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Robotic Mobile Fulfillment Systems: A survey on recent developments and research opportunities☆

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ABSTRACT

With the advancement of the autonomous mobile robots applied to Warehouses and the creation of the Robotic Mobile Fulfillment System after the market implementation of the *Kiva Robots*, it is necessary to carry out a deeper approach of the researches carried out to this date. The objective of this survey is to provide a unified and accessible presentation of the basic concepts of a warehouse system, such as its types, layouts, systems, and methodologies already applied to improve the activities, thus going to the latest research and methodologies focused on the development of new architectures and algorithms in *Robotic Mobile Fulfillment Systems (RMFS)*. The main contribution of this work is an attempt to present a comprehensive review of recent breakthroughs in the goods-to-person RMFS field, providing links to the most interesting and successful works from the state-of-the-art, but also to provide a presentation and summary of how a Warehouse systems works, in a way that allows future researchers to understand his taxonomies and principles of operation.

1. Introduction

Recent advances in the field of robotics had allowed several advances in diverse fields of study. As a result of this new trend, many applications can be improved to obtain better productivity, efficiency, robustness, and flexibility. While some applications require only one robot to perform tasks, others require multiple robots to perform certain actions. This methodology is called *multi-robot systems (MRS)*, a word that refers to systems of physical robots, where two or more robots perform a task using a cooperative approach. If the multi-robot system has multiple autonomous robots, several intelligent agents or a cognitive computing system, it can be defined as a multi-agent system (*MAS*) [2].

Despite the mew progresses in localization, mapping and exploration activities such as intelligent transportation using mobile robots, there are still problems that need solutions or improvement. Such as the ability to perform complex tasks similar to human execution, reliability on the robot's movement in the real world and the improvement of information analysis in a more rational way [3]. Some improvements and current challenges are also mentioned in [4], where the objectives can be better coordination in homogeneous or heterogeneous systems, the physical identity of agents and adaptations of artificial intelligence techniques to solve control problems.

According to [2], it is expected that by 2020 the use of robots to perform cooperative activities will exceed the investment of $20 million, much of this due to the exponential growth of the Internet of Things (IoT), and by 2025, over 4 million commercial robots will be installed in over 50,000 warehouses [5]. Consider for example a system with multiple robots that needs to carry out the transport of boxes in a warehouse autonomously, having a comprehensive area to run and with specific pickup and storage points. In addition to the necessary techniques for locomotion, mapping and sensing the environment, depending on the complexity of the task, these robots will also need an efficient network layer to maintain communication, or even a training control method for moving large objects in cooperation.

Although some surveys have been published in recent years addressing the field of Robotized & Automated Warehouses Systems. Were is presented a satisfactory and captivating analysis of this type of system, also addressing the available technologies, their subsystems, taxonomies, research areas, and possible gaps and research trends, they do not carry out a state-of-the-art analysis for the RMF system. In [6] and [7], despite having a complete explanation of how the system works, they state that the performance of an RMF system has hardly been studied scientifically. This affirmation is imprecise since some articles already

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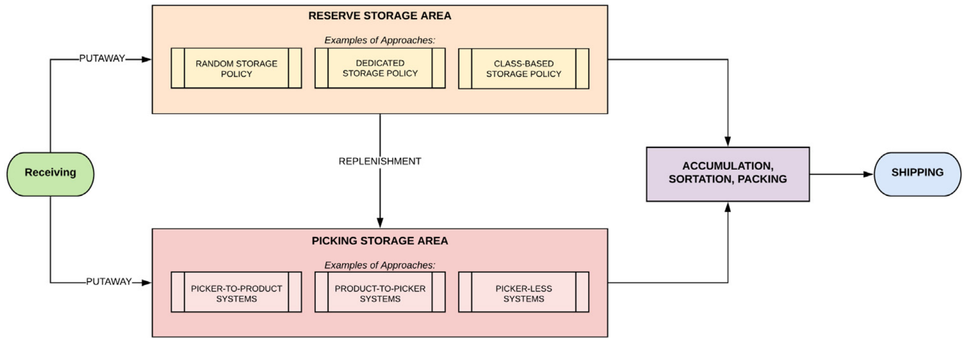


Fig. 1. An typical warehouse flow and operation according [1].

carry out this analysis, as will be seen in later topics. In [8], despite informing that there are already some works that analyze the performance of this field and provide engaging research questions, they do not address how the system implementations were made, and also use a different taxonomy, using *Robotic Moveable Rack system (RMR)*.

Thus, the following questions remain: What types of implementations available for RMFS? What are the challenges of the field? What frameworks are available? Also, it was possible to note that several articles did not use the correct taxonomy during the literature review or implementation of their work. An assumption we make is that the reasons for authors use different terms and definitions to represent the same thing is because RMFS is relatively new and still under development, so the access to articles is sometimes laborious and a little confusing. Considering these problems, the first contribution of this survey is to provide researchers a summary of how a Warehouse System works so that they know the current taxonomies and research areas, focusing on unify future taxonomies used. Finally, this survey also reviews the trends and research gaps found in RMF systems, compiling the latest successful articles published with their solutions and proposals.

The organization of this paper will be as follows: In the first section, an analysis of the basic concepts of a Warehouse will be presented, covering aspects of taxonomy, typology, layout, systems and a brief review on the study-of-the-art in the most common approaches and solutions for problems found in the area like *Routing*, *Bend Aisle*, *Location Assignment*, Warehouse Physical Layout (regular or irregular), Warehouse Characteristics as *Aisle* (*Bend Aisle*, *Cross Aisle*, and *Multi Aisle*). The second section will be conducted a review on the latest objectives and approaches on the field of multi-agent systems using mobile robots applied to Warehouses (a.k.a. Robotic Mobile Fulfillment Systems), thus proceeding to an analysis of the research gaps found and consecutively proposed areas for future work and research opportunities.

Finally, is worth mentioning that despite new autonomous robotic technologies emerged in recent years for Warehouse-like systems, such as the Bin-to-Person Picking, Collaborative Picking, Smart Moving, and Smart Sorting [9], this work aims to study the smart goods-to-person picking in RMFS. One of the reasons for not addressing and inserting the other systems is its recent implementation in the market, thus not having studies that address these new technologies.

2. An brief review on warehouses systems, layouts, and typologies

To elaborate the search process, we first used selection criteria for the search engines, where the selected ones must allow the use of logical expressions, must have a base of publications from the field, must allows text search publications, and must have few problems with the search algorithm. In this way, the search was carried out through digital libraries with a considerable impact or number of publications in the field of robotics, production, and logistics, as shown in Table 1. As exclusion criteria, only publications that included the use of robots (AGVs or AMRS) written in English were selected. In total, more than 250 articles returned, with 120 selected in the first run after the Title and Abstract reading, following by a second run with 75 publications selected for review after Full-Text reading.

Table 1
Digital libraries selected.

Digital Library	Website
IEEEXplore	https://ieeexplore.ieee.org
ScienceDirect	https://www.sciencedirect.com
SAGE Journals	https://journals.sagepub.com/
Springer Link	https://link.springer.com/

One of the first references to the storage of goods as a form of trade can be found in ancient Rome, where the increase in trade caused the need to construct buildings where this type of work was carried out, called *horreas* (for more information see [10]). Over the years, it was possible to notice the development of this system gaining strength with the creation of railroads in the United States and the great impulse and need for storage of goods during the consecutive Industrial Revolutions [11].

After the Second World War and with the new trend of technologies and research development in the field of Data Analysis, Artificial Intelligence, Machine Learning, and Robotics, the Warehouse system was divided into several Typologies, Layouts, and Systems. According to [12], a Warehouse is an industrial building, characterized as a facility primarily used for storage or distribution of materials. We can complement this technical definition through a more general view of its use today, Richards [13] defines that the main function of a Warehouse is to satisfy the form of exponential consumption, efficiently meeting the needs of the consumer so that the product is delivered in the right time, quantity and quality.

The typical flow of goods in a Warehouse can be seen in Fig. 1. According to [14], the whole process can be described as follows:

- The goods received are unloaded, where quantities are checked and quality checks are carried out;
- The approved goods are prepared for transport to storage, where a label, QR Code, Bar Code or Magnetic Label is added
- After transportation, the goods are stored in the Storage Area, following some storage policies [1]. If any material present at this location is requested, the process of *Order Picking* starts, where the products are listed, classified and sent to the Picking Storage Area;

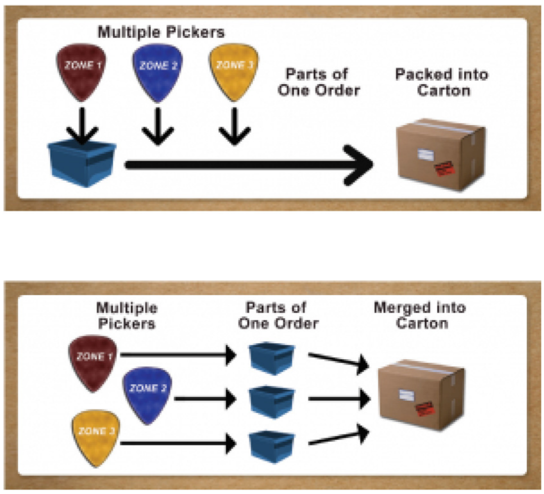


Fig. 2. *Pick-and-pass* and *pick-and-merge* methods.

- After that, the goods will be accumulated, assorted and packaged, thus proceeded to shipment.

It is worth mentioning that more than 60% of all operational costs of a Warehouse are attributed to *Order Picking* [14], with *Packing* being the biggest throttle in the entire fulfillment process [15]. According to [16], the sub-processes of *Order Picking* that have a major impact on the time needed to perform the activity is the traveling and the search for items, totaling approximately 70% of the collection time, and becoming one of the most important factors for achieving better efficiency in the operational level.

Because a Warehouses normally has to deal with different quantities of SKUs, some fundamental concepts and taxonomies must be scored [14]. Some policies commonly used during a *order-picking* can be seen below [16]:

- When multiple orders need to be picked simultaneously in a single *order-picking* is called *batch-picking*, where picking is done in a certain zone (*zoning*);
- A *zone* can be created considering some variables such as product size, temperature and safety procedures [16];
- Although the *zoning* method has some advantages, such as reducing the distance covered by the *picker* [16] and consecutively reducing the collection time, the products will need to be sorted during or after the process [14], increasing the total process time;
- One of the ways to reduce the total process time in the *zoning* is to use methods like *sequential zoning/pick-and-pass* and *parallel zoning/pick-and-merge* [16]; As can be seen in Fig. 2 [17], the *pick-and-pass* method is characterized by the collection of products from a *order*, made zone by zone sequentially until all parts of an order are reached. The *pick-and-merge* is the collection of products from a *order* from different zones at the same time, followed by the merge of all order parts;
- The product sorting can be done during the process (*sort-while-pick*) where the orders are separated into specific containers for each individual order, or after the execution of the same (*pick-and-sort*), where *wave picking* can be done in turns in the respective zones at the same time.

Considering this methods and taxonomies, the *Order Picking* process optimization can be divided into two major areas: *Routing*, characterized by the path planning and trajectory along the Warehouse, allowing the pickup of the goods (one or multiple) in the most efficient way possible (shortest path), and *Location Assignment*, characterized by the best location where the materials will be placed, promoting a better picking efficiency [18]. For a deeper look at *Order Picking* Design and Control approaches, de Koster et al. [19] addresses the most common issues, while van Gils et al. [20] provides a deeper analysis through the classification of operational problems, focusing in achieving a better efficiency combining planning problems. Regarding *Location Assignment*, [21] provide a study approaching the relationship between *Storage Assignment* effects on Order Picking efficiency.

In the last 23 years there has been considerable attention in the research and development of solutions for problems in traditional Warehouses, mostly in *Layout Design*, *Routing*, and *picking* [22]. Some *state-of-the-art* approaches to reduce operational costs and optimize trajectories regarding the *Order Picking* problem can be seen in Table 2, where some solutions in the fields of *Routing* (an deeper view of Routing approaches can be found in [23]), *Location Assignment*, Warehouse Physical Layout (regular or irregular), and Warehouse Characteristics as *Aisle* (*Bend Aisle*, *Cross Aisle*, and *Multi Aisle*), and Layout interference are also evaluated.

2.1. Warehouse typologies

As can be identified in [12], a Warehouse can be divided into several categories (see Fig. 3). Other typologies can be found in [14], which defines two more types of Warehouses, such as *Production Warehouses*, characterized by the storage of raw materials, semi-finished and finished products, and *Contract Warehouses*, responsible for the operation on behalf of one or more consumers. The Warehouse typology is directly linked to the type of activity developed, the type of product or goods, and the form of logistics and product management. For this study in question, only two types are interesting to be analyzed, much of this due to the large volume of material and goods that pass through, requiring a more efficient and faster logistics: *Fulfillment Centers* and *Distribution Centers*.

2.1.1. Fulfillment centers

According to [12], a Fulfillment Center (FC) (formerly called *Packing Warehouses*) has the distribution of goods as its primary use feature and can have different sizes. This type of facility can also be defined as an industrial property that allows an efficient movement and transport of goods directly to the consumer. The main focus is on delivering a final good to the consumer, executing order receipt, checking, labeling, packing, and shipment. Because this contact with the final consumer, can work with thousands to millions of Stock Keeping Unit (SKUs), it also has some characteristics as work in high speeds with good efficiency rates, individual piece pick or small parcel pick, and packing in corrugated boxes [15].

2.1.2. Distribution centers

Although its definition is similar to a *FC* [12], a Distribution Center (DC), it is a Warehouse Facility with finished goods ready to be redistributed or distributed locally to internationally [61]. Like the *FC*, its primary use is the distribution of goods, but it differs in one special function, the *DC* is *demand-driven*. This works using an adaptable network focused on a value-based outcome that changes according to the variables market share in near real-time. Other characteristics of this type of Warehouse that differs from the previous one can be described as picking on a larger scale through pallets and case quantities and a varied method of packing [15].

Table 2
Order picking approaches in regular and irregular warehouses.

Authors	Problem/Objective					Algorithm approach						Warehouse layout		Warehouse system			
	Routing	Location Assignment	Aisle Computation	Order-batching	Packing	Meta-heuristic	Heuristic	Evolutionary	Scheduling	Hybrid	Neural Network	Typical	Irregular	Manual	Robotized	Smart	Multi-Shuttle
[24]		o							o			o			o		
[25]	o	o				o						o				o	
[26]	o	o								o		o			o		
[27]	o							o				o					o
[28]	o					o						o		o			
[29]	o		o			o						o				o	
[30]					o		o					o		o			
[31]	o									o			o	o			
[32]	o					o						o			o		
[33]	o									o			o	o			
[34]	o						o					o				o	
[35]	o						o					o		o			
[36]	o								o			o		o			
[37]				o		o						o		o			
[38]				o				o				o		o			
[39]	o	o							o			o			o		
[40]	o	o							o			o			o		
[41]	o						o					o		o			
[42]				o						o		o		o			
[43]			o					o				o			o		
[44]		o									o	o			o		
[45]	o	o								o		o		o			
[46]	o									o		o		o			
[47]		o						o							o		
[48]		o							o			o		o			
[49]	o		o					o				o			o		
[50]	o	o					o					o		o			
[51]	o					o						o		o			
[52]	o	o								o		o			o		
[53]	o	o							o			o			o		
[54]		o									o	o		o			
[55]		o								o		o			o		
[56]			o							o			o		o		
[57]		o									o	o		o			
[58]	o						o					o			o		
[59]	o	o				o						o		o	o		
[60]			o									o		o			

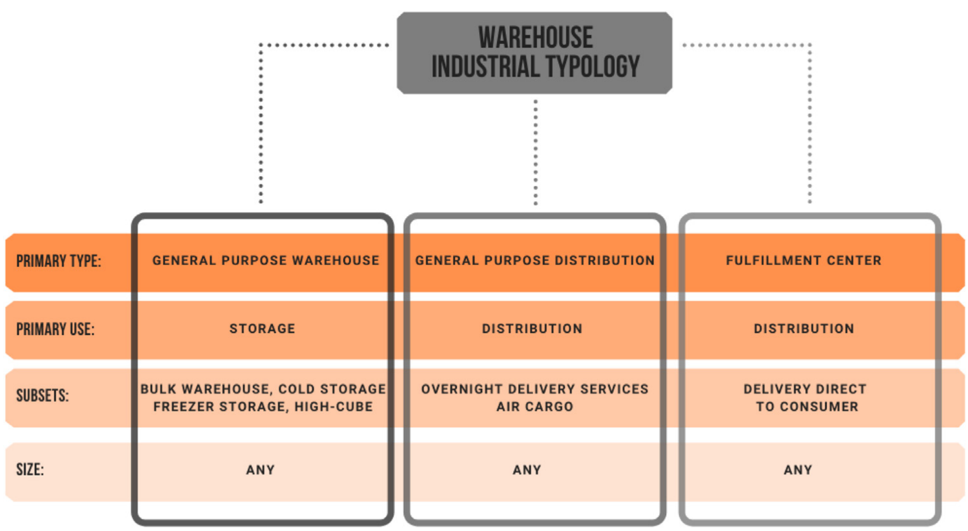


Fig. 3. Industrial warehouse typologies according [12].

A distribution center also has some subdivisions and taxonomies, which are classified depending on their region location and activity. For example, according to [62], a *European Distribution Center (EDC)* is a Warehouse of Type *DC* that distributes to at least five different countries. The four most common types of EDCs and their taxonomies can be seen in the Table 3.

2.2. Warehouse layouts

The warehouse layout design is one of the most important components to achieve optimization since it has a direct influence on the process of *order-picking*. To determine the ideal layout, it is necessary to consider the number of warehouse blocks and their sizes, the number of rack levels, and the locations of the *pickup and deposit (P&D)* of products. It is worth mentioning that this choice will also have a degree of influence on the routing method used by workers or robots [1,63].

According to [1], the types of Warehouses Layouts can be divided in *Traditional Layouts*, *Flying-V Layouts*, and *Fishbone Layouts*. However, some research has been carried out in the last years to discover new ways to optimize the layout of Warehouses, whether regular or irregular, new designs were proposed, like the *V-Shaped Layouts* [64], *Chevron aisles*, Layout Design from Multiple (P&D) Points [63], and *V-Shaped Layout* [64].

According to [29] Warehouses generally follow two basic design rules: *Picking aisles* must be straight and parallel to each other and *cross-aisles* must be straight. Considering these rules, the layout of a Traditional Warehouse is similar to that found in Fig. 4.

The selection between the layout designs will directly depend on the location of the P&D points. Considering the traditional design, the layout design of the Fig. 4 (middle) and Fig. 4 (right) have greater efficiency (smaller traveled time) compared to the traditional format Fig. 4 (left). It is also worth considering that the

Table 3
Taxonomies of *EDCs* according [62].

	SKUs Handling	Warehouse size	Objectives	Additional information
Warehouse EDC (WHS)	Medium, High	Medium, Large	Traditional activities (Storage, Picking, Transportation)	Created as part of a large system divided into different business units
Warehouse/Office EDC (WHS/OFF)	Low	Small	Traditional activities and Management-related activities	Typically distributes to a global market.
Warehouse/Management EDC (WHS/MGT)	High, Very High	Large	Traditional activities and Intensity management-related activities (Forecasting, Inventory, etc.)	Typically focused on local market
Warehouse/Factory EDC (WHS/FAC)	Very High	Large	Different activities (Traditional, Technical, Management, etc.)	Characterized by a high level of value and high intensity of activities

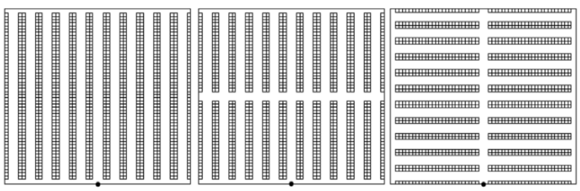
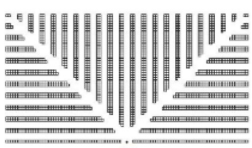
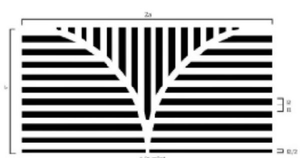


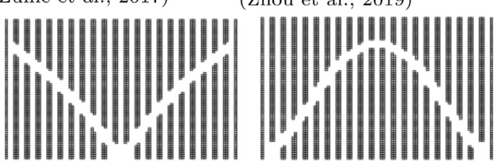
Fig. 4. Traditional layout designs from [63].



(a) Fishbone Layout according (Zunic et al., 2017)



(b) Fishbone Layout according (Zhou et al., 2019)



(c) Flying-V Layouts according Gue and Meller (2014)

Fig. 5. Irregular warehouse layouts design (See [35,63,64])

Fig. 4 (right) is more efficient in several parameters regardless of the location of the P& D than Fig. 4 (middle), but the last one is more common in practice [65].

However, it was discovered that *Flying-V Layouts* (Figs. 5(a), 5(b)), and *Fishbone Layouts* (Fig. 5(c)) can reduce up to 20% the traveled distance during the execution of *batch-picking* and 15% when it is necessary to carry out retrieval and storage in the same run (*dual-command*) [35] compared to traditional designs.

The *Fishbone Layout* design can reduce the time travel by up to 20% when compared to traditional warehouses, and up to 15% when running *dual-commands*, however, it has the disadvantage of limited access to the storage space and [65]. The *Flying-V Layouts* are less efficient than the *Fishbone*, reaching around 10% efficiency compared to traditional warehouses [65], but if the P&D points are located in front of each *picking aisle* the design of Fig. 5 (left) can reduce traveling by about 3% to 6%, while the design of Fig. 5 (right) can provide up to 2% reduction compared to a Traditional Warehouses with considerable size [63]. It is worth noting that one of the biggest drawbacks of these layouts concerning traditional design is that the facility must be 3%–5% larger [65].

2.3. Warehouse systems

According to [14], a *Warehouse System* can be defined as a set of equipment and policies applied to the collection, storage, and removal of items. Considering the level of automation applied to activities, been these physical, data-driven or decision-making, we can divide the system into the following: *Manual Warehouses*, *Automatic Warehouses*, *Automated and Robotized Warehouses*, *Multi-Shuttle Warehouses*, and *Smart Warehouses*. These taxonomies will be presented and discussed briefly in the next topics.

(a) Picking Cart (FABRICATOR, 2014)

(b) Fork Lift Truck (Galeskas, 2019)

(c) Reachtrucks (Linde, 2020)

(d) Manual Storage/Retrieve (S/R) (Corporation, 2009)

Fig. 6. Examples of item picking in manual warehouses (See [66–69]).

2.3.1. Manual warehouses

As the name says, a Manual Warehouse, also called *picker-to-product* [14], is characterized when the pickup or storage of products is done through manual activity, achieved through physical locomotion of workers, or with the aid of a manually guided vehicle/equipment. Some examples of the most traditional approach to collect items in this system can be seen in Fig. 6. According to [16], although this type of Warehouse may have some technology, it is mainly characterized by the locomotion of people or workers to execute the *order-picking* process.

2.3.2. Automatic warehouses

Automatic Warehouses are in the middle between a Manual Warehouse and an Automated Warehouse. According to [14] and [16], the biggest difference between the manual process is the *product-to-picker* approach, where the items or goods can be sent to the *picker* automatically or semi-automatically using an *carousel*, *rotary rack* or *Automated Storage/Retrieve System (AS/SR)* for example. Despite the similarities between an Automated Warehouse, it is correct to say that the real difference lies in the amount of autonomy and intelligence used to deliver the product to the *picker*.

Table 4
Main differences between AMRs, AGVs and AGCs.

	Automated Guided Vehicle (AGV)	Automated Guided Cart (AGC)	Autonomous Mobile Robot (AMR)
Rigid preset routes	O	O	
Fixed infrastructure	O	O	
Infrastructure requirements	O	O	
Product transport	O	O	O
Picking process assistance	O	O	O
Sortation assistance			O
Redeployable			O
Intelligent			O
Modular deployment			O

(a) Kiva Robot from Amazon Robotics (Bray, 2012)

(b) Adapto Shuttle-based System (VANDERLANDE, 2019)

Fig. 7. Warehouse robots (See [71,72]).

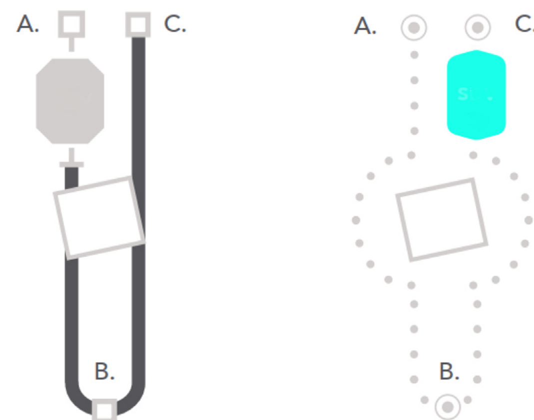


Fig. 8. AMR intelligent path planning from [79].

2.3.3. *Automated and robotized warehouses*

As mentioned in the previous topic, an Automated Warehouse is a type of system characterized by a considerable degree of intelligence to collect and process items with minimum human interference, or when a robotic system (AGVs, SDVs, Cooperative Robots, etc.) is added to perform the *order-picking* activities [14]. This type of system is generally used when you have items with high added value, small size or when the focus is high productivity and accuracy. The types of *picking equipment* most used in this type of system are *Layer Pickers*, *Dispensers* and *Robots* [16] (see Fig. 7). For [22], although *Automated Warehouses* are characterized by complex modeling due to several components interacting with each other, this type of system has widely used *shuttle-based storage* and *retrieve system* for picking automation (see Fig. 1). In addition to these types of picking equipment, the recent field of *Automated Mobile Robots (AMRs)* applied to logistics and *Warehouses* has grown considerably in recent years, and could reach an investment of $ 290 billion by 2040 [70]. In Section 3 a deeper analysis of this technology will be carried out, more information about new technologies and future research in this type of system can be found at [7].

2.3.4. *Smart warehouses*

A *Smart Warehouse* is characterized by the use of computational intelligence techniques in conjunction with the Internet of Things (IoT) for analytical approaches. In this type of Warehouses data regarding, transaction history, product location history, *stock planning*, *Receiving/Location Management*, *Inventory Management*, *Order picking* and *Shipping/Transport* are commonly stored, so can be used to carry out a diverse range of analyses, aiming to increase the productivity and efficiency of the Warehouse in real-time, short or long term.

According to [73], it is the use of IoT in this type of warehouse system that allows a Warehouse to be *smart*. The implementation of IoT into Warehouses has several advantages, such scalability, accurate breakdown prediction and reduction of unnecessary expenses [74]. Also, using some form of automation in conjunction with that allows a better *customer-focused* approach, and bring several strategic advantages, since the faster the delivery is made to the customer, the less the impact on the delivery network [75]. For [76], despite the advantages found in *Smart Warehouses*, disadvantages such as high cost (up to $ 200 per sq. Ft compared to $ 10 for a traditional Warehouse), and the possibility of a breakout due to use of different technologies should be considered.

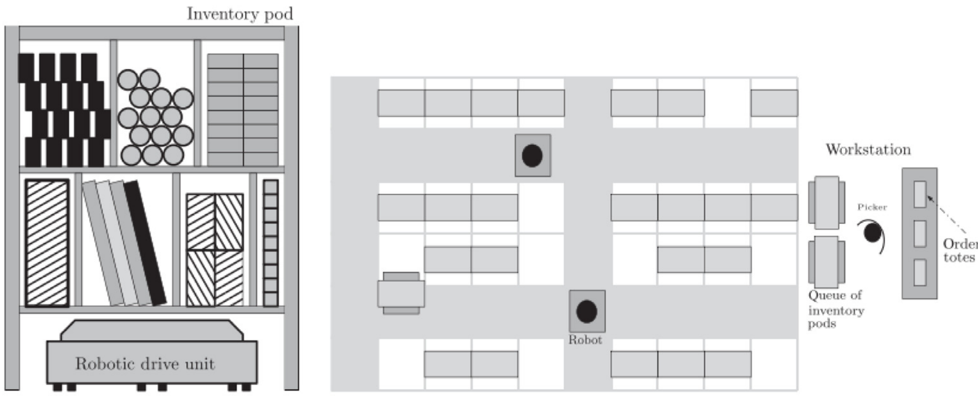
Finally, it is worth making a small observation, although a *Smart Warehouse* system is also a *Automated and Robotized* system, as it uses several computational intelligence techniques and reduces the need for human intervention, not always the reciprocal is true since one of the most important characteristics for a warehouse to become *smart* is the use of IoT for inventory management, analysis, and control.

3. Autonomous mobile robots (AMRs) applied to warehouses

A mobile robot can be defined as a set of elements that allow it to move around under its control [77]. If he can understand his environment without human interference, he can be considered autonomous [78]. Generally, his autonomous trajectory is made through an array of sensors, cameras, and maps that allow materials to be transported without the need for coordination with other transport flows (asynchronous transport). Although this type of solution has a similarity with the automatically guided vehicles (AGVs) and the automated guided carts (AGCs), they have some important differences as can be seen in Table 4.

Usually, AGVs and AGCs are controlled by pre-programmed software and their trajectory control system works based on magnetic tapes, bar codes, beacons or pre-defined paths. If the vehicle finds an object in the middle of his path, he will remain inert until the object is removed [79]. An AMR, on the other hand, can take new routes without human interference, bypassing the object that is impeding its trajectory (see Fig. 8). Also, it is not necessary to change the warehouse infrastructure, and in some cases, it can be integrated with other solutions such as Enterprise Resources Planning (ERPs).

In 2012, after Amazon© bought Kiva Robotics [71], a new era of AMRs applied to Distribution Centers and Fulfillment Centers



Robot and inventory pod Schematic of the RMF system with one workstation

Fig. 9. An RMF system according to [7].

COMPANY	SPEED	MAX WEIGHT	CHARACTERISTICS
6river	—	73 kg	*person-to-goods and goods-to-person non-lift AMR*
Amazon Robotics	1.3 m/s	1362 kg	*goods-to-person RMF*
fetch Robotics	1.5 m/s	68 kg	*goods-to-person RMF*
fetch Robotics	—	1500 kg	*goods-to-person pallet transport AMR*
swisslog	1.38 m/s	600 kg	*goods-to-person RMF*
Robotic	—	1600 kg	*goods-to-person RMF*
CONVEYCO	—	1600 kg	*goods-to-person RMF*

Fig. 10. RMFS and AMRs technologies available on market.

started. Although the conceptual idea of *Kiva Robots* was conceived in 1989 [7], the solution was implemented in [80]. This new technology allowed the creation of a new type of system, the *Robotic Mobile Fulfillment System (RMFS)*, characterized by the ability to lift and transport movable shelf racks through AMRs, delivering them to the pickers (*goods-to-person*) and increasing the productivity of Warehouse [7] by the double. Since then, several companies have started to develop similar technologies, such as fetch robotics©, 6rive©, Swisslog Holding©, CONVEYCO©, OTTO Motors©, and Hitachi©.

According to [7], an RMF system is based on three major components: Robots that communicate in a centralized or decentralized way (*Robot Drive Units*), the movable shelf racks that contain the stored products (*Inventory Pods*), and areas where workers perform replenishment, picking and packing *Workstations*. A representation of this system can be seen in Fig. 9. Also, Fig. 10 presents some of the AMRs provided by these companies, as well as their main characteristics.

Although the concept of *RMF* is based on the characteristic of lift and transport movable shelf racks [7,113], recently, new AMR technologies applied to the Distribution and Fulfillment Centers were launched for the *sorting*, and *compact picking* processes [114, 115]. In this way, we can adjust the definition of RMF systems, and define it as a *goods-to-person* AMRs based system, responsible to carry and transport small or large volumes of products in *order-picking* and *sorting* processes.

3.1. Literature review

This topic aims to review the latest *RMF* systems studies and researches published, dividing into some fields of research such as System Architecture, Scheduling and Performance & Improvements. In Table 5 it is possible to see the number of articles used in this review.

To elaborate the search process for this topic, we first used selection criteria for the search engines, where the selected ones must allow the use of logical expressions, must have a base of publications from the field, must allows text search publications, and must have few problems with the search algorithm. In this way, the search was carried out through digital libraries with a considerable impact or number of publications in the field of robotics, production, and logistics, as shown in Table 1. As exclusion criteria, only publications that included a proposal to the RMF system using autonomous robots (AMRs) written in English were selected. In total, more than 60 articles returned, with 40 selected in the first run after the Title and Abstract reading, following by a second run with 31 publications selected for review after Full-Text reading.

3.1.1. System architecture

One of the first articles found that proposed an AMR solution applied to the transport of objects can be found at [81]. The author uses sensors and an operational control center to better locate the robot, also adopting a global location trajectory planning based on static data, a local sensor-based trajectory planning for obstacle avoidance, Object and Pose Recognition to identify the pallet to be transported, and uses sensor fusion to obtain pose and object recognition.

The architecture proposed in [81] can be seen in Fig. 11. Considering the computational cost at the time the article was published, the trajectory planning was divided into two hierarchical levels: a global (lowest) an local (highest) trajectory planning. The global planning used the visibility graph approach in conjunction with the Dijkstra algorithm, and the local planning used the local criteria and heuristics. The two planners were combined with the location algorithm, making possible to move the robot around the workspace. For the robot localization, a *Extended Kalman Filter* was used with reflectors placed in the workspace. More recent and relatively similar work can be found at [83], which also uses a heuristic method for local planning, and demonstrates through a flowchart the method used for Local Search Optimization.

A more complete approach to a framework designed exclusively for warehouse systems compared to the previous work can be found at [82]. The authors used the concept of distributed autonomous intelligent units (*cells*) (actually called AMRs) and studied the effect of some motion planning algorithms. This framework is much more robust than the previous one, having a global

Table 5
RMFS Review.

Authors	System architecture	Computer vision	Scheduling	Path planning	MAPF	Performance & Improvements	Solutions in market
[81]							
[82]	O						
[83]							
[84]							
[85]							
[86]		O					
[87]							
[88]							
[89]							
[90]							
[91]			O				
[92]							
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[95]							
[96]				O			
[97]							
[98]							
[99]							
[100]					O		
[101]							
[102]							
[103]							
[104]							
[55]							
[105]							
[106]							
[107]						O	
[108]							
[109]							
[110]							
[111]							
[112]						O	O

memory, and a task manager in the highest control layer activity flow.

Regarding the motion planning (MP), there are some steps to follow: Robot Configuration parameters determination, Representation of robots and objects, an MP approach must be selected, and a search method must be chosen. For this work, the potential field approach was selected for the MP and the *Best First Method* for the search method. A congestion study is also carried out, running the experiment in a 4 by 4 grid (16 positions) (Fig. 12(b)). The authors conclude that it may be better for congestion efficiency if the robot waits if a future point is filled with another robot than looking for a new path. This is interesting to avoid congestion when using a system with multiple robots and there is a path overlap.

More recent architectures can be found at [84] and [85]. The first addresses the creation of a cyber–physical system model for smart warehouses, while the second features a modular robotic system with aisle-captive robots applied to small or medium-sized warehouses. It is worth mentioning that different from the previous frameworks, both studies propose a congestion-free system.

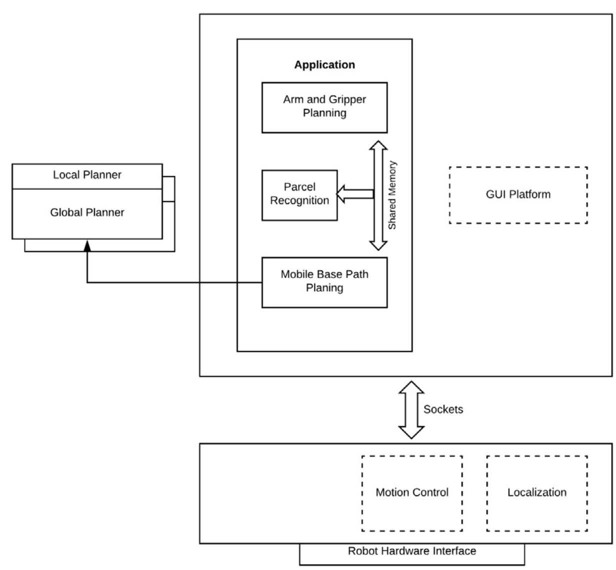
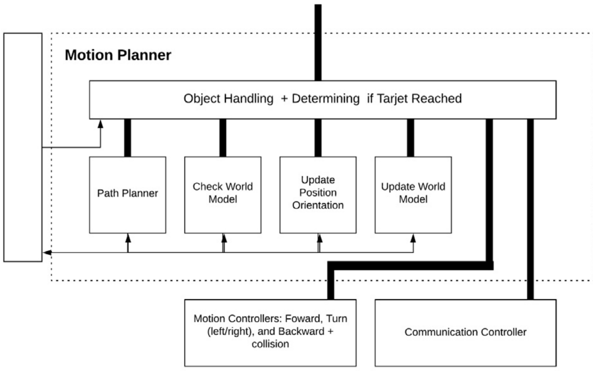


Fig. 11. Proposed AMR architecture from [81].

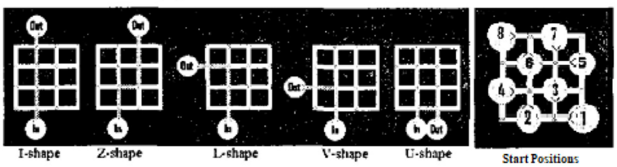
3.1.2. Path planing

As seen in section two, several algorithms have been developed to solve the problem of *order-picking*. Despite the different numbers of approaches, genetic algorithms are generally used for task allocation, and the A* algorithm for collision-free path-planning. In [96] an algorithm focused on collision-free is developed, simulating the trajectory in different Warehouse Layouts, analyzing the numbers of grids visited by the robot as a performance parameter, but the analysis is done for a single robot. In [97] a Path Planning algorithm for multi-robots applied to RMFS is developed based on the Dijkstra's algorithm, where some rules are added to the algorithm to avoid collisions between agents. To test the algorithm, the authors developed a 100 x 100 Warehouse Grid-like environment.

A research field that has been gaining attention in recent years is the Multi-Agent Path Finding (MAPF). Despite being a problem originated in the field of artificial intelligence for games, it received considerable space in RMFS. According to [116], the MAPF problem is a research area that addresses the issues and



(a) Motion Planner Architecture



(b) Considerations for Congestion Experiment

Fig. 12. AMR framework and analysis proposed by [82].

possible optimizations of path planning for multiple agents, being characterized by the non-collision key constraint while the agents perform the path concurrently. As you can imagine, this problem fits perfectly in the field of RMFS, since we have to work with several agents without there being a collision between them. More information about the MAPF problem and how it works can be found at [116].

The first implementation that considered MAPF for warehouse automation can be found at [98]. The authors propose a possible solution for Multi-Robot Path Planning through a new strategy, where planning is done for each robot separately together with a general strategy called M*. The planning for 100 robots achieved an 83% success rate with a median time to solution of 54 s. Despite a considerable result, M* is heavily memory limited, which can affect the resolution of large problems.

In [100] the *Online MAPF* is presented, which is used for efficiency and performance analysis for RMFS, and is characterized by a fixed set of agents solve a MAPF problem, but after an agent finds a target, it may be tasked to go to a different location [116]. In [102] the TAPF is presented, characterized by the generalized target assignment and path finding problem, where the simplified warehouse variant is used to reduce unnecessary waiting of agents between phases (more information about task assignment for multiple robots can be found in [117]). This proposal improved in [101], where two new algorithms are presented, the Prioritized Path Planning (TA-Prioritized) and the Task Assignment and Hybrid Path Planning (TA-Hybrid), being carried out tests in a large warehouse with up to 180 agents. Finally, in [103], a new framework for which solves the MAPF problem is presented for situations in which the agent is assigned a new goal location and required to keep moving (a.k.a. Lifelong MAPF) in RMFS. The authors propose a sequence of instant MAPF instances (Windowed MAPF) with replanning to specific time-steps. To evaluate the framework, CA*, ECBS, and CBS were used.

More information regarding MAPF algorithms can be found at [99]. The authors compiled some algorithms already applied to *RMF* systems, also providing a comparison between each one.

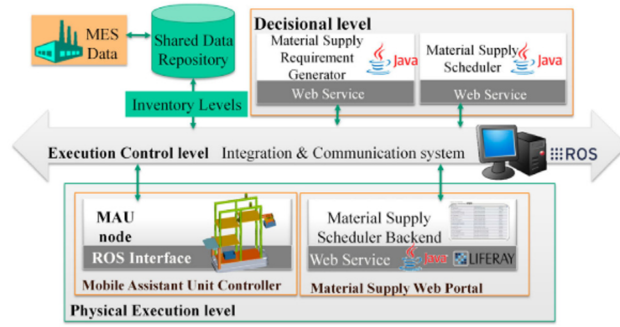


Fig. 13. SoA system proposed by Kousi et al. [94].

3.1.3. Scheduling

Although some *Scheduling* rules and their taxonomies have been studied previously [118], and performance analysis are already documented [119], the research of this method is for Robotized Warehouses is not widely addressed. However, Jin et al. [87] carries out a study that addresses the dynamic scheduling in Robotized Warehouses, proposing new rules for this new type of system.

The system presented by the authors is a reference to the *Kiva Robots*, where AlphabetSoup software is used to simulate the warehouse environment. In summary, the *shelf selection* and *task selection* rules are used, and some performance simulations considering the warehouse size and the number of robots is performed. The research concluded that when a warehouse is small the *Shortest Queue Length (SQL)* method is more efficient especially if the number of robots is large, while the *Shortest Travel Distance (STD)* becomes more efficient as the warehouse increases. It is worth mentioning, however, that the combination of the two can be best applied when a reduced number of robots are used.

One of the problems that can found in the integration of intelligent search algorithms with mobile robotics applications for material supply in production lines is carrying out the loading/unloading of items manually. To overcome this and other limitations found, Kousi et al. [88] implement a Service Oriented Architecture (SoA) that allows the dynamic scheduling of material supply operations through AMRs (called Mobile Assistant Units by the authors). The authors unite linear mechanisms with a gripping device to load/unload the robots in conjunction with an online monitoring system of inventory levels to improve the efficiency of material supply based on real-time needs. The implementation improved in [94] (see Fig. 13) with the addition of a discrete event simulation, and has an interesting methodology of performing an automatic generation of the material supply requirements and dynamic creation of assignments.

In [89], a study is carried out with the focus on discovering how to build efficient models that estimate the performance of an RMFS, also analyzing which shelf block size benefits the system throughput. The study is one of the first to consider a handling-speeds-based assignment rule (HSAR) since previous work used a random assignment rule (RAR) of workstations to robots. The authors constructed a semi-open queuing network (SOQN), solved through a two-phase approximation method to estimate the performance of RMFS that uses different assignment rules, and designed a neighborhood search approach to find a near-optimal assignment rule. As a result, the authors conclude that the HSAR outperforms RAR when workers have different handling times in a near-optimal way and in less time.

Regarding Scheduling using MAPF, in [90] scheduling models based on network flow, classical unary resource constraints together with path constraints, and optimal activities are presented.

The authors conclude that the Flow Model is more viable in small instances, while Optimal has better stability and scalability than the others. In [91] a complete study of the *Pod Repositioning* Problem is prepared, where the authors perform an analysis of the optimal location in the inventory that the pod should be placed again. An interesting contribution that can also be included in this category is the solution proposed by Xie et al. [95], were split orders are introduced to the RMFS based on a new MIP-model is used to integrate decision problems.

In [93], one of the first robust implementations of Scheduling in RMFS using MAPF is made, where in addition to simulated tests, real tests are also developed in co-simulation to verify the performance and effectiveness of the solution. The authors carried out an execution framework that can use existing single-shot MAPF planners with the possibility of overlapping and re-planning. An interesting feature of this framework is the possibility of implement in conjunction with state-of-the-art MAPF planners but without affecting the computational efficiency. Finally, a recent compilation of decision rules that can be applied to improve *scheduling* on *RMF* systems can be found at [92].

3.1.4. Performance & system improvements

A simpler and general review about this topic can be found in [106], were address the basic performance characteristics, the relationship between contexts and system design *RMF* with respect to performance, and some important taxonomies in this type of system. In [104] the first model of a *RMF* system is designed based on analytical models. System performance and robot usage values are estimated through parameters such as warehouse layouts and control policies. In addition, the article provides information on performance impacts regarding the length-to-width ratio, workstations locations, number of robots and number of orders that need to be completed per hour. In this way, it becomes an excellent reference for comparing results when creating new models or improvements.

Considering the previous impacts the following question can be made: What is the optimal speed and number of robot values in a Warehouse? The answer to this question can be found at [55]. The authors elaborate a study with numerical experiments and simulation of the analytical results using the Arena 14.0 software, describing the formulas that can be used to optimize the values of speed and number of robots for a mobile picking system.

An important factor that can directly affect performance in a robotized warehouse is the interaction between workers and robots. Although the *Human–Machine Interfaces (HMI)* are already known, very few studies have been carried out to verify the impact of this on RMF systems. One of the most complete studies can be found in [105], which analyzes tasks and behaviors done by novice users in *Robotized Warehouses*, developing some metrics to qualify and quantify the user's specifications.

Some performance analyzes concerning the Picking process were also found. In [106], a complete analysis of the RMFS performance characteristics for the Order Picking is achieved through a case study for the order picking of consumer goods in an e-commerce setting. The authors performed data collection approximately two years after the RMFS system was implemented and put into service. The case elaborated interviews with RMFS workers personnel and providers, presenting performance analyzes for the areas of Productivity, Uptime, Flexibility, Picking Accuracy & Operator Training, Space Utilization, Investment Cost, and Ergonomics. The authors conclude that the system has a good Uptime, Flexibility, Productivity, and that workers preferred the RMFS over manual since the training to perform some actions has been reduced.

Another topic with great importance in the management of robotized warehouses and already studied previously on AGVs is the battery management problem. According to [107], a bad policy can cause an additional cost of 15% to the system. According to the authors, factors such as battery cost, cost of robots, and a small required retrieval transaction throughput time directly influence in the battery management policy selection.

It is worth mentioning that some other variables can also directly influence the performance of a *RMF* system, Roy et al. [108] performs research of robot assignment strategies in storage areas where any pod can be stored in any available location and the effect of this on system performance. In [109] a study is carried out to improve the energy efficiency of a *RMF* system based on the work performed by the robot. And in [110] the impact of not using safety constraints is compared relative to operational inefficiency.

Finally, a recent and interesting performance improvement can be found at [111]. This research is one of the first studies that carry out the analysis and effect of different customer classes. The authors used a traditional layout with a random storage policy, and through high-dimension Markov models, the optimal number/capacity of robots, and the optimal number of pickers to maximize throughput is determined. According to the authors, these rules can be used by warehouse managers to achieve the optimal configuration of the system. Finally, future challenges proposed by the authors are the study of the methodology proposed in the unstable stochastic system and the addition of the reload function to robots.

3.1.5. Computer vision

A docking and re-charging methodology for mobile robots applied to Warehouses based on computer vision can be found at [86], where the proposed solution has a success rate of 97.33%. The system is based on a modified *AprilTag*©library, the pose detection is done through a *Kinect*, and its control is based on a *adapted enhanced ORB-SLAM* to self-localization. The *docking* works into two zones, the first is used to determine the location of the AprilTag©and to adjust the robot position, and the second for pose detection and adjustment pose.

3.1.6. Analysis of solutions in market

According to [120], one of the probably best-known solutions is the *Kiva Robots*©, the layout used in the application can be viewed in Fig. 14. The Kiva System is based on three important agents [120]:

- The *Job Manager (JM)* responsible for assigning drives, pods, and stations;
- A *drive unit agent (DUA)*, responsible for the task, path, and motion planning;
- An*Inventory Station Agent (ISA)*, responsible to manage the GUI, pick light objects and communicate with other agents regarding task activities.

According to [120], this type of system is based on some important rules: Must be an agent for each object, each agent needs to execute tasks with only the necessary information to perform their work, and the data for one activity can only be modified by the robot responsible for the corresponding activity. In terms of software architecture, the system has the following characteristics [120]:

- Each robot can communicate with each other through more than 100 types of XML messages;
- The path planning is done through a two-dimensional grid implemented by a traditional A * algorithm;
- Decisions are made by a simple *AI-style planner*;
- Rather than looking for global optimization, robots decisions are made on the fly using utility-based heuristics;
- An MySQL database is used to persist the data.

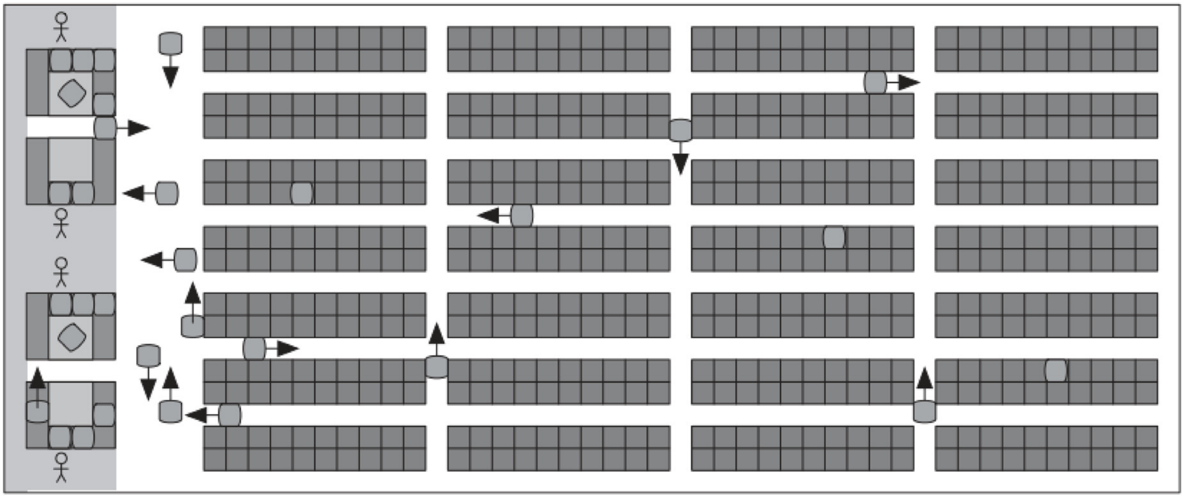


Fig. 14. Kiva warehouse layout [120].

4. Challenges and insights

Regarding the second section, some challenges can be found below:

- Analysis of the effects and interferences regarding the relation between paths and shelves characteristics in the Warehouse as *Bend Aisle* for example, in conjunction with the proposed *Routing* algorithms;
- Study and analysis of the algorithm for various Warehouse Layouts, showing which type the algorithm best applies;
- Implementation of a multi-layer control system that works with the *Scheduling* of the materials and the *Pick-Order* so that the operation is as efficient as possible;
- Elaboration of a deep analysis of the best storage points, considering the location, SKU data, Warehouse Layout, and picking;
- Although some works were found in the area of *Smart Warehouses* [73–76,121], apparently the technical concept of this type of technology is still a little misaligned and blur. Only a few studies were found using this type of warehouse system, so research in this area sounds promising due to the various difficulties that can be encountered in the development of this technology, such as:
  - What are the impacts, advantages, and disadvantages of using IoT in a Robotized Warehouse? How the metric is measured?
  - How to combine the power of IoT inventory management with the latest robotics trends to increase system efficiency
  - How to have a level of security and reliability in the system in order to avoid breakouts as much as possible?
  - What are the most promising IoT techniques for data analysis and computational intelligence in *Smart Warehouses* that can be used as a way to improve the system?
  - What is the quality metric used to determine safety, quality and efficiency in this type of system?
  - What trends, gaps, and developments need to be addressed today or in the years to come?
  - What are the relationship between system cost/maintenance, and the benefits in the short, medium and long term with the implementation of this system? What are the impacts at the end of the chain?
- There are several studies on modeling and mathematical analysis addressing the types of warehouses layout design, but the majority of studies that promoted solutions for the routing problem (see Table 2) focused on warehouses with traditional design. In this way, it would be interesting to address the proposed routing solution in the most common types of regular or irregular designs (Figs. 4, 5);
- If it is still preferable to present the routing solution only for traditional layouts, a comparison with the types of routing methods proposed in x could identify possible gaps or advantages;

Regarding the third section, some challenges can be found below:

- Considering the need for an excellent communication network, how to keep the system active and efficient even with the possibility of network outages?
- What kind of communication architecture can the best fit for this type of system?
- What is the impact of adding adaptable ad-hoc networks on efficiency and quality during the execution of activities?
- How to implement networks that have self-adaptability and self-healing for this type of system?
- What is the impact of fast charging batteries and what trajectory planning and scheduling techniques can be used to make the charging process more efficient?
- Although there is already some form of implementation or solution for the process of Health and Performance [122], no studies were found addressing this problem. This gap can be a promising research topic, especially with the growth of Big Data, Data Science and Data Visualization techniques in recent years.
- According to [123], some challenges that need to be approached are standards definitions for *indoor position systems (IPS)* better design tools;
- No reviews or surveys were found regarding the Scheduling Method for Robotized Warehouses. In addition, many of the articles that address this method are focused on AGVs or AR/SR. With the growth of intelligent autonomous robots, could be interesting to review the studies previously carried out and their due impacts on this new type of system;
- Regarding the Human–Machine Interface (HMI), how to design efficient HMIs so that even novice users have a positive impact on the system? How to make collaboration more natural" and efficient? How to improve the current systems and what are the challenges encountered?

- In relation to non-traditional Warehouse layouts, one of the reasons for their insertion are the following questions: Why there no tests performed on these layouts in all proposals? Why are they not used for RMFS systems? How feasible is changing layouts during execution? Is worth change the layout based on the orders?
- During our review, it was noted that the RMFS field, previously dominated by the goods-to-person picking methodology, is being subdivided into new sub-areas such as Bin-to-Person Picking, Collaborative Picking, Smart Moving, and Smart Sorting. Much of this is due to the implementation of these recent technologies by companies such as [9,79], and [124]. Despite the presence in the market, we have not found any work that addresses these new technologies, opening then a niche for possible future researches.
- Although an RMFS bin-to-person methodology was initially presented by Cosma et al. [81] and later by Kousi et al. [88], where a gripping device is used to load/unload items to the robot autonomously, these were the only works found that mention this type of technology. Regarding solutions on the market, the company [9] is one of the first companies to implement this type of technology. Thus, as it is a relatively recent topic, there is still no research that addresses this type of system deeper, opening doors for future researches.
- Considering that MAPF is an NP-hard problem, what solutions can reduce its complexity?
- How to scale MAPF up to one thousand robots, yet achieve good throughput?
- How to distribute MAPF without losing completeness?
- How to take the robots Kinodynamic constraints into account?
- How to do a optimal "lifelong" planning for RMFS?
- Although some of the parts used by Kiva Robots are presented in [80], the article is already out of date when we take into account technological developments in recent years. In this way, it becomes interesting new proposals that address the development of robots in terms of hardware and parts identification not only to assist the development of prototypes for research but also to present the advances and comparisons of emerging technologies. As no studies were found to carry out this analysis, it becomes a possible research field with several open questions, such as: What are the most effective sensors for this type of application? What are the best engines? What are the best mechanisms?

5. Conclusions and directions for futures research

For the Second Section, it was noted that most of the studies reviewed did not have any metrics for comparison, either with other studies or with other input variables to make a more concise analysis of the results. Much of this is due to the difficult elaboration of experiments on a real scale since dealing with a direct change in the Warehouses management would be extremely expensive and with a long analysis time. This consequently results in a higher incidence of only simulated approaches hindering a possible realistic implementation.

A possible solution to this problem would be to carry out real tests in small zones of the Warehouse so that the research does not directly interfere with the work of local operators. Another solution may be to add to the computational tests variables that have a small characteristic of realism, such as collision control and traffic control.

A research gap that can be deepened is the comparison between the traditional layouts types, addressing aspects of efficiency, warehouse size, costs and impact on the logistics chain. This would provide a better foundation for future research, especially for solutions involving *Smart Warehouses* and *Automated & Robotized Warehouses*. Another interesting gap that can be deepened is the analysis of traditional layouts with different P&Ds locations, showing the impact on the traveling time, the advantages and disadvantages.

For the third section, a topic that can be addressed in future research is the use of machine learning algorithms so that the system continues to evolve, especially the use of reinforcement learning. It is noticed that the area of *RMF* systems is still under development, although the research field of path planning and scheduling are already consolidated as they took advantage of some methodologies applied to AGVs, it is still necessary a major development in the area of HMIs, framework analysis on multiple warehouses layouts, health monitoring, and test bend frameworks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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