range	Ambient version 0 to 45 °C Cold storage version -30 to 0°C

Table 2.3 SwissLog PowerStore technical specifications

2.2 Solutions for Light Loads

The number of alternatives for handling small loads is more complex than that for heavy loads as shown in Table 2.2. Depending on requirements, in terms of number of SKUs managed and picking productivity, one solution may better fit the purpose than others. Considering these two parameters, number of SKU and picking productivity (expressed in order lines per hour) Figure 2.10 helps in clarifying the field of applicability of each light load automated storage system. It is important to underline that carousels and vertical lift module (i.e. green group) show the application field for a single subsystem, but both order lines per hour and SKU number can be enlarged by installing additional subsystems thus enlarging their application field.

In the following paragraphs the various systems, as classified in Figure 1.6 , are presented, miniload, horizontal and vertical carousel, vertical lift module, automated vehicle S/RS, robot-based compact S/RS, robotic mobile fulfillment system. Due to the high similarity of product designs from different suppliers, the focus is centered on differences. Tables in the Appendix are provided to summarize the main technical characteristics of each system type.

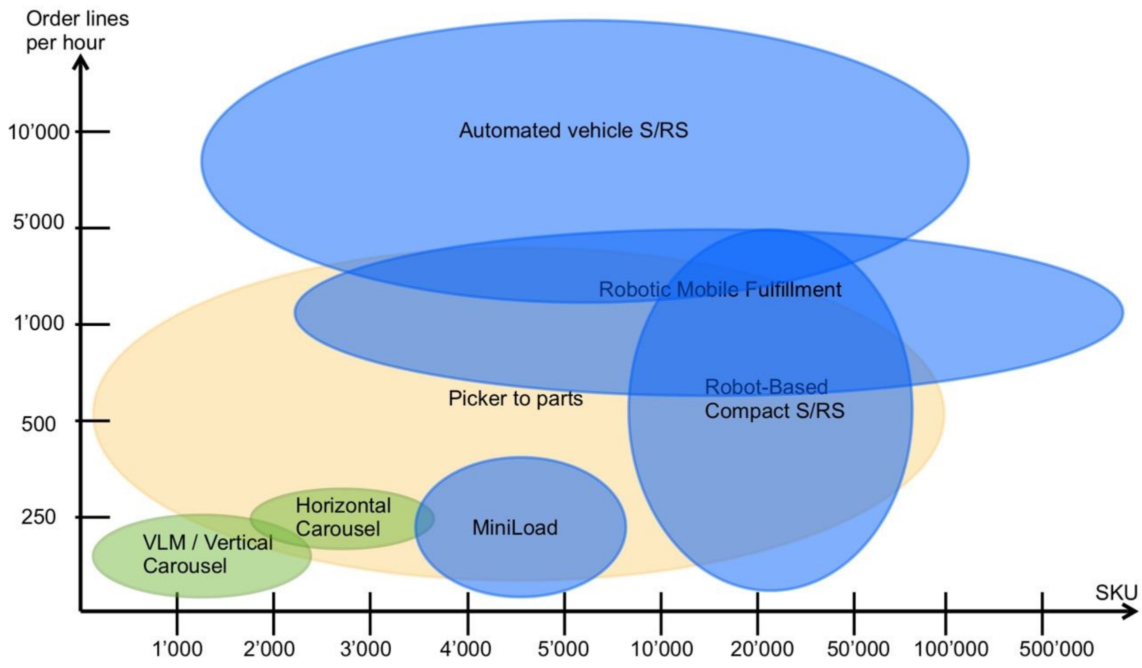

Figure 2.10 The field of application for AS/RSs in relation to the number of SKUs and picking productivity (Manzini, 2012).

2.2.1 MiniLoad AS/RS

With respect to unit load AS/RS, mini load AS/RS, according to gathered data, are generally smaller structures with lower maximum height, thus lighter and able to achieve higher accelerations and speeds.

Miniload systems are usually described as highly limited in terms of maximum throughput, due to the single crane working on all vertical levels and only one I/O point can be used per aisle (Azadeh et al., 2019A). However, miniload systems provide relatively cheap storage locations and can easily be scaled retrospectively. As a result, they are recommended as a storage system rather than as a competitive order picking system.

Dematic, RapidStore ML

Dematic offering on Miniload AS/RS is the RapidStore ML (Figure 2.11A). Various models are available depending on maximum height which ranges from 10 meters and 14m (single mast structure) to 20 meters (double mast). Single mast configuration exhibits better dynamic performances, while double mast allowing for multi deep storage density is more suitable for achieving better space utilization. Multiple load handling devices are available enabling single to triple deep storage of different load sizes and typology (trays, cartons and cases).

Ferretto Group, Miniload crane

Ferretto Group markets one double mast miniload AS/RS (Figure 2.11B) characterized by a remarkable maximum height of 25 meters and impressive maximum payload (500kg) which imply speeds slightly below market average. Available picking devices are many, telescopic forks or forks plus belts enabling single or double deep storage of boxes, totes and metal trays.

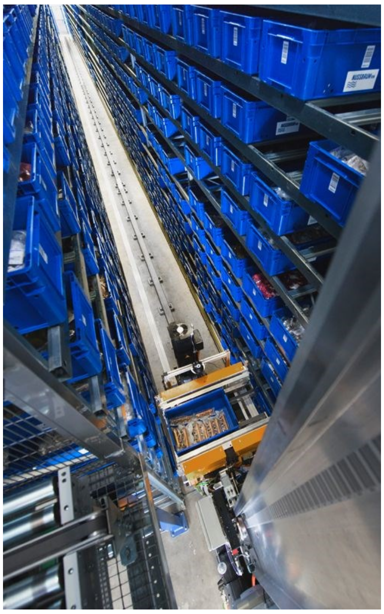

Figure 2.11 (A) Dematic RapidStore ML 10 [12]; (B) Ferretto Group, Miniload crane (furniture sector) [22]

Jungheinrich, STC 2B1A

In Figure 2.12, the single mast STC 2B1A by Jungheinrich with a travel speed of more than 6 m/s and maximum acceleration of more than 5.3 m/s² allows to significantly increase the number of deposit and withdrawal cycles performed in one hour, making it one of the most outstanding machine in its category.

Furthermore, it is equipped with SuperCaps, energy accumulators integrated in the miniload. They accumulate the energy generated during braking phases and feed it into the power supply system during acceleration, it is claimed that energy consumption and related costs can be reduced up to 25% [16]. Maximum height is 14 meters and the dual shuttle system maximum load is 100 kg meaning that two loads with weight not superior to 50 kg each can be handled at each cycle.

Figure 2.12 Jungheinrich Miniload STC 2B1A [16]

Mecalux, ML

Mecalux proposes a single and double mast configuration (Figure 2.13) differing in maximum height ranging from 10 to 13 meters, speeds and acceleration. The mast can be made of aluminum with maximum load equal to 50kg or steel and in this case maximum payload rises to 100kg. Depending on the chosen picking device dual shuttle achieving double deep storage can be installed.

Figure 2.13 Mecalux, ML50 [13]

SSI Schaefer, MiniLoad Crane

Schaefer Miniload Crane (Figure 2.14A) is available in single and double mast with latter reaching height of 24 meters and load up to 300 kg. It can store items quadruple deep in the rack. Dynamic features are around market average travelling speed of 5m/s and hoisting speed of 4 m/s.

SwissLog, Tornado

Swisslog Tornado offers the choice between two load handling devices suitable for different qualities of products – TelescopeLoader (i.e. telescopic forks) for totes or trays in ledger angle racks and CartonLoader (i.e. conveyor belt) for cartons, totes or trays on shelf racks.

Tornado miniload crane (Figure 2.14B) is available with single, double and quadruple deep storage as a standard. Maximum height of 24 meters is completed with a top of the class maximum corridor length of 150 meters.

Figure 2.14 On the left (A) SSI Schaefer, MiniLoad Crane [14]; on the right (B) SwissLog, Tornado [15]

2.2.2 Horizontal Carousel

Horizontal carousels have the big disadvantage of not presenting goods in an ergonomic and easily accessible way to the picker, thus compromising picking accuracy. For these reasons their vertical counterpart is much more popular and horizontal carousel market is declining (Azadeh et al., 2019). Horizontal carousels are usually grouped in pods to allow the picker to access several subsystems so that when one is rotating, he can operate on others and not waste time.

Kardex Remstar, Horizontal

Kardex Remstar Horizontal Carousels can be arranged in stations and depending on the installation size and concept, a number of different layouts are possible: dual station or triple and quadruple stations. Dual stations can be operated by one person and are arranged in a L-shape (Figure 2.15), with the access openings arranged in a right angle to each other, to reduce the picker travel distance. Triple and quadruple stations are suggested in case of a large range of items requiring frequent access, and they can be operated by multiple operators. The system layout is usually L-shaped but alternatively, the layout can be U-shaped or if all machines have the same length I-shaped. One picker can handle up to 400 order lines per station and hour.

Figure 2.15 Kardex Remstar, Horizontal carousels featuring L-shaped dual station [17]

Shelf spacing is adjustable depending on goods to be stored and maximum carrier payload is 900kg. Useable carrier height of the Horizontal Carousel is between 1.80 m and 3.65 m, while total system height ranges between 2.20m and 4.10m. Rotational speed is equal to 0.4m/s. Kardex horizontal carousels are closed from the side to increase safety and only self-lubricating bearings are used, which are very robust and reliable and decrease the maintenance effort.

2.2.3 Vertical Carousel

Vertical carousels consist of shelves or drawers that rotate up or down via the shortest path, automatically delivering stored items to an operator at an ergonomically positioned pick window. Vertical carousels are particularly suitable for storing many small high frequent items. They ensure maximum space utilization since no transportation aisle is needed. All vertical carousels are limited by maximum weights both for the shelves and for the entire unit. The maximum weight is limited due to the risk for imbalances and the fact that the entire shelving moves for each retrieval, which puts high pressure on the whole machine.

Kardex, Remstar Megamat RS

Megamat RS (Figure 2.16) is a product collection made of several configurations, from Megamat RS 180 designed for lightweight loads for example in vehicle manufacturing and in the electronics industry, to Megamat RS 650 for heavy loads up to 650 kg per carrier and capable of handling imbalances up to 2100 kg in the bigger configuration.

Picking accuracy is ensured by a wide range of options from the standard validation via barcode, handheld scanner or weight control to a wide range of other solutions such as Pick-to-Light, Put-to-Light and Laser/LED Pointer.

Figure 2.16 Kardex, Remstar Megamat RS [17]

Ferretto Group, Eurot

Ferretto group offers four models of vertical carousels called Eurot (Figure 2.17A) with different footprint, height and payload. Width goes from 2740mm to 3364mm, depth from 1103 to 1715mm, height from 2330 to 6530mm, and finally maximum payload is 7000kg with each carrier able to carry a maximum of 300 kg.

Jungheinrich, Paternoster

Jungheinrich Paternoster (Figure 2.17B) comes in two different widths: 3703 and 4953 mm and three different depths: 1836, 2036 and 2236 mm. The height ranges from 3040 to 14,890 but normally they are not higher than 9 meters due to that the maximum weight allowance for the entire unit is usually reached at this point. The shelves can handle up to 600kg each and the entire system has a capacity of up to 16 tons. The Paternoster is built to be able to handle imbalances within the system of up to 3 tons, which they claim to be highest value on the market [16]. The system is further equipped with warning systems to prevent this limit being exceeded.

Figure 2.17(A) On the left Ferretto Group, Eurot [22]; on the right Jungheinrich Paternoster [16]

2.2.4 Vertical Lift Module

Vertical lift modules are enclosed dynamic storage solutions that consist of two columns of trays with an inserter/extractor in the center. The inserter/extractor automatically locates and retrieves stored trays from either columns and presents them to the operator at a waist-high pick window.

A strong point of vertical lift modules is that they can be configured with single or multiple opening located at any heights. This is particularly useful because it allows to have opposite openings and reserve one for withdrawal and the other for replenishment. Furthermore, if the VLM is high enough to reach several floors, picking openings can be located at every level. It is to the be highlighted that picking openings subtract storage space, so a proper tradeoff between performances and space utilization is necessary.

An additional advantage of this system lies in its flexibility. Rack levels on both columns are not fixed and they are automatically adjusted depending on the stored goods. The height of the items placed in each storage tray is measured as it is put away, and loads can be stored as close as one inch apart to maximize storage density especially convenient in businesses with changing inventory.

Ferretto Group, Vertimag EF

Vertimag EF (Figure 2.18A) is the ideal solution for storing and handling material of any size, weight and size. The range includes 15 models each available with 4 different trays capacities. The warehouse can be equipped with the Ergo-Tech system, an exclusive solution of Ferretto Group, which allows to obtain the flows of a double bay and still working in perfect ergonomics. The structure provided by Ferretto Group is earthquake resistant and ready for outdoor installation.

Regarding the dimensions, footprint ranges from 1950 mm to 4240 in width and from 650 mm to 1030 mm in depth while height can reach up to 12 meters (15 m as self-supporting structure for outdoor installation). Minimum tray spacing is 25 mm. Maximum payload is 70000 kg and each tray can support 990 kg at maximum in the biggest configuration.

Jungheinrich, LRK

Jungheinrich lift racking (Figure 2.18B) is assembled according to the modular principle, meaning that the height of the unit can be quickly and cost-effectively adjusted to changes in location or working conditions. System height goes from 2250 mm to 30050 mm, width can be chosen between 1580 mm and 4380 mm while depth is in the range 2312 ÷ 4343 mm. Maximum payload is 70000 kg and each drawer support 725 kg at maximum. Jungheinrich also provides dynamic features claiming that maximum lift speed is 2 m/s and extractor speed (horizontally moving the drawer) is 0.7 m/s.

Figure 2.18 (A) On the left Ferretto Group Vertimag EF [22]; on the right Jungheinrich, LRK [16]

Kardex Remstar, Shuttle XP

Kardex Remstar provides VLMs in different configuration named Shutte XP. Lifting is performed through a tooth belt drive and maximum system loading is either 70 or 120 tons depending on the model. Other than the more traditional Shuttle XP 250, XP 700 and XP 1000, Kardex Remstar markets two other VLM Shuttle XPlus and Shuttle XPmultiple.

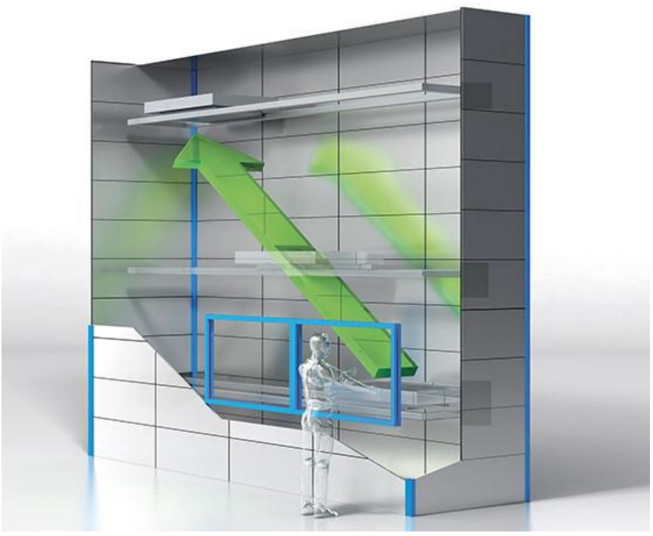

Figure 2.19 Working principle of the Kardex Remstar Shuttle XPlus [17]

The XPlus uses a storage and retrieval device that can move both horizontally and vertically and can hence be operated on wider VLMs, allowing access to additional storage locations, Figure 2.19. It requires fewer picking stations which results in increased space utilization. The Shuttle XPmultiple consists of three independent modular high-bay systems arranged in a tandem configuration with only one I/O point. Trays are moved from the rear system to the front one – and vice versa – by transfer units, Figure 2.20. Such solution is thought for special situations in buildings, such as corners where it is impossible to install two separate systems.

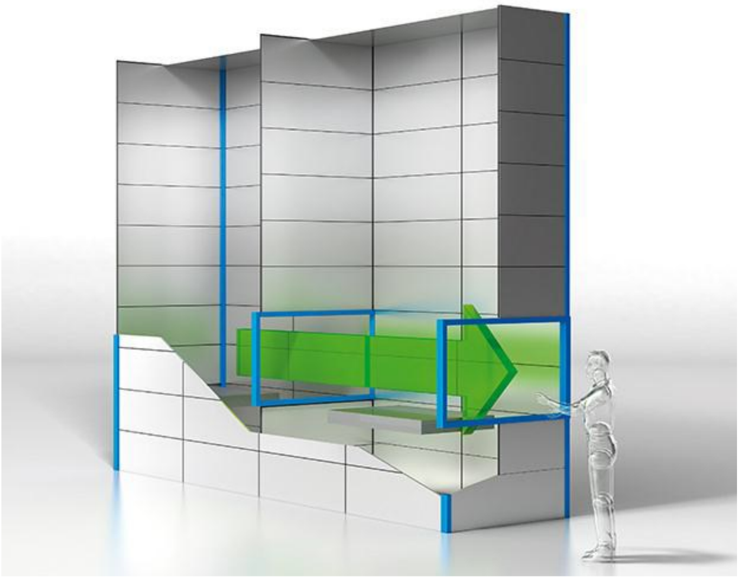

Figure 2.20 Working principle of the Kardex Remstar Shuttle XPmultiple [17]

The Shuttle XP can be configured to the needs of the customer in several ways. Each Shuttle XP can have up to 6 access points. The systems can also be equipped with a dual tray function. The Shuttle XP comes in fixed sizes with a width that varies from 1580 to 4380 mm and a depth from 2362 to 12,296 mm depending on which model is chosen, whereas the XPmultiple is the deepest one as it combines several VLMs. The height ranges between 2550 and 30,050 mm and can be adjusted in intervals of 100 mm. The trays within the Shuttle XP are stored based on the height of the goods in intervals of 25 mm.

SSI Schaefer, Logimat

Logimat by SSI Schaefer (Figure 2.21) includes numerous basic functions and is presented as an efficient storage and picking system. Its strengths are the choice of different drive options selectable according to design specifications and the low-maintenance gear-driven elevator. LogiTilt tilting mechanism helps for ergonomic picking of goods by reducing the picking depth

The width varies depending on the model from 2370 mm to 4570 mm and depth from 2712 mm to 3092 mm. Finally, height is in the range 2450-23850mm with minimum storage spacing of 25 mm. payload is 60 tons split in 700 kg maximum per tray.

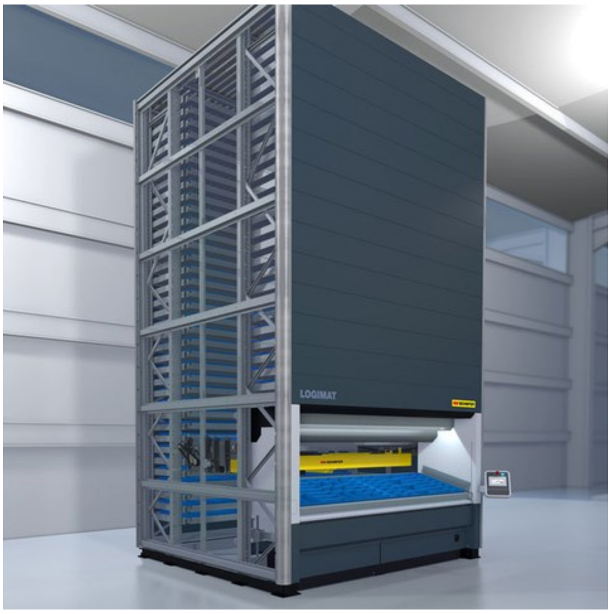

Figure 2.21 SSI Schaefer, Logimat [14]

2.2.5 Automated Vehicle S/RS

This is an emerging storage technology. Like the mini-load AS/RS, Automated Vehicle technology is a computer-controlled system that uses moving vehicles known as shuttles to put away, store and retrieve goods in a racking structure. A major advantage of these systems is that they are modular, scalable and flexible, meaning that adjustments in terms of storage space (adding or removing racks) and performance (adding or removing lifts and shuttles) are possible at any time with minimal structural modifications. Shuttle systems are mostly used for high frequent light goods handling. A common application is for e-commerce, since many small orders need to be shipped out at high speed.

Within the category of Automated vehicle S/RS, an important distinction between horizontal and vertical systems must be noted (see paragraph 1.6.4). Among the here analyzed systems only the last two, namely Skypod by Exotec and Perfect Pick by Opex, fall within vertical systems.

Daifuku, Shuttle Rack M

Shuttle Rack M on Daifuku website is claimed to be a miniload AS/RS, but it actually lies in the shuttle-based storage system category, in fact on each tier, shuttles are moving only horizontally storing and retrieving loads, while the vertical transportation of goods is in charge of vertical lifts.

Different shuttle vehicles are offered, it is possible to have single or double deep storage. The offering comprises both shuttle capable of handling a single load size or shuttle equipped with a clamping mechanism able to handle loads in different sizes () and shapes such as cartons, totes, or trays.

The load weight capacity is 40 kg. Shuttles in single deep configuration can move at horizontal speeds up to 3.3 m/s while in case of double deep, being the machine heavier, it is also slightly slower (3 m/s).

Figure 2.22 Daifuku, Shuttle Rack M, focus on clamping mechanism [11]

Dematic, Multishuttle

The Dematic Multishuttle design incorporates advanced engineering, aluminum construction, and a load extractor to achieve a lighter weight, faster operating speeds, higher payload capacity, and triple-deep storage capacity.

Different load extractors Static, Flex and Belted models allow to meet the customer’s unique requirements. Static handling systems are suitable to maximize space utilization and reduce cost in case of standardized load size. Flex configuration (Figure 2.23) exploits a flexible load handling technology, which allows high performance storage and retrieval of variable load size and package formats. The load extractor adjusts its telescopic arms to the exact width of the load to be handled for transfer on and off of the shuttle. Each telescopic extension arm has a small load capture finger made of carbon reinforced plastic that flips down behind the backside of the entity being retrieved, allowing for pulling on board the load safely. In the belted configuration Multishuttle is equipped with a belt conveyor load deck. that is used for handling cartons where the quality of packaging may be an issue. The conveyor belt eliminates the possibility that the bottom of the carton opens in any way causing product damage.

Figure 2.23 Dematic, Multishuttle in the Flex configuration with capture fingers [12]

The load weight capacity is 50 kg regardless the load extractor. Shuttle can move at speeds up to 4 m/s and average acceleration is 2 m/s^2.

KNAPP, OSR Shuttle Evo

Among the horizontal Automated Vehicle S/RS, the OSR Shuttle by KNAPP is the only systems whose shuttles are not aisle captive meaning that they are able to move from one aisle to other depending on needs as shown in Figure 2.24. This feature results in a list of big advantages, the number of vehicles is no more constrained to be equal to the number of tiers (i.e. number of aisles * number of levels), thus offering the possibility of decoupling performance and storage capacity from one another. The system can operate with only one shuttle per level, but whenever higher performance is needed several shuttles can be used per level to boost operations. Instead, if greater storage capacity is required, the additional rack line systems can be added to the rack block without having to use extra shuttles. This design also makes it very simple to access all articles from any workstation.

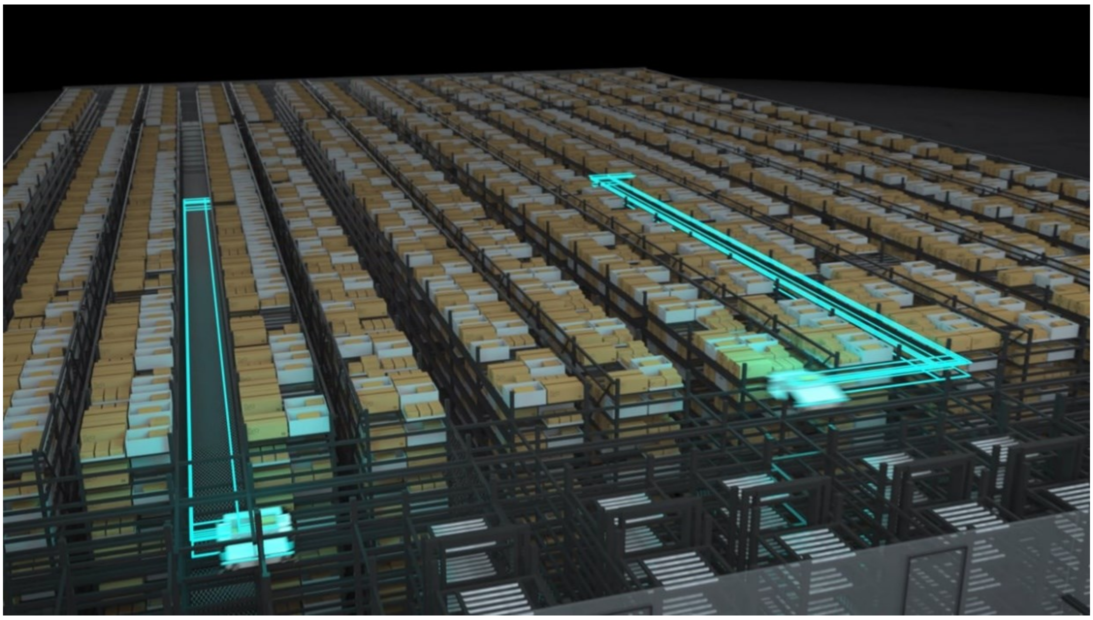

Figure 2.24 KNAPP, OSR Shuttle Evo, aisle changing AVS/R system [18]

Load extractor is standard and consists of telescopic forks capable of handling loads differing in size and shape. Cartons trays and totes weighting up to 50 kg can be stored single or double deep in the rack. Shuttle speed along aisle direction tops at 4 m/s with acceleration of 1 m/s^2 while for crosswise movements top speed is 2 m/s and acceleration of 1 m/s^2.

SSI Schaefer, Flexi and Navette

SSI Schaefer offers two very different types of shuttle systems called Flexi and Navette represented in Figure 2.25.

Starting with SSI Flexi it can be considered as a traditional Automated vehicle S/RS whose only motion allowed is in the x direction (i.e. along the aisle) at a maximum speed of 4 m/s. Peculiarity of this system is the rack conception with dynamically adjustable storage location sizes. Not only shuttles are able to handle loads of different shape and size (up to 50 kg), but the rack itself has no fixed storage locations, meaning that the number of loads that can be stored at each level is dynamically adjusted depending on load sizes, this allows for space-optimized shelf occupancy and maximum storage density. As well as having high-performance lifts installed at the end of the aisles SSI Flexi also allows any number of integrated lifts to be installed in any position throughout the aisles. It is therefore possible to combine highly dynamic solutions with automated storage, buffering, and integrated sequencing in just one system.

Figure 2.25 SSI Schaefer,(A) on the left Flexi; (B) on the right Navette, multi-level shuttle-based storage system [14]

Navette system is more curious because it is the only one among the analyzed systems able to operate on different levels. Thanks to two superimposed double depth lifting devices, SSI Navette can handle two storage levels and, in all, four loading units simultaneously. Furthermore, the Navette itself is able to move not only horizontally but vertically as well (vertical motion range is 3 meters) so that each vehicle can access up to eight storage levels. Compared to single-level shuttles, SSI Navette can duplicate operations, reducing travel times by doubling process efficiency.

In order to reach structures up to 24 meters high, several Navette machines with their respective racking systems can be placed one on top of the other. Lifts are needed as links between shuttles and working stations, number of lifts per aisle is defined according to customer requirements. Navette shuttles are able to carry four loads at a time with maximum weight of 35 kg each, maximum speed in the horizontal direction is 2.5 m/s with acceleration of 1.8 m/s^2. Lifts exhibit maximum speed of 2.5 m/s and equal acceleration 2.5 m/s^2.

SwissLog, CycloneCarrier

High storage density and excellent dynamics are the two, key characteristics of Swisslog CycloneCarrier (Figure 2.26). This shuttle storage and retrieval system offers double to quadruple deep storage of totes, trays and cartons with size ranging from 200 x 200 x 50 mm to 470 x 670 x 500 mm. Each storage level is equipped with one shuttle vehicle. Vehicles are available in two versions depending on the load handling device, fixed width for standardized load size and flexible width in case different loads are handled.

Figure 2.26 SwissLog, CycloneCarrier

Maximum load weight per transport unit is limited to 35 kg, which is the lowest value between the benchmarked systems but a configuration able to carry loads up to 50 kg is available with reduced dynamics. Standard shuttles reach speeds of 4.0 m/s and accelerations up to 2.0 m/s², while lifts show maximum speed of 4.0 m/s and acceleration up to 7.0 m/s²

EXOTEC, SKYPOD (vertical systems)

Skypod by Exotec are vertical AVS/R system. Similar to traditional shuttles, Skypod robots retrieve the standardized totes by means of telescopic platform from the rack. The difference from traditional shuttle based systems is that any robot can retrieve any item (in any level or aisle) and once the tote is loaded on board, the robot can navigate down the rack and on the floor towards the assigned order picking stations. The robot then rides up the workstation’s ramp, and the integrated pick-to-light system indicates to the picker which item and in what quantity to collect. Once manual operations are finished the robot descends the ramp and starts the next (Figure 2.27).

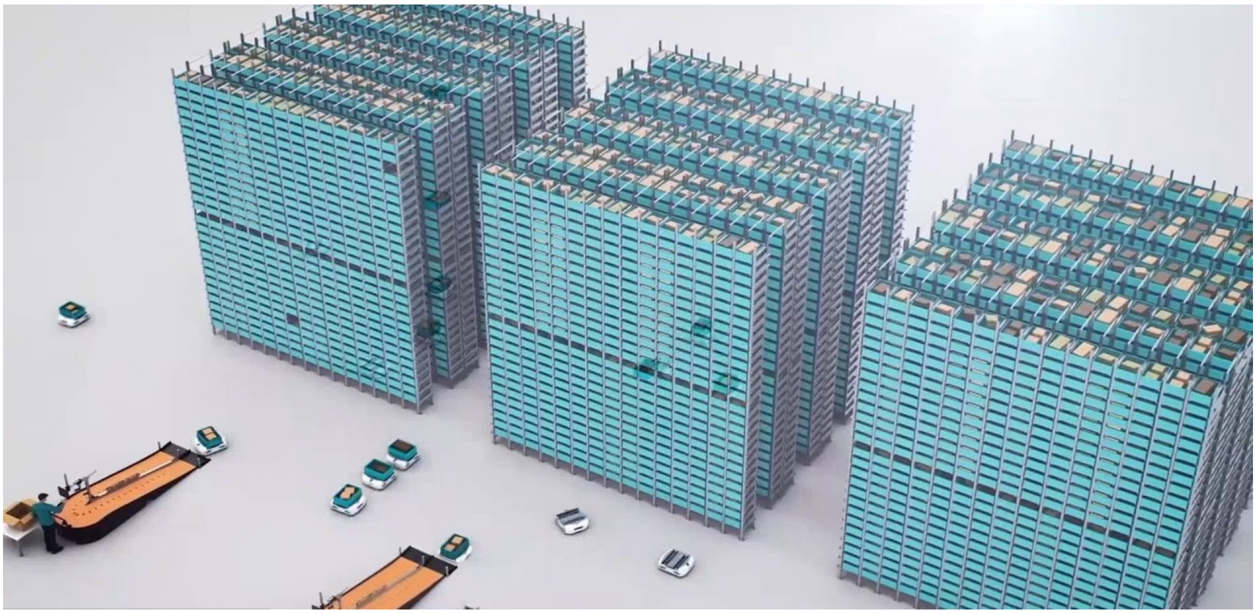

Figure 2.27 Exoetc Skypod [19]

Skypod robot can only store totes single deep in racks up to a height of 12 meters. Totes have standard base dimensions (650x450), but height can be adjusted to the need, maximum payload per bin is 30kg. Claimed robot velocity is 4m/s.

Skypod system provides an unmatched degree of flexibility in storage density, throughput and labor requirements. Additional rack and robots can be added or subtracted at any time to meet current activity levels.

OPEX, Perfect Pick (vertical systems)

Opex Perfect Pick (Figure 2.28) is another example of vertical shuttle system. Unlike Exotec system, it is a self-contained, standalone point solution, meaning that each aisle is separated from the others by thin walls and each aisle has dedicated working station located at one or both ends of the aisle. This direct interface eliminates the need for complex conveyor systems or transfer equipment, such as elevators or lifts.

Each robot can move both horizontally (along the aisle, x-axis) and vertically (y-axis), inside a module all robots have access to all storage locations. The number of robots inside each module can be scaled according to requirements. Perfect Pick's traffic control software monitors the position of all order picking bots in the aisle and directs their movements to ensure full resource optimization and operational efficiency. Modules have a maximum length of 62 meters and maximum height of 9.9 meters, while the module width is fixed and two alternatives are available, the standard configuration called Perfect Pick which store tote single deep (width is 2.74 m) and Perfect Pick HD, storing loads double deep and thus wider

(4.27 m). As noted for the Exotec Skypod, also the Perfect Pick features standard size boxes. To increase storage capacity several modules can be placed next to each other.

Figure 2.28 OPEX, Perfect Pick with iBots [20]

2.2.6 Robot-Based Compact S/RS

Swisslog, Autostore

AutoStore (Figure 2.29) is the most popular example of Robot-Based Compact S/RS. Small item order picking is delivered by autonomous robots traversing an aluminum grid above stacked storage bins. Autostore shows several unprecedented characteristics, storage capacity and floor space utilization are maximum, since robots need no aisle in between racks. Additionally, the size and form of the grid can adapt to any warehouse regardless the presence of columns or oddly shaped rooms achieving optimal space utilization. Finally, flexibility and scalability are other top feature of Autostore system, especially in term of storage space since the grid can be enlarged at any time without interrupting operations, concerning throughput however flexibility is somewhat limited since only a certain number of Robots can operate simultaneously.

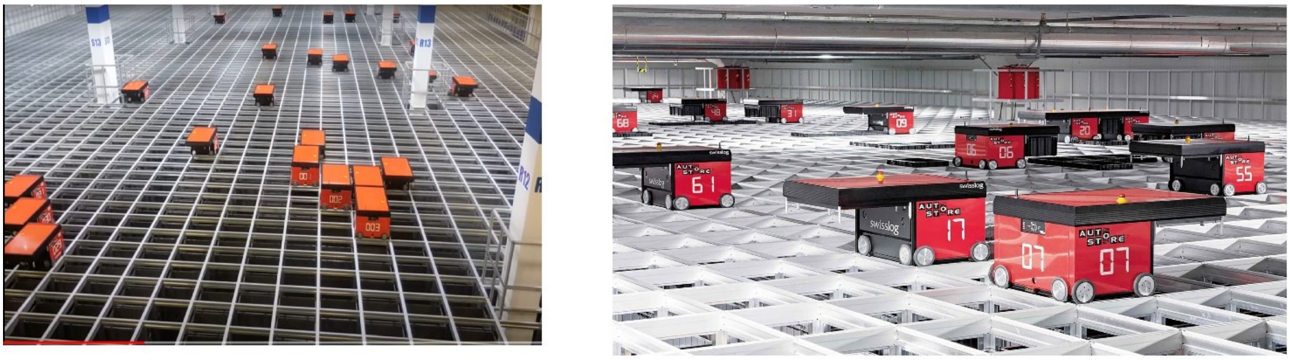

Figure 2.29 Swisslog, Autostore [15]

Bins are standardized and come with fixed length and width and three possible heights (L: 649 mm × W: 449 mm x (H: 220, 330 or 425 mm)). Each bin can be divided in up to 32 compartments and payload per bin is 30 kg. Bins can be stacked on top of each other up to 5.4 meters meaning that 24 low bins can be piled up.

An AutoStore system is usually made of 5,000 to 100,000 bins but bigger systems up to 300,000 bins are possible. Each AutoRobot can retrieve and store about 25 bins per hour.

2.2.7 Robotic Mobile Fulfillment Systems

Mobile fulfillment systems consist of several robots able to lift and carry small racks. Human operators stand at workstations placed along the perimeters of the storage area, which is filled with racks and robots. Robots fetch specific inventory racks from storage area and bring them to the station where an operator performs either replenishments or order fulfillment operations (Enright & Wurman, 2011).

Robotic mobile fulfillment system is the perfect solution for those business characterized by product variability, in fact this new automation system support products with different size and shape cartons, bins, trays and even garment on hanger because the rack itself can be adjusted to accommodate drawers, bins or hanging bars.

Amazon was a pioneer in the use of robots in fulfilment centers. In 2012 they acquired Kiva a Boston-based robotics start-up, but since then Amazon has withdrawn Kiva Robots from the open market to guarantee complete exclusivity (Bogue, R. 2016). This decision however led other manufacturers the opportunity to fill the gap by taking inspiration from Kiva system, in particular Swisslog CarryPick is the most well-known solution developed in Europe.

Amazon Robotics

After Amazon acquired Kiva in 2012, they decide to rename the system to Amazon Robotics. These robots (Figure 2.30) are 76 cm long, 64 cm wide and 41 cm high and able to lift racks weighting up to 350 kg. Lifting is performed through a ball-screw mechanism powered by a single DC motor, which lifts the shelf about 10 cm. Robots are powered by rechargeable lead-acid batteries and they roam around the warehouse exploiting barcode stickers placed on the racks and on the floor (Figure 2.31) (Bogue, R. 2016).

Figure 2.30 Amazon Robotics [Bogue, R. 2016]

Even if racks are extremely flexible and able to accommodate a huge variety of different goods, robot dynamic performances and the risk of rack capsizing impose a constrain on rack maximum height so that center of gravity doesn't overcome a certain limit.

Figure 2.31 A sea of merchandise stored in thousands of yellow pods fills Amazon's 1.1 million-square-foot fulfillment center in Carteret (France) [21]

Swisslog, Carrypick

Carrypick by Swisslog (Figure 2.32) has a working principle which is extremely similar to that of Amazon robots. The main difference consists in the robot itself whose batteries are charged using an inductive mat on the floor, thus eliminating the robot idle time while charging. Even CarryPick Robots have a payload of 600 kg almost twice the value of their competitor.

The CarryPick has four clamp-on devices to lift and move shelves unlike Kiva's single screw-on mechanism. But similar to Kiva, which uses barcoded spots on the floor, the CarryPick Robots follow white lines on the floor to navigate around the storage area.

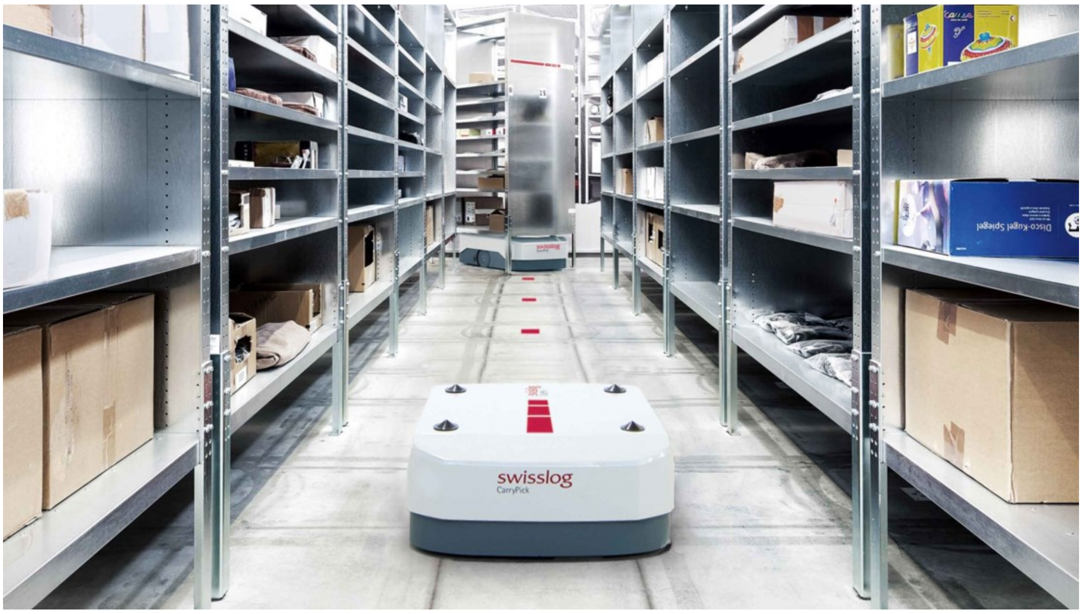

Figure 2.32 Swisslog, CarryPick [15]

2.2.8 A-Frame

A-frame is a fully automated order picking solution. Orders are filled automatically requiring zero order picking labor. As the A-Frame system fills anywhere from up to 800 orders per hour (when picking to conveyor), on up to 2,500 or more orders per hour (when picking to totes or cartons), the only labor requirement is replenishment (Boywitz et al., 2019). The advantage of A-Frames is that replenishment and picking are separate. A-Frames are replenished during low load periods and carry out picking fully automatically during peak load periods.

A-Frame applications include any business requiring high-speed order fulfillment with minimum labor, high accuracy and throughput such as e-commerce, retail, store and wholesale. Industries that utilize A-Frame technologies include cosmetics, pharmaceuticals, health and beauty and office supplies.

SSI Schaefer, A-Frame

The A-Frame manufactured by SSI Schafer is shown in Figure 2.33A. Storage modules are available either with straight or inclined channels. The straight design can offer approximately 10% more space for channels or products compared to the inclined design. With the inclined design, products lean to just one side of the channels, this way, better alignment, easier replenishment and higher quality can be guaranteed [14]. Product channels width is variable in the range 55 – 120 mm.

Both ejection speed and the speed of the conveyor can be adjusted to meet throughput requirements. Ejectors are capable of dispensing a maximum of 4 pieces per second while conveyor maximum speed is 2.2 m/s. Also A-frame length varies depending on the application, but maximum value for each module is 2500 mm.

Peculiarity of the product offered by SSI Schaefer is that each side of the storage module can be split in two levels, in such a casa there are two level of ejectors per side allowing to achieve maximum throughput (Figure 2.33B).

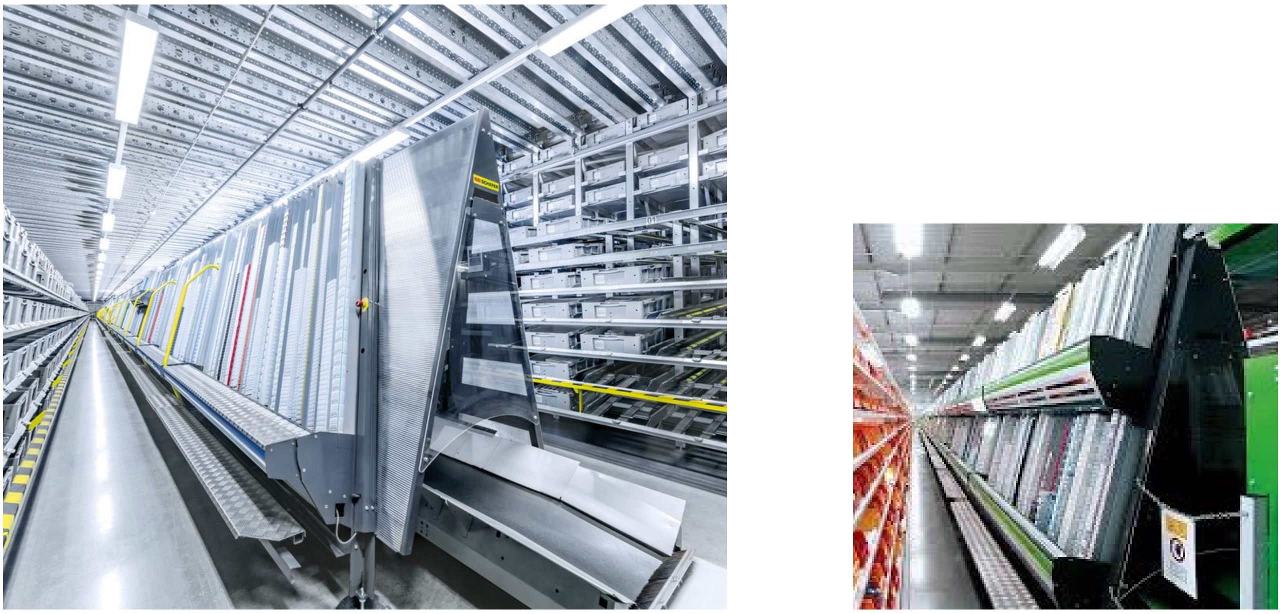

Figure 2.33 SSI Schaefer, (A) On the left A-Frame; (B) on the left two level A-Frame, called Multi Pemat [14]

Inther, A-Frame

A distinctive feature of Inther A-frame is the PUMA unit (Positioning Unit Measurement Apparatus) shown in Figure 2.34. Such system, positioned on top of the A-Frame, calculates the height and thus the number of articles in the product channel. This is an additional quality check and monitors the stock status of the packages allowing to keep refilling errors at a minimum.

Restrictions on article dimensions impose maximum width and depth of 25 mm and maximum weight per article is 500g. Belt conveyor speed is up to 1 m/s while ejectors allow to pick as many as 5 items per second.

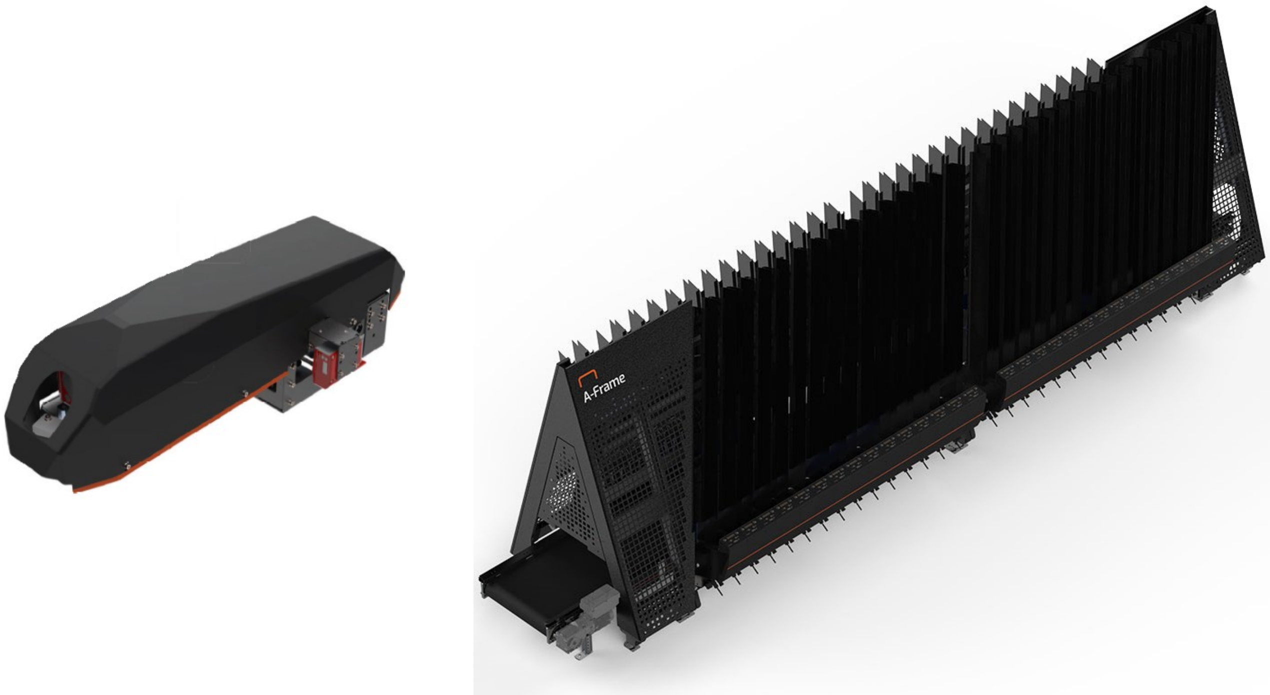

Figure 2.34 (A) On the left PUMA unit; (B) on the right complete Inther A-frame [27]

3. Decision making aid for automated industrial storage systems selection

This section links the theoretical framework discussed in chapter 1 with the market state of the art analyzed in chapter 2. In particular a practical guide has been developed for assisting managers in the complex decision of the right small load automated storage system. As far as palletized loads are concerned, the reduced number of automated alternatives makes the selection process quite straightforward, in fact in case of pallet load handling, the main issue would be deciding whether an automated solution can bring any benefit with respect to standard and cheaper fixed raking system with picker-to-part picking, but such topic is beyond the scope of this thesis work. Focus is therefore on light load automated storage systems because the wide set of options available makes the selection process very complex.

To address such problem the multi criteria decision method used is the AHP method. Section 3.1 provides an introduction on such method while sections 3.2 is devoted to explaining its working principle and how to implement it. In section 3.3 seven evaluation criteria regarded as the most influencing on the decision process are identified and each of them is discussed in a separate sub section. Section 3.4 is dedicated to prioritizing the seven identified criteria on the base of a real case study. Finally, section 0 presents the obtained results.

3.1 Introduction on the AHP method

The Analytic Hierarchy Process (AHP) is a multi-criteria decision methodology (MCDM) formulated by the mathematician Thomas L. Saaty in the 1970s and subsequently applied to decision making problems in multiple areas. In order to better understand this methodology its acronym should be defined:

- *Analytic* means that the method, analytical, involves the decomposition of any complex problem in its constituent elements;
- *Hierarchy* indicates a hierarchical tree of dominance, i.e. a pyramid at the top of which is placed the general objective and below it, arranged in successive levels, the criteria and sub-criteria;

- *Process* means a process that includes a series of actions, modulations or functions that lead to a goal.

AHP applies quantitative methodologies to decision making to prioritize and quantify often intangible and subjective judgments (Falcone, De Felice, & Saaty, 2009). Thanks to AHP, decision problems which look complicated due to the high number of factors linked together and due to the multiplicity of information to be considered, can be solved without leading the problem back to a single criterion. The decision maker is therefore able to evaluate each object of analysis as a whole thanks to the separate judgements given to each decision criterion (Brunelli, 2015).

The representation of the problem in hierarchical form is as shown in Figure 3.1.

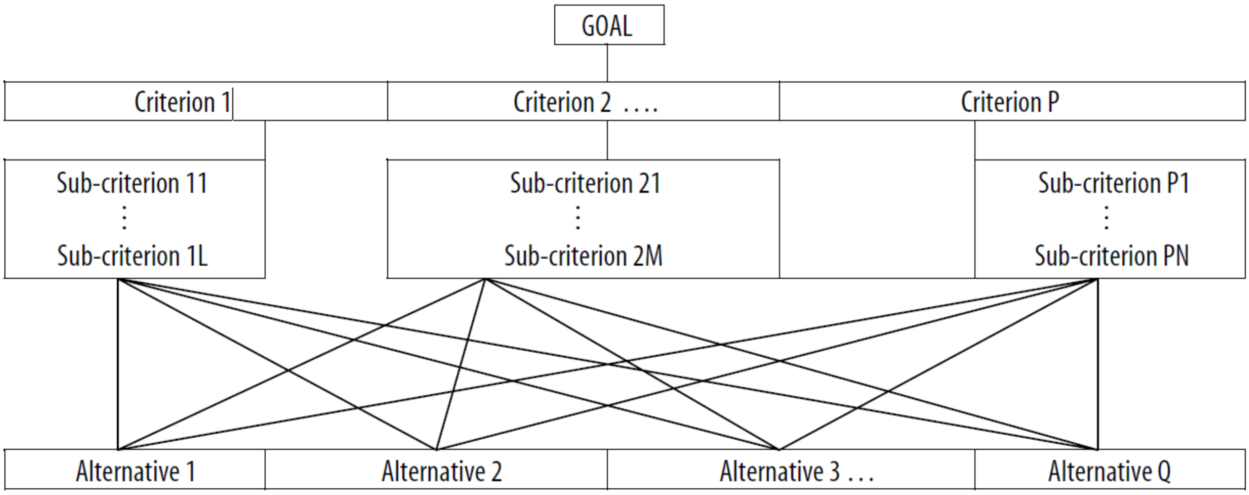

Figure 3.1 Generic hierarchic structure [Bhushan et al., 2004].

Generally speaking, it is important to remember that, since some of the criteria could be contrasting, the best option is not the one which optimizes each single criterion, but rather the one which ensure the best trade-off among all different criteria.

3.2 AHP functioning and implementations

The AHP method attributes a weight to each evaluation criterion on the basis of the decision makers pairwise comparison of all the criteria. Higher weight means that higher importance is attributed to the corresponding criterion.

Once criteria ranking is defined, each alternative is pairwise-compared to the others with respect to a specific criterion. Basically the decision-maker must choose which alternative between A or B best meets the analyzed criterion, indicating with a numerical score how much the chosen alternative A is better than B (or vice versa depending on the case).

Finally, the AHP combines the criteria weights and the alternatives scores, determining a global score for each alternative, and a consequent final ranking. Such global score is simply the weighted sum of the scores it obtained with respect to each one of the criteria (Bhushan et al., 2004).

Three steps are needed to implement the Analytic Hierarchy Process (Brunelli, 2015):

I. Computing the vector of criteria weights
II. Computing the matrix of alternative scores
III. Ranking the alternatives

In the following sub-sections these three steps are analyzed one by one. It is assumed that m evaluation criteria are considered, and n alternatives are to be evaluated. Afterwards a technique for checking result reliability is presented.

3.2.1 Computing the vector of criteria weights

Computing the vector of criteria weights requires creating a *pairwise comparison matrix* **A** of dimension $m \times m$. In such matrix each entry a_{jk} represents the importance of the jth criterion with respect to the kth criterion. A value of $a_{jk} > 1$ means that the jth criterion has a greater importance than the kth criterion, on the contrary if $a_{jk} < 1$, it means that the jth criterion has a lower importance with respect to the kth criterion. If, according to the decision maker, two criteria have equal importance, then the entry a_{jk} is equal to 1. Likewise, a_{jj}, being the comparison of a certain criterion with respect to itself, is equal to 1 for all j. Last property is that entries a_{jk} and a_{kj} must always satisfy the following constraint:

$$a_{jk} * a_{kj} = 1$$

The level of importance of one criterion with respect to another is measured on a numerical scale from 1 to 9 as shown in Table 3.1. Such scale known as fundamental scale or Saaty scale allows to transform a qualitative judgment into an objective numerical judgment.

The interpretation column gives suggestions and helps the decision maker in attributing the correct value to each pairwise comparison. It is to be noted that also intermediate values are possible.

Value of ajk	Interpretation
1	*j* and *k* are equally important
3	*j* is slightly more important than *k*
5	*j* is more important than *k*
7	*j* is strongly more important than *k*
9	*j* is absolutely more important than *k*

Table 3.1 Table of relative scores.

After matrix A is built, it is necessary to derive the *normalized pairwise comparison matrix* $\boldsymbol{A_{norm}}$ by making equal to 1 the sum of the entries on each column, each entry of $\boldsymbol{A_{norm}}$ is computed as:

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}}$$

Once the *normalized pairwise comparison matrix* $\boldsymbol{A_{norm}}$ is completed, the *criteria weight vector* $\boldsymbol{w}$ (that is an *m*-dimensional column vector) can be obtained by averaging the entries on each row of $\boldsymbol{A_{norm}}$:

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m}$$

3.2.2 Computing the matrix of alternative scores

The matrix of alternative scores is a $n \times m$ real matrix $\boldsymbol{S}$. In such matrix each entry s_{ij} represents the score of the *i*th alternative with respect to the *j*th criterion. Before building matrix $\boldsymbol{S}$, a pairwise comparison matrix $\boldsymbol{B}^{(j)}$ is needed for each of the m criteria, $j=1,\ldots,m$. The matrix $\boldsymbol{B}^{(j)}$ is a $n \times n$ real matrix, where each entry $b_{ih}^{(j)}$ represents the evaluation of the *i*th option compared to the *h*th option with respect to the *j*th criterion.

In order to translate decision maker's pairwise comparisons into numerical values the same evaluation scale presented in Table 3.1 can be used. Exactly as described for the evaluation of alternatives, a value of $b_{ih}^{(j)} > 1$ means that the *i*th alternative is considered better than the *h*th alternative, on the contrary if $b_{ih}^{(j)} < 1$ means that the *i*th criterion is not as good as the *h*th alternative. If, according to the decision maker, two alternatives are considered as equivalent with respect to the *j*th criterion, then the entry $b_{ih}^{(j)}$ is equal to 1. Likewise, $b_{ii}^{(j)}$, being the comparison of a certain criterion with respect to itself, is equal to 1 for all *i*. Last property is that entries $b_{ih}^{(j)}$ and $b_{hi}^{(j)}$ must always satisfy the following constraint:

$$b_{ih}^{(j)} * b_{hi}^{(j)} = 1$$

Once all matrixes $\boldsymbol{B}^{(j)}$ are built, one for every criterion, the same two steps procedure described for matrix **A** have to performed. First it is required to divide each entry by the sum of the entries in the column, then to average the entries on each row. This way the score vectors $s^{(j)}$ with $j=1,\dots,m$. Such vector is made of the scores of the evaluated alternatives with respect to the *j*th criterion. Finally, the *score matrix* ***S*** is obtained from the vector $s^{(j)}$:

$$S = [s^{(1)} \dots s^{(m)}]$$

3.2.3 Ranking the alternatives

Having built the *weight vector* ***w*** and the *score matrix* ***S***, the final global ranking of the alternatives is obtained by multiplying S and w:

$$v = S * w$$

The *i*th entry v_i of *v* represents the global score assigned by the AHP to the *i*th option.

3.2.4 Consistency check

It often happens, that when performing many pairwise comparisons, some inconsistencies arise. AHP offers an effective technique for checking the consistency of the evaluations made by the decision maker when building each of the pairwise comparison matrices (i.e. *A* and $B^{(j)}$). To determine the consistency of the matrix the *Consistency index* ***CI*** must be calculated. The consistency index is obtained as:

$$CI = \frac{\lambda_{max} - m}{m - 1}$$

Where *m* is the number of alternatives and λ_{max} is a scalar number calculated as the average of the elements of the vector whose *j*th element is the ratio of the *j*th element of the vector $\boldsymbol{A \cdot w}$ to the corresponding element of the vector ***w***.

If the decision maker was perfectly consistent ***CI*** would be equal to zero, which in real scenario is never the case. Small inconsistency is however accepted, in particular for the AHP to show reliable results it should be:

$$\frac{CI}{RI} < 0.1$$

RI is called *Random index* and is equal to the consistency index in case the entries of the pairwise comparison matrix were completely random. RI values for small problem (i.e. m≤10) are shown in Table 3.2.

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Table 3.2 Values of the Random Index (RI) for small problems

3.3 Alternatives and evaluation criteria

The analyzed alternatives are the eight light-load automated storage systems described in chapter 1 and 2, miniload AS/RS, Horizontal Carousel, Vertical carousel, vertical lift module, shuttle-based S/RS, robot-based compact S/RS, robotic mobile fulfillment system and A-Frame, i.e. all the alternative systems available on today market.

Choosing the evaluation criteria which are most relevant in the selection process is a more sensitive task. Seven parameters are considered namely throughput, picking accuracy, scalability, storage and retrieval interference, flexibility in product dimensions, space utilization, picking ergonomics. In the following subsections they are explained and analyzed one by one providing literary references on why they were taken into account. Moreover, for each selection criterion a table is shown providing the score of the eight alternatives with respect to the given criterion, that is the score vector ***s*** presented in section 3.2.2 Computing the matrix of alternative scores. In that same section are explained the step by step procedure and formulas to be applied, while exact calculations can be found in the Appendix A.2.2 Computing the matrix of alternatives scores. Lastly it is to be noted that the tables displayed in section 3.3 derive from the online software AHP Online System - AHP-OS [28] which was used to present the data in a more pleasant way besides verifying the accuracy of the calculations personally performed on Microsoft Excel.

3.3.1 Throughput

Throughput is generally defined as the number of units that are processed and moved through your building, either during stocking or when fulfilling orders per unit of time.

Throughput is one of the key criteria for evaluating a system performance, indeed, Manzini et al., 2012 affirms that for designers, throughput capacity is the most important criterion. Apart from Manzini, throughput is almost universally regarded as a crucial factor in storage system evaluation (Pazour et al., 2014; Zaerpour et al., 2019; Rupasighe et al., 2019; Merschformann et al., 2019; Zapata et al., 2020).

With regard to throughput the eight analyzed automated storage systems are ranked as shown in Table 3.3. The step by step calculations necessary to reach this result are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 8.3%

Cat		Priority	Rank
1	Miniload AS/RS	1.8%	8
2	Horizontal Carousel	4.2%	5
3	Vertical Carousel	3.0%	7
4	Vertical Lift Module	3.4%	6
5	Shuttle-based S/RS	27.7%	2
6	Robot-based Compact S/RS	11.7%	4
7	Robotic Mobile Fulfillment	14.3%	3
8	A-Frame	33.9%	1

Table 3.3 Ranking of the alternatives with respect to throughput [28]

Starting from the bottom of the ranking, miniload AS/RS shows the worst performances in terms of throughput rate with values of about 100-150 order lines per hour. The reason is that there can be at most one crane per aisle, thus posing a limit on maximum performance.

Carousels and Vertical Lift module have similar picking productivities ranging from 200 to 500 order lines per hour. Since these systems have no buffer, throughput is largely dependent on the demand pattern. Every time a change of storage unit is required, the picker has to wait some time to allow the carousel rotation until the desired storage unit is presented in front of him. To mitigate such problem and shorten these picker idle times, it is common to assign one picker to several subsystems. As far as Vertical Lift module is concerned, storage and retrieval of a tray takes even more time than a small carousel rotation. However with most modern vertical lift modules, while the operator is working on a tray, the inserter/extractor is able of retrieving the following one, thus minimizing operator idle time (see Figure 1.14). Horizontal carousel generally performs better than VLM and vertical carousel because its configuration in pods allows the picker to operate several subsystems without any travelling. Furthermore, since the rotation is horizontal, rotational speed can be slightly higher than that of a vertical carousel which moves against gravity.

Robot-based compact S/RS, like all of the following systems, exploits buffers to achieve fast changeover times and robot-based compact S/RS are capable of throughput of about 400 order lines per hour. RMF system shows similar throughput performances, its slight advantage derives from the fact that each pod is directly accessible and there is no need to dig to retrieve the desired box.

The shuttle-based system was designed to overcome miniload AS/RS productivity constraints and having one shuttle per aisle per level, it can reach up to 800 order lines per hour. Finally, A-frame offers the highest throughput rate among the considered systems achieving values up to 4000 order lines per hour.

3.3.2 Picking accuracy

Picking accuracy refers to the percentage of storage and retrieval operations correctly executed over the total. It is another key indicator in the evaluation of automated storage systems because there is no point in performing high speed operations if the final order does not contain the correct items. Inaccuracies are mainly to be reconducted to the picking phase, after the machine brings the box, shelf or tray in front of the operator, it is his responsibility to pick the correct item among those presented in front of him. Such inaccuracies may be mitigated or amplified depending on how the storage and retrieval system presents the SKU to the picker. Pazour et al., 2014, Rupasighe et al., 2019, Zapata et al., 2020 and Manzini claimed that together with throughput, picking accuracy is an essential parameter in the storage system selection process.

In Table 3.4, the ranking of the alternatives with respect to picking accuracy is illustrated. The step by step calculations necessary to reach this result are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 6.9%

Cat		Priority	Rank
1	Miniload AS/RS	16.3%	2
2	Horizontal Carousel	4.0%	8
3	Vertical Carousel	8.2%	5
4	Vertical Lift Module	8.2%	5
5	Shuttle-based S/RS	16.3%	2
6	Robot-based Compact S/RS	16.3%	2
7	Robotic Mobile Fulfillment	4.5%	7
8	A-Frame	26.1%	1

Table 3.4 Ranking of the alternatives with respect to picking accuracy [28]

Horizontal carousel and RMF system perform very similarly as far as picking accuracy is concerned. Both present a variety of SKU stored in a vertical shelf, which forces the operator to bend and stretch to reach the desired items. They are therefore more prone to picking errors. The slight advantage of RMF is motivated by the picker not moving among different subsystems, which can increase the possibility to make mistakes, but staying still at the workstation.

Vertical carousel and vertical lift module present items stored in trays. Errors may derive from the variety of SKU presented in front of the operator. With respect to horizontal carousel, the shelf is at waist height allowing the operator to have full visibility on the shelf and improving picking ergonomics, thus increasing picking accuracy.

Miniload AS/RS, shuttle-based S/RS and robot-based compact S/RS are very similar in terms of picking accuracy because for all three systems a single box at a time is presented to the picker which is waiting at the workstation. Error probability is reduced because of the small variety of items contained inside the box with respect to that of a shelf or tray.

On top of the list is again A-frame because picking operations are fully automated, thus eliminating human error which is by far the most relevant source of inaccuracy.

3.3.3 Scalability

It is to be noted the difference between short-term pick demands and long-term demand variation. Scalability refers to the ability of adapting the automated storage and retrieval system according to long term needs. AS/RS can be scaled in terms of the maximum number of SKU stored or in terms of picking productivity which in turn can be scaled either by adding/removing picking stations or by accelerating/decelerating storage and retrieval operations. Huang et al. (2015) analyze robot-based goods handling systems and identify scalability as a key element in evaluating and rating these systems and the main reason is the initial investment benefit.

Errore. L'origine riferimento non è stata trovata. shows the ranking of the eight analyzed system with respect to scalability. The step by step calculations necessary to reach this result are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 7.0%

Cat		Priority	Rank
1	Miniload AS/RS	9.8%	4
2	Horizontal Carousel	4.0%	6
3	Vertical Carousel	4.0%	6
4	Vertical Lift Module	7.4%	5
5	Shuttle-based S/RS	19.1%	3
6	Robot-based Compact S/RS	23.7%	2
7	Robotic Mobile Fulfillment	28.1%	1
8	A-Frame	4.0%	6

Table 3.5 Ranking of the alternatives with respect to scalability [28]

Horizontal carousels, vertical carousels and A-frame system are ranked lowest because existing subsystems, due to their design, cannot be scaled. In order to manage increased or decreased long-term demand, the only possibility is that of adding/removing entire subsystems.

The vertical lift module ranks slightly better because the height of the module can be increased to some extent and new trays can be added. Furthermore, picking openings can be closed to provide more storage space or opened to provide increased picking productivity.

Miniload AS/RS provides great scalability as far as maximum number of stored SKU is concerned because adding new storage racks or expanding (both in height and length) existing racks is easy and inexpensive. The problem is that the increase in storage capacity is hardly accompanied by an increase in throughput. In fact, the constraint of having no more than one stacker crane per aisle means that an increase in the number of SKUs stored corresponds to a decrease in productivity.

Shuttle-based S/RS is able to solve this problem. Likewise, miniload AS/RS, scaling shuttle-based S/RS in terms of maximum number of stored SKU is easy because racks can be extended in height and length and, at the same time, it is possible to add shuttles and eventually lifts thus balancing storage capacity and throughput rate.

Lastly, robot-based S/RS and RMF system have the best performances with respect to scalability. The first allows to increase the number of maximum stored SKUs by extending the metallic frame on which robots roams, and productivity can be adjusted simply by varying the number of robots. In the same way, RMF system offers the possibility to increase storage capacity by adding new pods, while adding more robots allows to increase throughput.

3.3.4 Storage and retrieval interference

The interference between storage and retrieval operations is a big concern for those systems characterized by a single Input/Output point, namely horizontal carousel, vertical carousel and miniload AS/RS, because the operations of storing and retrieving cannot be performed simultaneously (Merschformann et al., 2019, Pazour et al., 2014). It is then not surprising that those three systems rank lowest in the storage and retrieval interference classification as shown in **Errore. L'origine riferimento non è stata trovata.**.

The step by step calculations necessary to reach this result are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 6.7%

Cat		Priority	Rank
1	Miniload AS/RS	4.9%	6
2	Horizontal Carousel	3.2%	7
3	Vertical Carousel	3.2%	7
4	Vertical Lift Module	7.1%	5
5	Shuttle-based S/RS	13.9%	4
6	Robot-based Compact S/RS	18.4%	2
7	Robotic Mobile Fulfillment	18.4%	2
8	A-Frame	30.9%	1

Table 3.6 Ranking of the alternatives with respect to storage and retrieval interference [28]

Compared to horizontal carousel, vertical carousel, miniload AS/RS has the great advantage of allowing storage and retrieval operations while the operator is intent on picking or replenishment tasks. In carousels this cannot happen since while the operator is working on a certain tray, carousel rotation is not possible.

Vertical lift module is capable of partially overcoming the problem of single I/O point, by introducing additional access points, so that they can be reserved either for inbound or outbound operations. The main problem is that even if multiple access points can be implemented, there still is a single S/R device.

Shuttle-based S/RS, RMF systems and robot-based compact S/RS are characterized by a smaller interference between storage and retrieval, because the higher number of workstations and independent robots allows to devote some of them to picking operations and some other to replenishment, thus allowing to perform both at the same time. In particular, the shuttle based system is classified slightly lower because in addition to shuttles it uses lifts whose number is limited to one per rack. This constraint prevents the complete simultaneity of operations whenever storage and retrieval are adressed to the same rack. On the other side RMF systems and robot-based compact S/RS can assign a certain number of robots (depending on current needs) to replenishments operations only, thus not affecting picking productivity.

A-frame is ranked first in this category. Picking is accomplished by automatic dispensers which are positioned at the bottom of the storage module and push one or more bottommost items towards the conveyor. Replenishment is usually performed manually, an operator stores the items by stacking them on top of each other in the storage channels. This solution allows to fully decouple storage and retrieval.

3.3.5 Flexibility in product dimensions

Flexibility in product dimensions refers to the range of product dimensions which can be stored in a certain storage system, obviously the wider the dimension range the more flexible is the system to accommodate new types of products. Pazour and Meller (2014), relying also on Noble and Tanchoco (1993), consider unit load size and the adaptability of the storage system to handle unit loads of different sizes to be a major issue in the evaluation of the best storage system.

Consistency Ratio CR: 8.6%

Cat		Priority	Rank
1	Miniload AS/RS	7.2%	6
2	Horizontal Carousel	20.5%	2
3	Vertical Carousel	13.1%	4
4	Vertical Lift Module	23.5%	1
5	Shuttle-based S/RS	9.2%	5
6	Robot-based Compact S/RS	4.4%	7
7	Robotic Mobile Fulfillment	20.5%	2
8	A-Frame	1.7%	8

Table 3.7 Ranking of the alternatives with respect to flexibility in product dimensions [28]

The step by step calculations performed to obtain the ranking shown in Table 3.7 are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

A-frame system is only capable of processing small box-shaped items with width and depth ranging from 60 to 120 mm, such feature strongly restricts the application field of A-frame.

Robot based S/RS, miniload AS/RS and shuttle-based S/RS handle SKU stored in bins. Robot based S/RS does not allow to choose bin dimension, they have standard size of 450 mm x 650 mm, only the bin height can be chosen between a couple of alternatives. However internal space can be subdivided in compartments. Miniload AS/RS can handle bins, cartoons and totes of different sizes. Compared to the two previous systems, shuttle-based S/RS allows the handling of trays, which is not possible for the miniload AS/RS because cranes reach horizontal accelerations three to five times higher than shuttles and items on the tray could easily move and fall.

Vertical carousel stores items in trays which can be divided in smaller compartments, but flexibility is compromised by the fixed height between two consecutive trays which imposes a constraint on maximum item height. Horizontal carousel and RMF system both store items in racks/pods thus items can have very different shapes and in particular very different heights, it is also possible to store garment on hanger. Lastly vertical lift module is on top of the list because trays height can be dynamically adjusted thus allowing to store the widest variety of different products.

3.3.6 Space utilization

Space utilization or volume utilization can be measured as the ratio between the cubic space storage capacity (i.e. volume actually occupied by items) and the total available cubic space of the portion of building devoted to the storage function. The goal is to maximize space utilization so that the largest number of SKUs can be stored in the smallest space. Baby et al., 2013 regarded space utilization, together with proper storage and vehicle loading speed, the most important parameters affecting warehouse efficiency.

The step by step calculations performed to obtain the ranking shown in Table 3.8Table 3.7 are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 5.9%

Cat		Priority	Rank
1	Miniload AS/RS	12.5%	5
2	Horizontal Carousel	5.6%	6
3	Vertical Carousel	24.2%	1
4	Vertical Lift Module	20.4%	2
5	Shuttle-based S/RS	15.1%	4
6	Robot-based Compact S/RS	15.9%	3
7	Robotic Mobile Fulfillment	4.7%	7
8	A-Frame	1.5%	8

Table 3.8 Ranking of the alternatives with respect to space utilization [28]

A-frame because of its structure has the lowest space utilization, mainly due to two reasons, the impossibility to develop in height and the need to ensure sufficient space for the conveyor belt in the center of the A-frame.

RMF and horizontal carousel performance in terms of space utilization are limited by the height restriction. Both systems have a maximum height limited by the picker having to reach objects positioned at the top level of the pod. With respect to RMF, horizontal carousel performs better because they do not require aisles for robot movements.

All other automated storage systems can exploit the height in a facility thus achieving better space utilization. Miniload AS/RS and shuttle-based S/RS are very similar, they both require aisles for the movement of crane and shuttles, although as a result of the smaller size of shuttles compared to a crane, the aisles dedicated to the latter are generally wider, 1150mm average aisle width against 950 mm of the shuttle-based S/RS. Robot-based compact S/RS do not require aisles as bins are stacked one next to the other with no separating space, however some space is needed on top of the grid to allow for robot motion and bins extraction.

Finally, vertical lift module and vertical carousel are on top of the list because they take advantage of all the height of the facility and need no aisle. Vertical lift module is ranked below even if it is capable of dynamically adjusting the height of the trays, because it must leave some free space for the extractor machine to move.

3.3.7 Picking ergonomics

Although all the analyzed systems feature automatic storage and retrieval, picking and replenishment operations are carried out manually. Such operations asks for high human energy expenditure posing workers at risk to develop musculoskeletal disorders (MSD). The main features of the system such as physical dimension of the shelf, item positions and dimensions inevitably influence the picking ergonomics (Battini et al., 2017).

The step by step calculations performed to obtain the ranking shown in **Errore. L'origine riferimento non è stata trovata.** are reported in the appendix A.2.2 Computing the matrix of alternatives scores.

Consistency Ratio CR: 2.8%

Cat		Priority	Rank
1	Miniload AS/RS	22.8%	1
2	Horizontal Carousel	2.4%	8
3	Vertical Carousel	6.1%	6
4	Vertical Lift Module	8.2%	5
5	Shuttle-based S/RS	22.8%	1
6	Robot-based Compact S/RS	22.8%	1
7	Robotic Mobile Fulfillment	3.2%	7
8	A-Frame	11.7%	4

Table 3.9 Ranking of the alternatives with respect to picking ergonomics [28]

Horizontal carousel and RMF system are the worst performing due to their design. Storing items in vertical racks (or pods in case of RMF) at different heights forces the operator to bend and stretch to reach the desired items. In addition, horizontal carousels are often clustered in groups so that an operator can access different subsystems. This design obliges the worker to walk from carousel to carousel, further increasing the energy expenditure.

Vertical carousel and vertical lift module present items at an ergonomic height, roughly corresponding to waist level, but items are distributed along the tray whose dimension can be wider than 4 meters and deeper than 1 meter, forcing the operator to move sideways and bend forward to reach the desired objects. Vertical carousels can be also clustered in group causing the same problem already mentioned for the horizontal carousel. Vertical lift module performs better because modern systems allow to tilt the tray towards the operator, so that visibility is improved and most importantly the bending forward to reach objects in depth is reduced, thus significantly improving ergonomics.

A-frame system has fully automatized picking, which could be regarded as the best achievable solution from an ergonomic point of view. Storage channel replenishment however is to be performed manually, requiring the operator to insert the small boxes inside the storage channel and walking along the A-frame. It is classified ahead of the carousels because no bending forward is expected.

Lastly miniload AS/RS, shuttle-based S/RS and robot-based compact S/RS are designed to allow the operator to be stationary at the workstation and items to be presented to him at an ergonomic height inside small boxes so that he does not have to walk or bend at all.

3.4 Evaluation criteria hierarchy

Once the criteria are defined it is essential to give them weights according to their importance. The problem is that every company has its unique needs. Different companies manage products with very different characteristics (perishable products or slow moving products, for example) and also the demand pattern can vary greatly in terms of peaks and average demand or order size. For this exact reason, the seven evaluation criteria always take different importance depending on the company and business. Each warehouse has its own requirements and therefore it is not possible to define a criteria vector weights always valid. It is duty of the warehouse manager to estimate the relative importance of these 7 factors in his/her own specific context.

In order to show the application of the decision making tool developed, it was decided to refer to the Shimano case study. The choice came down to this case study for a few reasons. First, Dematic was chosen because as one of the largest suppliers of materials handling equipment in the world (see Table 1.1 Top 20 worldwide materials handling system suppliers [7]), it offers all eight automated storage systems considered in the analysis. Companies that do not offer all systems had to be excluded. For example, Swisslog does not sell carousels, so, even if for a given business carousels resulted the most suitable solution, they could not be implemented, and the analysis would be misleading.

The Shimano case was picked because it is one of the most recent projects published by Dematic and because of the wide range of information available (which are essential in defining the evaluation criteria weight). Lastly, Shimano has been chosen because in its warehouses it handles a wide variety of relatively small products in small batches, thus making it comparable to many other businesses that, although managing different products, have similar needs.

Before diving into criteria weight evaluation for the specific case of Shimano, it is necessary to briefly introduce the company, its objectives and requirements when it commissioned Dematic to rebuild its warehouse in the Sydney metropolitan area in 2015.

3.4.1 Shimano case study

Today as it was five years ago, Shimano is a world-leading Japanese multinational manufacturer and distributor of cycling, fishing and rowing equipment and accessories. The goal for the project was to merge together the two warehouses located in Sydney one of which was devoted to cycling and the other to fishing equipment. Although the two businesses distribute completely different products to a completely different customer base, there were obvious synergy in that they both handle a lot of relatively small products, parts and components. Having the two warehouses merged would have allowed to enhance the quality of their service offering to customers and to benefit from economies of scale, which in turn enables to reduce distribution costs.

The primary requirement and expectation for the project was an increased service level (defined in paragraph 0) which mainly depends on throughput capacity and picking accuracy. Furthermore, both fishing and cycling warehouses were historically based in Sydney Sutherland Shire where land costs are significantly higher with respect to other suburban areas and for this reason maximizing space utilization was critical. Since fully renewing the warehouse was going to be a big investment, another key concern was related to scalability, i.e. the ability to accommodate future growth. Scalability was doubly influential because, by building and purchasing only those structures and systems that are needed at the moment, it allows to reduce the initial investment, still leaving the possibility of expansion in the future.

3.4.2 Computation of the criteria weights vector

To obtain the criteria weight vector, as carefully explained in paragraph 3.2.1, the afore mentioned parameters throughput, picking accuracy, space utilization and scalability together with the other three evaluation criteria considered relevant for the storage system selection problem are pairwise compared and the vector showing the relative importance of each criterion is obtained. It is to be highlighted that the comparison of these criteria was based on the specific requirements of the Shimano company, referring to the data and publications available online both written by Dematic itself [24,25] or external magazines [26].

The criteria weight thus obtained is shown in Table 3.10, while complete calculations are reported in paragraph A.2.1 Computing the vector of criteria weights.

	Throughput	Picking accuracy	Scalability	Storage & retrieval interference	Flexibility in product dimensions	Space utilization	Picking ergonomics	**CRITERIA WEIGHT vector**	Ranking
Throughput	0,236	0,281	0,268	0,222	0,200	0,219	0,188	**23,06%**	**1**
Picking accuracy	0,157	0,188	0,214	0,185	0,200	0,219	0,188	**19,30%**	**3**
Scalability	0,094	0,094	0,107	0,185	0,200	0,088	0,125	**12,76%**	**4**
Storage & retrieval interference	0,079	0,094	0,036	0,074	0,050	0,073	0,125	**7,58%**	**6**
Flexibility in product dimensions	0,118	0,094	0,054	0,074	0,100	0,109	0,125	**9,63%**	**5**
Space utilization	0,236	0,188	0,268	0,222	0,200	0,219	0,188	**21,72%**	**2**
Picking ergonomics	0,079	0,063	0,054	0,037	0,050	0,073	0,063	**5,96%**	**7**

Table 3.10 Computation of the criteria weights vector and criteria ranking

Following the previously described factors (throughput, picking accuracy, space utilization and scalability), which are obviously ranked as most relevant, there is flexibility in product dimension. Such feature is quite relevant for the new Shimano warehouse because dealing with both cycling and fishing equipment means dealing with a great variety of different products with varying shapes and sizes.

Storage and retrieval interference came in second to last place because being Shimano a manufacturer the flow of material is quite predictable, allowing to schedule with accuracy time to be dedicated to storage and time dedicated to replenishment, something that can be more difficult in distribution centers or e-commerce warehouses.

Finally, picking ergonomics turns out to be the least relevant criterion, not because it is of little importance in general, but because when considering automatic storage systems, the manual operations carried out by the worker represent only a small fraction of the retrieval process, i.e. picking; moreover, all the systems investigated guarantee good ergonomic standards and difference between is limited.

3.5 Results

The results provided by the decision-making assistance tool are reported in Table 3.11, while complete calculations may be found in section A.2.2. The Table 3.11 clearly highlights how the most suitable solution for the new Shimano warehouse is the shuttle-based storage and retrieval system. Even if shuttle-based system is the best performing system only as far as picking ergonomics is concerned (which is the least influential criterion), this result should come as no surprise because it provides the best trade-off and best overall performances. The automated storage system suggested by the decision-making tool turns out to be the same as the one actually implemented by Dematic, thus confirming the reliability of the decision making tool.

	Relative Ranking	Systems	Final Ranking
	10,15%	MiniLoad AS/RS	6
	6,04%	Horizontal Carousel	8
	9,95%	Vertical Carousel	7
v=S*w=	11,21%	Vertical Lift Module	5
	18,29%	Shuttle-based S/RS	1
	15,69%	Robot-based Compact S/RS	3
	12,24%	Robotic Mobile Fulfillment	4
	16,44%	A-Frame	2

Table 3.11 Automated storage and retrieval systems final ranking for the Sydney Shimano warehouse

The solution provided by Dematic is indeed their Multishuttle goods-to-person (GTP) order fulfillment system. The Multishuttle itself occupies only 200 square meters of floorspace and additional 200 square meters are dedicated to the three goods-to-person workstations and conveyors. Storage capacity exceeds 6000 plastic totes, which are stored double deep in the metallic rack over 16 levels reaching a height of 12 meters, each level being served by its own shuttle as depicted in Figure 3.2.

To further improve performances, stock locations are assigned dynamically. The Dematic iQ software analyzes how often each SKU is required and after a certain SKU is retrieved, it adjusts the SKU storage location, so that fast-moving SKU will be found towards the front of the system, while slow-moving SKU will be placed towards the rear. The Multishuttle system is able to supply approximately 200 totes per hour to each of the three workstations. The system is serviced by two lifts, one feeding totes into the aisle and the second feeding totes out, both lifts are capable of handling two totes at a time.

As explained in paragraph 3.3.2, the shuttle-based storage and retrieval system is one of the best performing in terms of picking accuracy, but to further reinforce this property in the Shimano warehouse all workstations are equipped with Pick-to-light displays that suggest to the operator the number of items required for each order, virtually eliminating the possibility of picking errors.

Figure 3.2 Overview of the three Goods-to-Person workstations and Multishuttle system

The Dematic system layout was designed with expansion in mind. Space has been reserved adjacent to the Multishuttle system for a future aisle, which would provide 50% more storage capacity, together with additional workstations to enable a further increase in throughput and guaranteeing scalability.

To allow the handling of the large number of different SKUs managed inside the Shimano warehouse, each tote can be divided into a maximum of eight compartments by means of easily removable dividers.

Finally, the system is serviced by two lifts, one feeding totes into the aisle and the second feeding totes out, both lifts are capable of handling two totes at a time. All three workstations are dual purpose meaning that they can be used for picking and for replenishment without the need for set up or operation stop.

4. Conclusion

This thesis begins with an introductory overview of the functions of a warehouse, the different management policies, and the different categories of order picking systems. The attention is then concentrated on the automated storage and retrieval systems. The characteristics and functioning of the main systems belonging to the automated storage and retrieval category are presented. In chapter two, the solutions currently marketed on the market by the largest material handling suppliers are analyzed in detail and compared.

The last chapter is the most interesting of the thesis, because after discussing the seven factors that are considered most relevant for the automated storage system selection process, it presents the core of the thesis, the model that was developed by the author with the aim of assisting the warehouse manager in the difficult decision of the most suitable automated storage system. Such model was validated by means of the Shimano case study, which showed the shuttle-based system was the most suitable overall but did not excel in any of the criteria taken into consideration, thus achieving the exact same result actually implemented by Dematic in the Shimano warehouse in Sydney. This tool is therefore to be considered a support based on numbers and rigorous calculations in a decision making process, that of warehouse automation, which is often guided simply by experience and feeling rather than statistics.

Commenting on reliability of the proposed MCDA tool, it is necessary to provide a couple of clarifications firstly on the cost issue and secondly on the validation process of the developed support tool. In the real world cost of implementation, cost of use and return on investment (ROI) play a primary role in the process of selecting one storage system over another and need to be carefully considered. Nevertheless, these factors, which might deserve a separate discussion, have been omitted from the discussion because they go beyond the scientific dissertation and exceed the original purpose of the work. About the tool reliability, it is evident that it still requires an extensive validation process. The Shimano case study alone is clearly not sufficient to confirm the full reliability of the instrument, other case studies from different industries and involving different automated storage systems need to be analyzed and need to match successful implementations. The Shimano case study was presented as a demonstration of its usefulness and benefits, awaiting full validation in the future.

The present study highlighted on one side, the warehouse managers growing interest in the implementation of automated order picking systems and on the other also to be noted the increasing involvement from material handling suppliers towards the development of deeper warehouse automation solution is to be noted. This upward trend leads to believe that this study is a necessary contribution in the field of automatic storage and retrieval systems literature.

Furthermore, as previously discussed, academic research about the storage system selection is scarce and wide range of options available on the market with their different operating principles, make it difficult to perform a complete comparison and evaluation. This thesis therefore contributes to the existing literature in the warehouse automation stream by providing a simple analytical aid to the decision making process.

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A. Appendix

A.1 Automated storage and retrieval system technical specifications

Company	Product Name	# Mast	Load storage density	Height of the grid [m]	Payload per bin/tray [kg]	Throughput	Vertical (Hoisting) speed [m/s]	Horizontal (Travelling) speed [m/s]	Vertical Acceleration [m/s2]	Horizontal Acceleration [m/s²]	Temperature [°C]
Daifuku	**Unit Load AS/RS**	1 or 2	Double Deep	36	3000	n.d.	1,7	4,2	n.d.	n.d.	- 30 ÷ 50
SSI Schaefer	**Exyz**	1 or 2	Multi Deep	45	1200	n.d.	1,5	4	n.d.	n.d.	-20 ÷ 35
SSI Schaefer	**Lift & Run**	2	Multi-Deep	9	n.d.	1000 (only 1 tray)	0,6	4	n.d.	0,8	-28 ÷ 35
Dematic	**RapidStore UL**	1	Triple Deep	33,5	2270	60 [double cycles/h]	1,3	3,6	0,7	0,7	-20 ÷ 35
SwissLog	**Vectura**	1 or 2	Multi Deep	45	3500	45 [double cycles/h]	1,5	5	n.d.	n.d.	- 30 ÷ 50
System Logistics	**Stacker Crane**	1 or 2	Double Deep	40		n.d.	n.d.	4	n.d.	n.d.	- 30 ÷ 35
Ferretto Group	**Stacker Crane**	1 or 2	Double Deep	40	1500	n.d.	1	3,5	1	0,4	-20 ÷ 35
Mecalux	**MT**	1 or 2	Triple Deep	45	1500	n.d.	1,1	3,7	0,5	0,45	- 30 ÷ 40

Table A.1 Unit load AS/RS

Company	Product Name	Aisle width [mm]	Aisle length [m]	# Mast	Load storage density	Height of the grid [m]	Payload per bin/tray [kg]	Vertical (Hoisting) speed [m/s]	Horizontal (Travelling) speed [m/s]	Vertical Acceleration [m/s2]	Horizontal Acceleration [m/s2]
Dematic	**RapidStore ML14**	1060	n.d.	1 or 2	Quadruple	14	100	3	6	3,9	5,2
Ferretto Group	**Trasloelevatore MiniLoad**	n.d.	n.d.	1	Double deep	25	500	1	4	1	1
Jungheinrich	**STC 2B1A**	n.d.	110	1	Quadruple	14	100	3	6	4	5,3
Mecalux	**ML 100**	n.d.	n.d.	1 or 2	Double deep	12	100	1,5	3,3	0,75	0,8
SSI Schaefer	**Miniload Crane 1**	850 ÷ 1500	n.d.	1 or 2	Multi deep	18	100	4	5	4	3
SwissLog	**Tornado**	n.d.	150	1	Quadruple	24	250	3	6	4	4
System Logistics	**Trasloelevatore MiniLoad**	n.d.	n.d.	1 or 2	Multi deep	22	650	n.d.	5,5	n.d.	n.d.
TGW	**MUSTANG**	n.d.	n.d.	1 or 2	Multi deep	25	100	3	6	3	3,5

Table A.2 MiniLoad crane

Company	Product Name	Carousel lenght [mm]	Carrier Width [mm]	Carrier depth [mm]	Carrier height [mm]	Carrier payload [kg]	Rotational speed [m/min]
Kardex Remstar	**Horizontal**	5900 to 46700	622 or 825 or 960	460 or 560 or 610	1854 to 3658	450 or 680 or 900	24

Table A.3 Horizontal Carousel

Company	Product Name	Machine dimesnion			Unit Imbalance [kg]	Payload per carrier [kg]	Total Load [ton]
		Width [mm]	Depth	Height			
Ferretto Group	**Eurot**	2740 ÷ 3364	1103 ÷ 1715	2330 ÷ 6530	n.d.	130 ÷ 300	2,8 ÷ 7
Jungheinrich	**Paternoster**	3703 ÷ 4953	1836 ÷ 2236	3040 ÷ 14890	3000	600	16
Kardex Remstar	**Megamat RS**	1875 ÷ 4275	1251 ÷ 1711	2210 ÷ 10010	600 ÷ 2100	180 ÷ 650	6 ÷ 19

Table A.4 Vertical Carousel

Company	Product Name	Machine dimesnion			Unit height Pitch [mm]	Vertical Speed [m/s]	Payload per level [kg]	Total Load [ton]
		Width	Depth	Height				
Ferretto Group	**Vertimag**	2434 ÷ 4734	3374 ÷ 4134	3000 ÷ 15000	75	n.d.	300 ÷ 990	70
Jungheinrich	**Lift racking**	1580 ÷ 4380	2312 ÷ 4343	2250 ÷ 30050	75 ÷ 150	2	725	70
Kardex Remster	**Shuttle XP**	1580 ÷ 4380	2362 ÷ 4343	2550 ÷20050	50 ÷ 100	0,75 ÷ 2	560 ÷ 1000	67 or 120
SSI Schaefer	**Logimat**	2370 ÷ 4570	2712 ÷ 3092	2450 ÷ 23850	100	n.d.	700	60

Table A.5 Vertical Lift

Company	Product Name	Shuttle motion		Max Load storage density	Bin dimension [mm]			Height of the grid [m]	Payload per bin/tray [kg]	Throughput [order lines per hour per port]	Vertical (Hoisting) speed [m/s]	Horizontal (Travelling) speed [m/s]	Vertical Acceleration [m/s2]	Horizontal Acceleration [m/s2]	Temp. [°C]
		VERT. (y-axis)	HORIZ. (x-axis)		Length	Depth	Height								
Daifuku	**Shuttle Rack M**	SINGLE-level	Single-Aisle	Double Deep	190 ÷ 450	200 ÷ 650	≥ 80	18	40	n.d.	1,7	3 ÷ 3,3	4,9	2	n.d.
Dematic	**Multishuttle**	SINGLE-level	Single-Aisle	Multi Deep	200 ÷ 850	150 ÷ 625	50 ÷ 600	12,2	50	500	n.d.	4	n.d.	2	0 ÷ 40
KNAPP	**OSR Shuttle**	SINGLE-level	Multi-Aisle	Multi Deep	250 ÷ 850	250 ÷ 650	n.d.	24	50	n.d.	5	4	7	1	n.d.
SSI Schaefer	**Flexi**	SINGLE-level	Single-Aisle	Quadruple Deep	≤ 860	≤ 680	n.d.	30	50	n.d.	4	4	7	n.d.	0 ÷ 45
SSI Schaefer	**Navette**	MULTI-level	Single-Aisle	Double Deep	n.d.	n.d.	n.d.	3 ÷ 24	4 x 35	n.d.	2,5	2,5	2,5	1,8	4 ÷ 40
SwissLog	**Cyclone-Carrier**	SINGLE-level	Single-Aisle	Quadruple Deep	200 ÷ 470	200 ÷ 670	50 ÷ 500	25	35 ÷ 50	1000	4	4	7	2	0 ÷ 45
EXOTEC	**SKYPOD**	MULTI-level	Multi-Aisle	Single Deep	650	450	220 - 320	12	30	450	4	4	n.d.	n.d.	n.d.
OPEX	**Perfect Pick**	MULTI-level	Single Aisle	Double deep	76,2	50,8	20,3 ÷ 35,6	9,9	36	400	n.d.	n.d.	n.d.	n.d.	n.d.

Table A.6 Automated Vehicle Storage and Retrieval Systems

Company	Product Name	Bin dimension [mm]			Height of the grid [m]	Payload per bin/tray [kg]	System capacity [# bins]	Throughput [order lines per hour per port]	Horizontal (Travelling) speed [m/s]	Horizontal (Travelling) acceleration [m/s2]	Lift Speed [m/s]	Temp. [°C]
		Length	Depth	Height								
SwissLog	**AUTOSTORE**	649	449	220 - 330 - 425	5,4	30	5000 ÷ 30000	350/650	3,1	0,8	1,6	5 ÷ 40

Table A.7 Robot-Based Compact S/RS

Company	Product Name	Mobile Rack dimension [mm]			Vehicle Load Capacity [kg]	Horizontal (Travelling) speed [m/s]	Horizontal (Travelling) acceleration [m/s2]
		Length	Depth	Height			
Amazon	**Amazon Robotics**	1000	1000	1800 ÷ 2400	600	Loaded: 1 m/s Unloaded: n.d.	n.d.
SwissLog	**CARRYPICK**	1300	900	2500	600	Loaded: 1 m/s Unloaded: 1,5 m/s	n.d.

Table A.8 Robotic Mobile Fulfillment Systems

Company	Product Name	Channel lenght	Channel width	Channel height	Product channel width	Number of levels	Ejection Speed [pcs/sec]	Conveyor speed [m/s]
SSI Schaefer	A-frame	1460 ÷ 2500	n.d.	n.d.	55 ÷ 120	1 or 2 per side	4	2,2
Inther	A-frame	2565	1279	2023	25 ÷ 200	1	5	1

Table A.9 A-Frame

A.2 AHP calculations

A.2.1 Computing the vector of criteria weights

Pair-wise comparison matrix --> A							
	Throughput	Picking accuracy	Scalability	Storage & retrieval interference	Flexibility in product dimensions	Space utilization	Picking ergonomics
Throughput	1	1 1/2	2 1/2	3	2	1	3
Picking accuracy	2/3	1	2	2 1/2	2	1	3
Scalability	2/5	1/2	1	2 1/2	2	2/5	2
Storage & retrieval interference	1/3	1/2	1/3	1	1/2	1/3	2
Flexibility in product dimensions	1/2	1/2	1/2	1	1	1/2	2
Space utilization	1	1	2 1/2	3	2	1	3
Picking ergonomics	1/3	1/3	1/2	1/2	1/2	1/3	1
SUM	**4,233**	**5,333**	**9,333**	**13,500**	**10,000**	**4,567**	**16,000**

Table A.10 Pairwise comparison matrix A [m x m]

Normalized Pair-wise comparison matrix --> A_norm									
	Throughput	Picking accuracy	Scalability	Storage & retrieval interference	Flexibility in product dimensions	Space utilization	Picking ergonomics	**CRITERIA WEIGHT vector**	Ranking
Throughput	0,2362	0,2813	0,2679	0,2222	0,2000	0,2190	0,1875	**23,06%**	**1**
Picking accuracy	0,1575	0,1875	0,2143	0,1852	0,2000	0,2190	0,1875	**19,30%**	**3**
Scalability	0,0945	0,0938	0,1071	0,1852	0,2000	0,0876	0,1250	**12,76%**	**4**
Storage & retrieva	0,0787	0,0938	0,0357	0,0741	0,0500	0,0730	0,1250	**7,58%**	**6**
Flexibility in produ	0,1181	0,0938	0,0536	0,0741	0,1000	0,1095	0,1250	**9,63%**	**5**
Space utilization	0,2362	0,1875	0,2679	0,2222	0,2000	0,2190	0,1875	**21,72%**	**2**
Picking ergonomic	0,0787	0,0625	0,0536	0,0370	0,0500	0,0730	0,0625	**5,96%**	**7**

Table A.11 Normalized pairwise comparison matrix A_norm [m x m]

Step 3 consistency check									
	Throughput	Picking accuracy	Scalability	Storage & retrieval interference	Flexibility in product dimensions	Space utilization	Picking ergonomics	**WEIGHTED SUM VALUE**	**Weighted Sum Value / Criteria Weight**
Throughput	0,2306	0,2895	0,3190	0,2273	0,1926	0,2172	0,1789	1,6549	7,1773
Picking accuracy	0,1537	0,1930	0,2552	0,1894	0,1926	0,2172	0,1789	1,3799	7,1501
Scalability	0,0922	0,0965	0,1276	0,1894	0,1926	0,0869	0,1192	0,9044	7,0880
Storage & retrieval interference	0,0769	0,0965	0,0425	0,0758	0,0481	0,0724	0,1192	0,5314	7,0151
Flexibility in product dimensions	0,1153	0,0965	0,0638	0,0758	0,0963	0,1086	0,1192	0,6754	7,0151
Space utilization	0,2306	0,1930	0,3190	0,2273	0,1926	0,2172	0,1789	1,5584	7,1756
Picking ergonomics	0,0769	0,0643	0,0638	0,0379	0,0481	0,0724	0,0596	0,4230	7,0952

Values of the random Index				
n	**RI**			
2	0			
3	0,58		λ_max =	7,1024
4	0,9		Consistency index (CI) =	0,0171
5	1,12		Consistency Ratio =	1,29%
6	1,24			
7	1,32			
8	1,41			
9	1,45			
10	1,51			

Table A.12 Consistency check

A.2.2 Computing the matrix of alternatives scores

Throughput

Pairwise comparison matrix B [n x n]								
Throughput	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	1/4	1/3	1/3	1/9	1/8	1/8	1/8
Horizontal Carousel	4	1	2	2	1/7	1/5	1/5	1/8
Vertical Carousel	3	1/2	1	1/2	1/7	1/5	1/5	1/7
Vertical Lift Module	3	1/2	2	1	1/7	1/6	1/6	1/7
Shuttle-based S/RS	9	7	7	7	1	5	4	1/3
Robot-based Compact S/RS	8	5	5	6	1/5	1	1/2	1/4
Robotic Mobile Fulfillment	8	5	5	6	1/4	2	1	1/3
A-Frame	8	8	7	7	3	4	3	1
SUM	**44,000**	**27,250**	**29,333**	**29,833**	**4,990**	**12,692**	**9,192**	**2,452**

Table A.13 Pairwise comparison matrix B with respect to Throughput

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Throughput	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,023	0,009	0,011	0,011	0,022	0,010	0,014	0,051	1,89%
Horizontal Carousel	0,091	0,037	0,068	0,067	0,029	0,016	0,022	0,051	4,75%
Vertical Carousel	0,068	0,018	0,034	0,017	0,029	0,016	0,022	0,058	3,27%
Vertical Lift Module	0,068	0,018	0,068	0,034	0,029	0,013	0,018	0,058	3,83%
Shuttle-based S/RS	0,205	0,257	0,239	0,235	0,200	0,394	0,435	0,136	26,25%
Robot-based Compact S/RS	0,182	0,183	0,170	0,201	0,040	0,079	0,054	0,102	12,65%
Robotic Mobile Fulfillment	0,182	0,183	0,170	0,201	0,050	0,158	0,109	0,136	14,87%
A-Frame	0,182	0,294	0,239	0,235	0,601	0,315	0,326	0,408	32,49%

Table A.14 Normalized pairwise comparison matrix B with respect to Throughput

Consistency check									
Throughput	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,019	0,012	0,011	0,013	0,029	0,016	0,019	0,041	8,396
Horizontal Carousel	0,076	0,047	0,065	0,077	0,038	0,025	0,030	0,041	8,385
Vertical Carousel	0,057	0,024	0,033	0,019	0,038	0,025	0,030	0,046	8,289
Vertical Lift Module	0,057	0,024	0,065	0,038	0,038	0,021	0,025	0,046	8,197
Shuttle-based S/RS	0,170	0,332	0,229	0,268	0,263	0,633	0,595	0,108	9,895
Robot-based Compact S/RS	0,151	0,237	0,164	0,230	0,053	0,127	0,074	0,081	8,826
Robotic Mobile Fulfillment	0,151	0,237	0,164	0,230	0,066	0,253	0,149	0,108	9,132
A-Frame	0,151	0,380	0,229	0,268	0,788	0,506	0,446	0,325	9,519

λ_max =	8,830
Consistency index (CI) =	0,119
Consistency Ratio =	8,41%

Table A.15 Consistency check with respect to Throughput

Picking accuracy

Pairwise comparison matrix B [n x n]				Pairwise comparison matrix B [n x n]				
Picking accuracy	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	4	3	3	1	1	4	1/3
Horizontal Carousel	1/4	1	1/3	1/3	1/4	1/4	1	1/3
Vertical Carousel	1/3	3	1	1	1/3	1/3	3	1/2
Vertical Lift Module	1/3	3	1	1	1/3	1/3	3	1/2
Shuttle-based S/RS	1	4	3	3	1	1	4	1/3
Robot-based Compact S/RS	1	4	3	3	1	1	4	1/3
Robotic Mobile Fulfillment	1/4	1	1/3	1/3	1/4	1/4	1	1/2
A-Frame	3	3	2	2	3	3	2	1
SUM	**7,167**	**23,000**	**13,667**	**13,667**	**7,167**	**7,167**	**22,000**	**3,833**

Table A.16 Pairwise comparison matrix B with respect to Picking accuracy

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Picking accuracy	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,140	0,174	0,220	0,220	0,140	0,140	0,182	0,087	16,25%
Horizontal Carousel	0,035	0,043	0,024	0,024	0,035	0,035	0,045	0,087	4,12%
Vertical Carousel	0,047	0,130	0,073	0,073	0,047	0,047	0,136	0,130	8,54%
Vertical Lift Module	0,047	0,130	0,073	0,073	0,047	0,047	0,136	0,130	8,54%
Shuttle-based S/RS	0,140	0,174	0,220	0,220	0,140	0,140	0,182	0,087	16,25%
Robot-based Compact S/RS	0,140	0,174	0,220	0,220	0,140	0,140	0,182	0,087	16,25%
Robotic Mobile Fulfillment	0,035	0,043	0,024	0,024	0,035	0,035	0,045	0,130	4,66%
A-Frame	0,419	0,130	0,146	0,146	0,419	0,419	0,091	0,261	25,38%

Table A.17 Normalized pairwise comparison matrix B with respect to Picking accuracy

Consistency check									
Picking accuracy	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,163	0,165	0,256	0,256	0,163	0,163	0,186	0,085	8,832
Horizontal Carousel	0,041	0,041	0,028	0,028	0,041	0,041	0,047	0,085	8,532
Vertical Carousel	0,054	0,123	0,085	0,085	0,054	0,054	0,140	0,127	8,473
Vertical Lift Module	0,054	0,123	0,085	0,085	0,054	0,054	0,140	0,127	8,473
Shuttle-based S/RS	0,163	0,165	0,256	0,256	0,163	0,163	0,186	0,085	8,832
Robot-based Compact S/RS	0,163	0,165	0,256	0,256	0,163	0,163	0,186	0,085	8,832
Robotic Mobile Fulfillment	0,041	0,041	0,028	0,028	0,041	0,041	0,047	0,127	8,445
A-Frame	0,488	0,123	0,171	0,171	0,488	0,488	0,093	0,254	8,962

λ_{max} =	8,673
Consistency index (CI) =	0,096
Consistency Ratio =	6,82%

Table A.18 Consistency check with respect to Picking accuracy

Scalability

Pairwise comparison matrix B [n x n]								
Scalability	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	3	3	3	1/4	1/4	1/4	3
Horizontal Carousel	1/3	1	1	1/3	1/5	1/4	1/4	1
Vertical Carousel	1/3	1	1	1/3	1/5	1/4	1/4	1
Vertical Lift Module	1/3	3	3	1	1/4	1/4	1/4	3
Shuttle-based S/RS	4	5	5	4	1	1/2	1/4	5
Robot-based Compact S/RS	4	4	4	4	2	1	1	4
Robotic Mobile Fulfillment	4	4	4	4	4	1	1	4
A-Frame	1/3	1	1	1/3	1/5	1/4	1/4	1
SUM	**14,333**	**22,000**	**22,000**	**17,000**	**8,100**	**3,750**	**3,500**	**22,000**

Table A.19 Pairwise comparison matrix B with respect to Scalability

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Scalability	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,070	0,136	0,136	0,176	0,031	0,067	0,071	0,136	10,30%
Horizontal Carousel	0,023	0,045	0,045	0,020	0,025	0,067	0,071	0,045	4,28%
Vertical Carousel	0,023	0,045	0,045	0,020	0,025	0,067	0,071	0,045	4,28%
Vertical Lift Module	0,023	0,136	0,136	0,059	0,031	0,067	0,071	0,136	8,25%
Shuttle-based S/RS	0,279	0,227	0,227	0,235	0,123	0,133	0,071	0,227	19,06%
Robot-based Compact S/RS	0,279	0,182	0,182	0,235	0,247	0,267	0,286	0,182	23,24%
Robotic Mobile Fulfillment	0,279	0,182	0,182	0,235	0,494	0,267	0,286	0,182	26,33%
A-Frame	0,023	0,045	0,045	0,020	0,025	0,067	0,071	0,045	4,28%

Table A.20 Normalized pairwise comparison matrix B with respect to Scalability

Consistency check									
Scalability	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,103	0,128	0,128	0,248	0,048	0,058	0,066	0,128	8,802
Horizontal Carousel	0,034	0,043	0,043	0,028	0,038	0,058	0,066	0,043	8,237
Vertical Carousel	0,034	0,043	0,043	0,028	0,038	0,058	0,066	0,043	8,237
Vertical Lift Module	0,034	0,128	0,128	0,083	0,048	0,058	0,066	0,128	8,158
Shuttle-based S/RS	0,412	0,214	0,214	0,330	0,191	0,116	0,066	0,214	9,216
Robot-based Compact S/RS	0,412	0,171	0,171	0,330	0,381	0,232	0,263	0,171	9,174
Robotic Mobile Fulfillment	0,412	0,171	0,171	0,330	0,762	0,232	0,263	0,171	9,546
A-Frame	0,034	0,043	0,043	0,028	0,038	0,058	0,066	0,043	8,237

λ_max =	8,701
Consistency index (CI) =	0,100
Consistency Ratio =	7,10%

Table A.21 Consistency check with respect to Scalability

Storage & retrieval interference

Pairwise comparison matrix B [n x n]								
Storage & retrieval interference	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	3	3	1/3	1/5	1/5	1/5	1/5
Horizontal Carousel	1/3	1	1	1/3	1/4	1/5	1/5	1/5
Vertical Carousel	1/3	1	1	1/3	1/4	1/5	1/5	1/5
Vertical Lift Module	3	3	3	1	1/4	1/4	1/4	1/4
Shuttle-based S/RS	5	4	4	4	1	1/2	1/2	1/3
Robot-based Compact S/RS	5	5	5	4	2	1	1	1/3
Robotic Mobile Fulfillment	5	5	5	4	2	1	1	1/3
A-Frame	5	5	5	4	3	3	3	1
SUM	**24,667**	**27,000**	**27,000**	**18,000**	**8,950**	**6,350**	**6,350**	**2,850**

Table A.22 Pairwise comparison matrix B with respect to Storage & retrieval interference

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Storage & retrieval interference	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,041	0,111	0,111	0,019	0,022	0,031	0,031	0,070	5,46%
Horizontal Carousel	0,014	0,037	0,037	0,019	0,028	0,031	0,031	0,070	3,34%
Vertical Carousel	0,014	0,037	0,037	0,019	0,028	0,031	0,031	0,070	3,34%
Vertical Lift Module	0,122	0,111	0,111	0,056	0,028	0,039	0,039	0,088	7,42%
Shuttle-based S/RS	0,203	0,148	0,148	0,222	0,112	0,079	0,079	0,117	13,84%
Robot-based Compact S/RS	0,203	0,185	0,185	0,222	0,223	0,157	0,157	0,117	18,13%
Robotic Mobile Fulfillment	0,203	0,185	0,185	0,222	0,223	0,157	0,157	0,117	18,13%
A-Frame	0,203	0,185	0,185	0,222	0,335	0,472	0,472	0,351	30,33%

Table A.23 Normalized pairwise comparison matrix B with respect to Storage & retrieval interference

Consistency check									
Storage & retrieval interference	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,055	0,100	0,100	0,025	0,028	0,036	0,036	0,061	8,070
Horizontal Carousel	0,018	0,033	0,033	0,025	0,035	0,036	0,036	0,061	8,309
Vertical Carousel	0,018	0,033	0,033	0,025	0,035	0,036	0,036	0,061	8,309
Vertical Lift Module	0,164	0,100	0,100	0,074	0,035	0,045	0,045	0,076	8,616
Shuttle-based S/RS	0,273	0,134	0,134	0,297	0,138	0,091	0,091	0,101	9,088
Robot-based Compact S/RS	0,273	0,167	0,167	0,297	0,277	0,181	0,181	0,101	9,069
Robotic Mobile Fulfillment	0,273	0,167	0,167	0,297	0,277	0,181	0,181	0,101	9,069
A-Frame	0,273	0,167	0,167	0,297	0,415	0,544	0,544	0,303	8,937

λ_max =	8,683
Consistency index (CI) =	0,098
Consistency Ratio =	6,92%

Table A.24 Consistency check with respect to Storage & retrieval interference

Flexibility in product dimensions

Pairwise comparison matrix B [n x n]								
Flexibility in product dimensions	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	1/4	1/3	1/3	1/2	4	1/4	7
Horizontal Carousel	4	1	2	1/2	4	5	1	9
Vertical Carousel	3	1/2	1	1/2	2	4	1/2	8
Vertical Lift Module	3	2	2	1	3	4	2	6
Shuttle-based S/RS	2	1/4	1/2	1/3	1	5	1/4	7
Robot-based Compact S/RS	1/4	1/5	1/4	1/4	1/5	1	1/5	8
Robotic Mobile Fulfillment	4	1	2	1/2	4	5	1	9
A-Frame	1/7	1/9	1/8	1/6	1/7	1/8	1/9	1
SUM	**17,393**	**5,311**	**8,208**	**3,583**	**14,843**	**28,125**	**5,311**	**55,000**

Table A.25 Pairwise comparison matrix B with respect to Flexibility in product dimension

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Flexibility in product dimensions	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,057	0,047	0,041	0,093	0,034	0,142	0,047	0,127	7,36%
Horizontal Carousel	0,230	0,188	0,244	0,140	0,269	0,178	0,188	0,164	20,01%
Vertical Carousel	0,172	0,094	0,122	0,140	0,135	0,142	0,094	0,145	13,06%
Vertical Lift Module	0,172	0,377	0,244	0,279	0,202	0,142	0,377	0,109	23,77%
Shuttle-based S/RS	0,115	0,047	0,061	0,093	0,067	0,178	0,047	0,127	9,19%
Robot-based Compact S/RS	0,014	0,038	0,030	0,070	0,013	0,036	0,038	0,145	4,80%
Robotic Mobile Fulfillment	0,230	0,188	0,244	0,140	0,269	0,178	0,188	0,164	20,01%
A-Frame	0,008	0,021	0,015	0,047	0,010	0,004	0,021	0,018	1,80%

Table A.26 Normalized pairwise comparison matrix B with respect to Flexibility in product dimension

Consistency check									
Flexibility in product dimensions	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,074	0,050	0,044	0,079	0,046	0,192	0,050	0,126	8,980
Horizontal Carousel	0,294	0,200	0,261	0,119	0,368	0,240	0,200	0,162	9,218
Vertical Carousel	0,221	0,100	0,131	0,119	0,184	0,192	0,100	0,144	9,116
Vertical Lift Module	0,221	0,400	0,261	0,238	0,276	0,192	0,400	0,108	8,817
Shuttle-based S/RS	0,147	0,050	0,065	0,079	0,092	0,240	0,050	0,126	9,244
Robot-based Compact S/RS	0,018	0,040	0,033	0,059	0,018	0,048	0,040	0,144	8,345
Robotic Mobile Fulfillment	0,294	0,200	0,261	0,119	0,368	0,240	0,200	0,162	9,218
A-Frame	0,011	0,022	0,016	0,040	0,013	0,006	0,022	0,018	8,223

λ_max =	8,895
Consistency index (CI) =	0,128
Consistency Ratio =	9,07%

Table A.27 Consistency check with respect to Flexibility in product dimension

Space utilization

Pairwise comparison matrix B [n x n]								
Space utilization	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	3	1/2	1/2	1	1/2	4	9
Horizontal Carousel	1/3	1	1/4	1/4	1/3	1/4	2	6
Vertical Carousel	2	4	1	2	1	3	4	9
Vertical Lift Module	2	4	1/2	1	1	3	4	9
Shuttle-based S/RS	1	3	1	1	1	1/2	4	9
Robot-based Compact S/RS	2	4	1/3	1/3	2	1	3	9
Robotic Mobile Fulfillment	1/4	1/2	1/4	1/4	1/4	1/3	1	6
A-Frame	1/9	1/6	1/9	1/9	1/9	1/9	1/6	1
SUM	**8,694**	**19,667**	**3,944**	**5,444**	**6,694**	**8,694**	**22,167**	**58,000**

Table A.28 Pairwise comparison matrix B with respect to Space utilization

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Space utilization	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,115	0,153	0,127	0,092	0,149	0,058	0,180	0,155	12,86%
Horizontal Carousel	0,038	0,051	0,063	0,046	0,050	0,029	0,090	0,103	5,88%
Vertical Carousel	0,230	0,203	0,254	0,367	0,149	0,345	0,180	0,155	23,55%
Vertical Lift Module	0,230	0,203	0,127	0,184	0,149	0,345	0,180	0,155	19,67%
Shuttle-based S/RS	0,115	0,153	0,254	0,184	0,149	0,058	0,180	0,155	15,59%
Robot-based Compact S/RS	0,230	0,203	0,085	0,061	0,299	0,115	0,135	0,155	16,04%
Robotic Mobile Fulfillment	0,029	0,025	0,063	0,046	0,037	0,038	0,045	0,103	4,85%
A-Frame	0,013	0,008	0,028	0,020	0,017	0,013	0,008	0,017	1,55%

Table A.29 Normalized pairwise comparison matrix B with respect to Space utilization

Consistency check									
Space utilization	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,129	0,177	0,118	0,098	0,156	0,080	0,194	0,139	8,482
Horizontal Carousel	0,043	0,059	0,059	0,049	0,052	0,040	0,097	0,093	8,358
Vertical Carousel	0,257	0,235	0,236	0,393	0,156	0,481	0,194	0,139	8,882
Vertical Lift Module	0,257	0,235	0,118	0,197	0,156	0,481	0,194	0,139	9,035
Shuttle-based S/RS	0,129	0,177	0,236	0,197	0,156	0,080	0,194	0,139	8,382
Robot-based Compact S/RS	0,257	0,235	0,079	0,066	0,312	0,160	0,145	0,139	8,687
Robotic Mobile Fulfillment	0,032	0,029	0,059	0,049	0,039	0,053	0,048	0,093	8,326
A-Frame	0,014	0,010	0,026	0,022	0,017	0,018	0,008	0,015	8,444

λ_{max} =	8,575
Consistency index (CI) =	0,082
Consistency Ratio =	5,82%

Table A.30 Consistency check with respect to Space utilization

Picking ergonomics

Pairwise comparison matrix B [n x n]								
Picking ergonomics	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame
MiniLoad AS/RS	1	7	4	3	1	1	6	3
Horizontal Carousel	1/7	1	1/4	1/4	1/7	1/7	1/2	1/5
Vertical Carousel	1/4	4	1	1/2	1/4	1/4	3	1/3
Vertical Lift Module	1/3	4	2	1	1/3	1/3	3	1/2
Shuttle-based S/RS	1	7	4	3	1	1	6	3
Robot-based Compact S/RS	1	7	4	3	1	1	6	3
Robotic Mobile Fulfillment	1/6	2	1/3	1/3	1/6	1/6	1	1/5
A-Frame	1/3	5	3	2	1/3	1/3	5	1
SUM	**4,226**	**37,000**	**18,583**	**13,083**	**4,226**	**4,226**	**30,500**	**11,233**

Table A.31 Pairwise comparison matrix B with respect to Picking ergonomics

Normalized Pair-wise comparison matrix --> B_norm [n x n]									
Picking ergonomics	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**SCORE VECTOR**
MiniLoad AS/RS	0,237	0,189	0,215	0,229	0,237	0,237	0,197	0,267	22,59%
Horizontal Carousel	0,034	0,027	0,013	0,019	0,034	0,034	0,016	0,018	2,44%
Vertical Carousel	0,059	0,108	0,054	0,038	0,059	0,059	0,098	0,030	6,32%
Vertical Lift Module	0,079	0,108	0,108	0,076	0,079	0,079	0,098	0,045	8,40%
Shuttle-based S/RS	0,237	0,189	0,215	0,229	0,237	0,237	0,197	0,267	22,59%
Robot-based Compact S/RS	0,237	0,189	0,215	0,229	0,237	0,237	0,197	0,267	22,59%
Robotic Mobile Fulfillment	0,039	0,054	0,018	0,025	0,039	0,039	0,033	0,018	3,33%
A-Frame	0,079	0,135	0,161	0,153	0,079	0,079	0,164	0,089	11,74%

Table A.32 Normalized pairwise comparison matrix B with respect to Picking ergonomics

Consistency check									
Picking ergonomics	MiniLoad Crane	Horizontal Carousel	Vertical Carousel	Vertical Lift Module	Shuttle-based S/RS	Robot-based Compact S/RS	Robotic Mobile Fulfillment	A-Frame	**Weighted Sum Value / Criteria Weight**
MiniLoad AS/RS	0,226	0,171	0,253	0,252	0,226	0,226	0,200	0,352	8,433
Horizontal Carousel	0,032	0,024	0,016	0,021	0,032	0,032	0,017	0,023	8,121
Vertical Carousel	0,056	0,098	0,063	0,042	0,056	0,056	0,100	0,039	8,089
Vertical Lift Module	0,075	0,098	0,126	0,084	0,075	0,075	0,100	0,059	8,248
Shuttle-based S/RS	0,226	0,171	0,253	0,252	0,226	0,226	0,200	0,352	8,433
Robot-based Compact S/RS	0,226	0,171	0,253	0,252	0,226	0,226	0,200	0,352	8,433
Robotic Mobile Fulfillment	0,038	0,049	0,021	0,028	0,038	0,038	0,033	0,023	8,036
A-Frame	0,075	0,122	0,190	0,168	0,075	0,075	0,166	0,117	8,428

λ_max =	8,278
Consistency index (CI) =	0,040
Consistency Ratio =	2,81%

Table A.33 Consistency check with respect to Picking ergonomics

Final ranking

Matrix of Alternatives S [n x m]

	0,019	0,163	0,103	0,055	0,074	0,129	0,226
	0,047	0,041	0,043	0,033	0,200	0,059	0,024
	0,033	0,085	0,043	0,033	0,131	0,236	0,063
S =	0,038	0,085	0,083	0,074	0,238	0,197	0,084
	0,263	0,163	0,191	0,138	0,092	0,156	0,226
	0,127	0,163	0,232	0,181	0,048	0,160	0,226
	0,149	0,047	0,263	0,181	0,200	0,048	0,033
	0,325	0,254	0,043	0,303	0,018	0,015	0,117

Criteria weight vector w

	0,231
	0,193
	0,128
w =	0,076
	0,096
	0,217
	0,060

	Relative Ranking	Systems	Final Ranking
	10,15%	MiniLoad AS/RS	6
	6,04%	Horizontal Carousel	8
	9,95%	Vertical Carousel	7
v=S*w=	**11,21%**	Vertical Lift Module	5
	18,29%	Shuttle-based S/RS	1
	15,69%	Robot-based Compact S/RS	3
	12,24%	Robotic Mobile Fulfillment	4
	16,44%	A-Frame	2

Table A.34 Multiplication of matrix of alternatives S by criteria weight vector w