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Article

Automated Storage and Retrieval Systems: An Attractive Solution for an Urban Warehouse's Sustainable Development

Aurélie Edouard ^{1,2,*} , Yves Sallez ³ , Virginie Fortineau ⁴, Samir Lamouri ¹ and Alexandre Berger ²

¹ LAMIH-UMR CNRS 8201, Arts et Métiers Sciences et Technologies, Institute of Technology, 75013 Paris, France; samir.lamouri@ensam.eu

² Groupe La Poste, 75015 Paris, France; alexandre.berger@laposte.fr

³ LAMIH-UMR CNRS 8201, Université Polytechnique Hauts-de-France, CEDEX 09, 59313 Valenciennes, France; yves.sallez@uphf.fr

⁴ Vivalto Santé Group, 75116 Paris, France; vfortineau@vivalto-sante.com

* Correspondence: aurelie.edouard@ensam.eu; Tel.: +33-6-6467-4417

Abstract: In recent years, there has been an increasing awareness of sustainable development issues. Supply chain actors have become more and more aware of this situation, especially since the regulatory, social and societal pressures in this area are becoming more and more numerous. This state of affairs is not without consequences on company practices and economic. As a result, the urban warehouse model is emerging as one of the solutions studied in the urban logistics context. The characteristics, constraints and challenges of this model are presented in this article in order to define this new logistics facility. Secondly, automated storage and retrieval systems (AS/RS), today considered as a solution from Industry 4.0, are studied through a case study in order to determine their potential to meet the challenges of urban warehouses. Their ability to optimize available surfaces by densifying stocks in limited spaces is particularly demonstrated.

Keywords: urban logistics; urban warehouses; Industry 4.0; Logistics 4.0; automated storage/retrieval systems; case study



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1. Introduction

Climate change is a global emergency that goes beyond national borders. Transformative steps are urgently needed to shift the world onto a sustainable and resilient path. To tackle climate change and its negative impacts, United Nations (UN) members reached a breakthrough on 12 December 2015 with the historic Paris Agreement [1]. The Agreement sets long-term goals to reduce global greenhouse gas emissions so as to limit the global temperature increase to two degrees Celsius by the end of the century. To achieve this target, the UN developed “The 2030 Agenda for Sustainable Development” defining seventeen goals to “Transform Our World” [2]. The eleventh goal aims to make cities inclusive, safe, resilient and sustainable in the context of our increasingly urbanized world.

However, e-commerce has grown considerably in recent years and has brought new challenges, such as the need to meet the demand for fast, flexible, home deliveries and managing the return of goods (reverse logistics) [3]. This affects logistics systems that need to carry out smaller lot sizes and increased freight volumes. As a result, this trend has raised concerns, especially in cities, about traffic congestion, noise, security, and greenhouse gas emissions and involves practices in conflict with the UN goals.

Consequently, the objective of reducing and eliminating the negative impacts of logistics activities has become a major concern of the actors involved in the field. It has led to the implementation of new solutions such as access restrictions to city centers, green vehicles such as cargo bikes or electric vehicles, self-pick-up points, or facilities that allow the consolidation of goods before the last mile of delivery [4]. “Urban warehouses”

are a new type of warehouse that have developed in this context, which we describe in this article.

The goal of these new logistics facilities is to build warehouses as close as possible to consumers, allowing them to offer a variety of services such as proximity stock, deliveries in a few hours and with eco-friendly vehicles, mutualization, and returns management. To make these new logistics facilities a sustainable solution, the development of a robust organizational model is essential and is missing in the scientific literature. Indeed, the constraints of the urban environment, in which these facilities are located, require these installations to respond particularly to the challenges of optimizing available space, the modularity of processes and the carbon neutrality of the activities.

To address these challenges, the technologies and tools associated with the Industry 4.0 concept appear to be a performance driver for this model. Indeed, Industry 4.0 tools are known to bring significant improvement to organizational processes and have widespread use in warehousing [5,6]. This reasoning is reinforced by the ninth goal of the UN which is “build resilient infrastructure, promote sustainable industrialization and foster innovation”. This presents the innovation and technological progress as a key to find lasting solutions to both economic and environmental challenges, such as increased resource and energy-efficiency.

In this article we decided to particularly address the processes of storage and retrieval by evaluating, through a case study, automated storage and retrieval systems (AS/RS). These are known to offer better workstation ergonomics for employees, better speed and traceability of flows, a guarantee of “zero error” and the optimization of available space by densifying stocks in limited spaces. This work aimed to study the impact of an AS/RS implementation on a partner’s customer model in order to characterize the relevance of using such solutions in urban warehouses.

This article is organized as follows: Section 2 first presents the research context by mentioning the urban logistics issues, the industrial partner of the research and defining the concept of urban warehouses. A comparison between “traditional” and “urban” warehouses is developed. This comparison illustrates the challenges faced by these new facilities due to the constraints of the urban environment in which they are located and limiting the use of standard solutions. Section 3 presents a methodological approach to respond to the problem addressed by this work and discusses 4.0-based solutions to improve the performance of urban warehouses. Finally, a case study is described in Section 4 and a response to it is discussed in Section 5. Finally, Section 6 concludes the article and presents research perspectives and limitations.

2. Research Context and Industrial Partnership

2.1. Urban Logistics: An Issue for Sustainable Logistics

In the past few years, the priority has been to move large volumes of products through the supply chain as quickly, economically and reliably as possible [7]. As a result, warehousing and distribution centers have decentralized to the urban periphery where land is cheaper and readily available. This phenomenon has been called “logistics sprawl” and has led to an increase in the distances traveled by road [8]. Today, urban centers are a major destination for retail trade and generate significant levels of goods movement [9]. The e-commerce boom, characterized by the fragmentation and individualization of deliveries [10], has amplified this phenomenon and raises concerns about traffic congestion, noise, safety and greenhouse gas emissions in cities [11].

In response to these concerns, urban logistics, defined by Taniguchi and Thompson [12] as “a process of optimizing logistics and transportation activities carried out by private companies in urban areas, while taking into account the traffic environment, congestion and energy consumption in a market economy”, is a wide research field aiming to reconcile economic and ecological efficiencies to serve local development. In this context, the application of new organizational policies within cities and the search for alternatives to improve the flow of goods is a major step towards the sustainability of this process. New models

have been experimented in recent years for city centers. Among the most widespread are: traffic restrictions in urban areas (low emission zones, off-peak deliveries, tolls, etc.), the use of public transport for the delivery of goods (“tram for goods”), the creation of collecting points (parcel lockers, pedestrian drives, “click & collect”), the spread of “green” vehicles (electric vehicles, cargo bicycles, drones), and the establishment of facilities that allow the consolidation of goods before the last mile of delivery (urban distribution or consolidation centers, transit points) [4].

2.2. *The Industrial Partner: An Historical and Major Logistics Stakeholder*

In order to adapt to changing needs, companies operating in this field must adapt their strategy. For example, in recent years, La Poste, the French postal services company, has been faced with the decline of its historical business, postal services (6.7%/year on average over the period 2014–2019), which has been further accelerated by the health crisis (down to 18.1% in 2020) [13]. This decline is mainly due to changes in user practices. In response, the group presented its new strategic plan “La Poste 2030” in February 2021, which aims to develop offers to better serve its customers and simplify their lives [14]. To achieve this, it has chosen to diversify by offering new local services. These services aim to draw on the experience and territorial coverage of its postal network and on the skills of subsidiaries that have been created or acquired. This may achieve a new economic balance and preserve jobs and the network. Among the new services tested in recent years, the “proximity stock” offer was created, proposing a logistical solution based on mini warehouses in the heart of the city (urban warehouses) to bring the storage of goods closer to its customers and to respond in a more efficient and sustainable way to the need for urgent deliveries. This offer has been upgraded from an experimental level to a strategic one by integrating the “Log’issimo” brand, launched in December 2021, which brings together the local logistics solutions from the first to the last kilometer offered by La Poste.

Still poorly described in the scientific literature and addressed by the terms “urban warehouse” or “city warehouse” and “micro-fulfillment center” in industrial reports, urban warehouses have become an upcoming model within the ecosystem of urban logistics. The characterization of urban warehouses is given below, regarding traditional warehousing.

2.3. *Urban Warehouses Characterization Regarding Traditional Warehousing*

The concept of the urban warehouse model is to bring the storage of goods as close as possible to the end consumers, the majority of whom live in urban areas [15]. It is part of the downtown supply chain, encompassing a set of activities such as purchasing, manufacturing, logistics and distribution, as shown in Figure 1 (inspired by [16]).

The main warehouse mission can be summarized with the quote of the seven R’s of logistics, one of the most important concepts in logistics management: “deliver the right product, in the right quantity and right quantity, in the right place, at the right time, at the right price, in the right condition” [17]. To do so, the warehousing fulfills the traditional four main macro-processes of warehousing: receiving, storage, order picking and shipping; and subfunctions, presented in Figure 2, inspired by the work of V. Khanzode and B. Shah [18].

The receiving process is the first one in the warehouse. It involves the arrival of goods by truck and their unloading. Once unloaded, they can be checked, sometimes processed (e.g., unpacked and repacked) and prepared for storage. The next process, storage, involves arranging the items in storage locations according to assignment and zoning guidelines. The storage area is usually composed of two parts: the reserve area, where products are stored in the most economical way, in large quantities on pallet racks, and the forward area, where they are stored in smaller quantities on shelves for easy retrieval by an order picker. The transfer of items from the reserve area to the forward one is called replenishment. Then, order picking refers to the search and removal of items from their storage locations corresponding to customer orders. The items are then sorted and orders consolidated so that items destined for the same customer can be grouped

together for a single shipment. Next, the products are verified, packaged and labeled for their shipment to end consumers. Warehouses can also perform value-added functions to personalize the consumer experience, such as adding parts or manuals to prepared packages, testing or repairing products, and managing the collection of empty packaging or products for recycling.

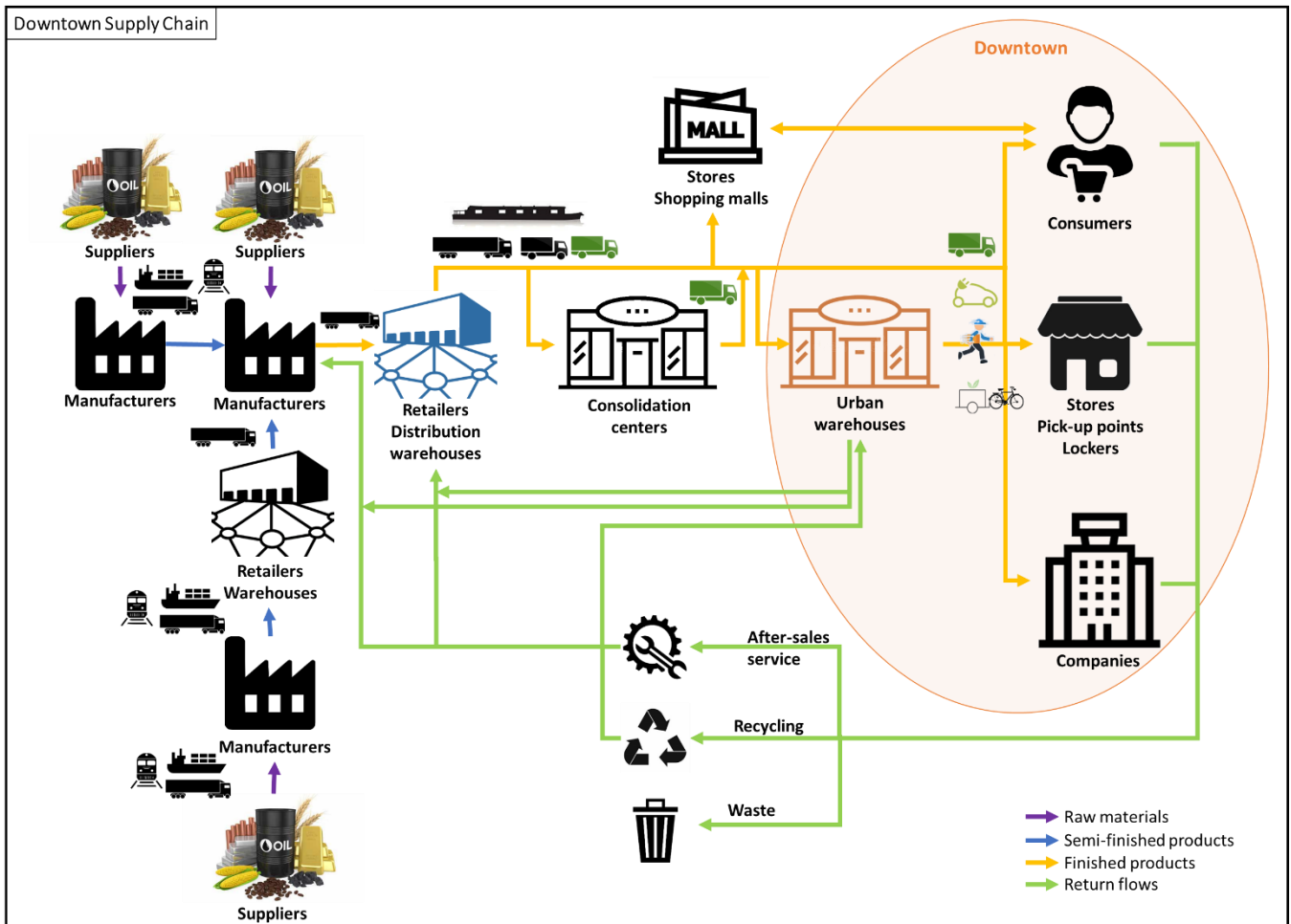


Figure 1. Urban warehouses integration into the downtown supply chain.

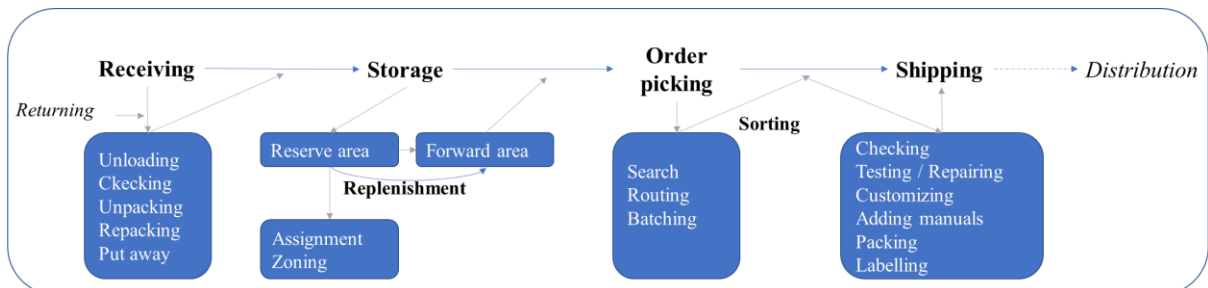


Figure 2. Warehouse macro-processes with their sub-functions.

Traditionally, warehouses that distribute goods in urban areas are called distribution warehouses (blue icon in Figure 1). These are located outside cities, in part because of lower infrastructure costs. Dablanc and Rakotonarivo have reported that the average distance in 2008 between downtown Paris and the warehouses serving it was 16 km [19]. These warehouses generally consist of numerous receiving docks to accommodate delivery trucks

(super trucks, heavy trucks, straight trucks) coming from manufacturers and suppliers, a storage area composed of several parallel aisles where products are stored in storage equipment (pallet racks, bin racks) and shipping docks from which vehicles leave for the city center for last mile delivery (straight trucks, light commercial vehicles) [20]. These facilities are large spaces (in 2017, 8 out of 48 real estate transactions were for areas larger than 30,000 square meters) [21] capable of accommodating a high volume of products to be stored and then prepared to meet consumer orders [22].

However, unlike these “traditional” warehouses, the urban warehouse processes must adapt to the constraints of their urban environment, leading to the development of specific internal organizations and technical solutions. Urban warehouses (orange icon in Figure 1), because of their location in the city centers that they specifically cover, face specific constraints: lower storage rate, quicker processing lead time, shorter distances to end consumer, etc. (see section below); leading to higher operating costs. They are generally smaller than “traditional” warehouses (a few hundred to a few thousand square meters) and have atypical volumes that restrict the number of products that can be handled.

Table 1 below summarizes the main characteristics of each of these types of warehouses and shows their significant differences.

Table 1. Main characteristics of each type of warehouse.

Features	Traditional Warehouses	Urban Warehouses
Type of activities		
Volumes stored (in no. of references)	Millions	A few thousand
Volume of orders processed	High	Medium
Order processing time	H+, D, D + 1, D + 2, D + 4	H+, D, D + 1
Product storage time	Low (a few hours to a few days)	Medium (a few hours to a few weeks)
Modes of entry transportation	Trucks (super trucks, trucks, carriers)	Straight trucks
Modes of exit transportation	Straight trucks, light commercial vehicles (electric or thermal cars and electric or thermal vans)	Light commercial vehicles (cars and electric vans), cargo bikes, walking
Number of customers	Multiple clients	Few clients
Operating Expense Costs	Mediums	Very high
Exploited space typology		
Exploited areas	Large spaces (several thousand m ²)	Small spaces (a few hundred to a few thousand m ²)
Main storage equipment	Pallet racks, shelves	Shelves
Location	Outside the cities	Downtown
Geographic coverage	Urban peripheries, suburbs, downtown	Downtown
Main type of construction	New	Rehabilitated
Type of clients		
Targets	All	Luxe, urgence, niche
Types of orders		
Nb of items/order	From 1 unit to hundreds	1 to 3 units
Processing times	Medium, fast	Fast, express
Majority handling units	Pallets, boxes/bins	Products, boxes/bins
Types of products		
Dimensions	Small, medium, large	Small, medium
Weight	Low, medium, high	Low, medium (max 30 kg)
Hazardousness	Possible	Complex

2.4. Urban Warehouses Challenges

Because of the specific constraints linked to their location, urban warehouses face specific challenges. In addition to the challenges related to the expectations of urban consumers (quicker processing lead time, customized services, higher valued services), the report published by Roland Berger and FM Logistic [23], majors players in the supply chain industry, provides an exhaustive list of the ultra-urban environment challenges:

scarcity and high cost of space, negative perception of warehouses and transport flows by neighboring populations, the need for modularity to adapt to changing needs, and the imperative to respect the environment. Each challenge is detailed below.

Cities are spaces with a limited supply of available and affordable commercial and industrial land to establish and operate logistics facilities [9,21]. As a result, the spaces that are generally available for this new activity need to be rehabilitated and are therefore complex, as they were initially intended for a different use. They often have “atypical” logistical characteristics, different from the standards observed in the field of warehousing, including being located in a basement or with restricted access to trucks, or having poorly positioned columns or piping and low or high ceiling heights. In addition, given the cost of urban real estate and availability, spaces must be limited in size, often a few hundred to a few thousand square meters. Consequently, these constraints of land scarcity and high cost of surfaces generate the first issue: a need to optimize the use of the selected spaces to carry out the activities of the urban warehouse. This means configuring the storage space and the systems that manage it to be as dense as possible. However, as the economic model of the urban warehouse is still uncertain, especially due to the lack of long-term visibility on customer expectations (volumes, references, etc.), it is necessary to think about the modularity and reconfigurability of the facilities in order to anticipate the evolution of demand and needs. This appears as a second specific issue of urban warehouses.

The negative perception of warehouses and transport flows by neighboring populations, especially due to their negative environmental impact, forces the sector’s actors to develop organizational systems with a low to neutral impact on the environment. In principle, the urban warehouse model is designed around this objective, aiming to convince users in urban areas to integrate without disturbance, even improving their living environment. Indeed, by bringing the stock of products closer to the final consumer, deliveries can be made via light means of delivery (electric vehicles, bicycle-cargoes, walking), which may reduce congestion in cities, noise pollution and greenhouse gas emissions. However, the response to the issues of greening urban warehouse processes and improving the perception of neighboring populations is not limited to being close to the end consumer. For example, it also involves rethinking the management of returns and waste, and in particular finding an alternative to single-use packaging.

3. Problem Statement: A Methodological Approach to Provide 4.0-Based Solutions to Improve the Performance of Urban Warehouses

The specific constraints and challenges that urban warehouses are facing imply that the services they offer are only available to a few customers, mainly players in the emergency, niche and luxury goods sectors, with high operating cost. Increasing the flexibility and process performance of an urban warehouse is an issue to ensure their economic viability and requires a structured and specific approach.

As expressed previously, the main challenges of urban warehouses are storage surface utilization and modularity, shorter lead times, customized services, higher valued and green services. We believe that the Industry 4.0 concept and its associated technologies can be appropriate responses to such challenges, because they enable real-time information and action, adapted and flexible automation, and efficient algorithms and machine learning to adapt to various customers and types of products.

3.1. 4.0. and Urban Warehouse: How to Improve the Performance of the Logistic Process?

The concept of Industry 4.0 emerged in 2011 at the Hannover Fair [24] and refers to the fourth industrial revolution. More than 100 different definitions have been given to it. Alexandre Moeuf et al. [25], having studied these definitions, chose the following definition to sum-up the concept: “a new approach for controlling production processes by providing real time synchronization of flows and by enabling the unitary and customized fabrication of products.”

In the field of logistics, the use of Industry 4.0 technologies is associated with the term “Logistics 4.0” [26]. Several researchers in this field have conducted recent investigations on their use in warehouses [6,26,27]. They are grouped into nine technological groups which are: big data analytics, cloud computing, internet of things (IoT), cyber-physical systems, augmented reality (AR), artificial intelligence (AI), cyber security, 3D printing, and robotics and automation. These technology groups encompass a variety of technological solutions. For example, mobile and collaborative robots and exoskeletons are part of the “robotics and automation” group. Figure 3 illustrates their positioning within the processes of a warehouse. It is based on two axes:

1. The macro-processes of warehousing that encompass the activities presented in Section 2.3;
2. Le Moigne’s model [28], which proposes to break down an organization into three systems: decision (headquarters of the decision centers), information, and operating (headquarters of the load centers), including a physical part and an informational part.

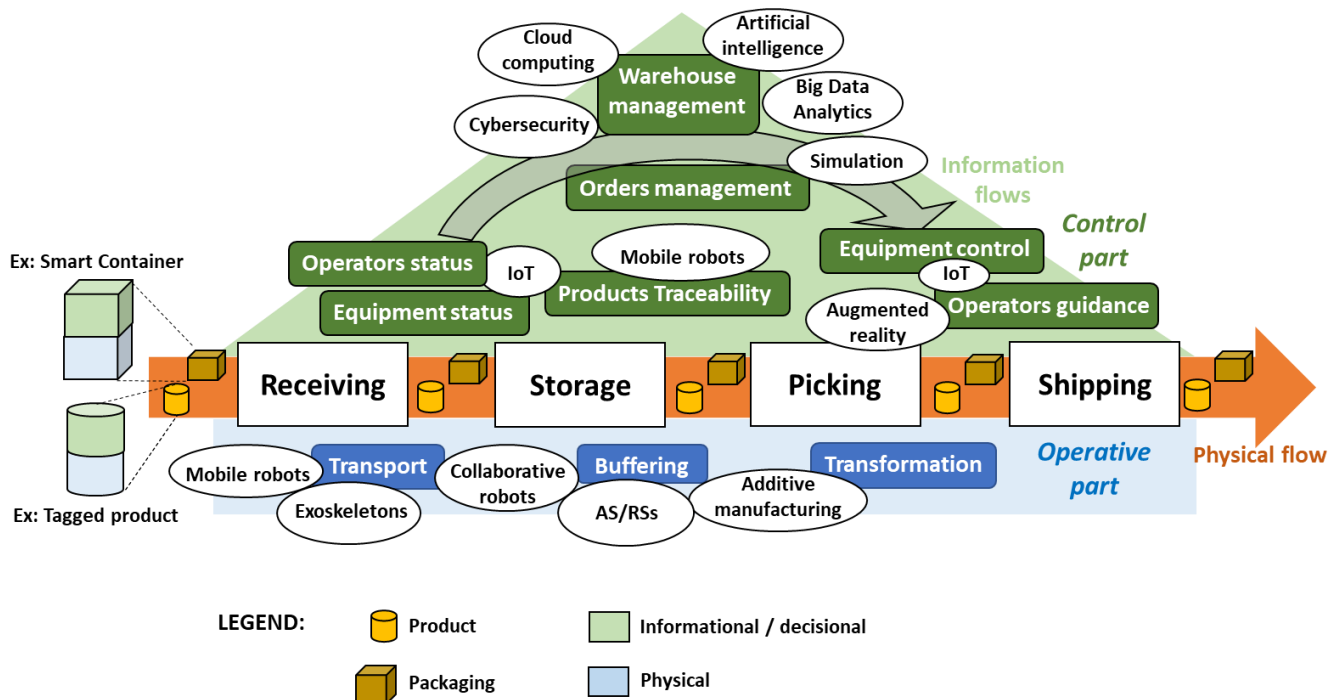


Figure 3. 4.0 tools positioning within the warehouse process.

Industry 4.0 tools and technologies may be adapted to each step of the logistic process, and in all its dimensions: physical, operative and control. But the issue that industries are facing is: which technologies for which application? How to adapt them to the specific challenges of urban warehouses? With which performance result and economic impact? In other words, our research question is: how to adapt the 4.0 contributions to improve the logistic process in urban warehouses? This question leads to the following, correlated problems:

1. Evaluating the impact of 4.0 technologies regarding the performance of urban warehouse
2. Designing logistics solutions combining 4.0 technologies to adjust the urban warehouse logistic.

3.2. Intelligent Storage and Retrieval Systems for Urban Warehouses Based on 4.0 Technologies: Issues and Methodology

Urban warehouses face the challenge of storage surface utilization and quick processing lead time, we found it relevant to focus on the steps of storage and order picking. Among the very active market of technological solutions in logistics, AS/RS have been

identified as relevant solution to address these challenges. Generally, AS/RS are known and adopted for their ability to offer better ergonomics for workers, better speed and traceability of flows, guaranteeing “zero error” and allowing the optimization of available surfaces by densifying stocks in limited spaces. Indeed, with these installations, the number and size of circulation aisles are considerably reduced or even eliminated. Moreover, some of these offer the possibility to take advantage of all available volumes (high heights). With these systems, it is easier to take advantage of “atypical surfaces” that could not be considered until now.

Introduced in the 1950's, they were originally shelving solutions served by mechanized carts running in the aisles in order to store products on pallets and extract these products from storage in order to execute orders in an automated way. While these solutions introduce automation and computers into the warehouse, the need for human intervention and action was needed for these processes to operate. Now, they combine 4.0 technologies (robotics and automation; internet of things; artificial intelligence and cloud computing) in order to reach an “intelligent” level. Indeed, automation enhancements via smart devices offer the means for faster reaction times when a process interruption occurs. Sensors (IoT) can be used to monitor the status of systems in a production or distribution process and send alerts when performance parameters fall out of place. Smart connected sensing devices integrated with AS/RS enhance functionality and provide overall greater autonomy. Data availability and security controls enable operators to make better, more informed decisions.

The maturity of 4.0 technologies has made this type of solution affordable. Inaccessible until the 2010s due to their high cost and lack of flexibility [29], AS/RS have gained popularity, offering intelligent solutions that fit a large number of users, thanks to their flexibility, variety of sizes and diversity of budgets. Scientific publications confirm this trend. In the Scopus database, if we refer to articles that have the terms “AS/RS” or “automated storage and retrieval system” included in their title, abstract or keywords, the following trends can be noticed: the first article was published in 1970; between 1970 and 2000, three articles were published on average per year against almost six between 2000 and 2010, and since 2010 this average has more than doubled to reach 22 articles published in 2021.

The contribution of this paper is the design of a storage and retrieval solution and the evaluation of its performance and economic impact, combining 4.0 technologies, at the highest level of the Porter and Heppelman 4.0 maturity scale [30]: autonomy. In other words, the goal is to design a storage and retrieval intelligent system, in the sense given by Walter Fritz et al. [31], in which “a system is an autonomous intelligent system, if it has the following properties: receives sensations from its environment and determines the present situation, chooses its own sub-goals guided by its goal, builds plans based on its experience in order to achieve its sub-goal, executes the chosen plan and can learn regardless of time”.

4. Case Study: An Intelligent ASRS System to Improve the Urban Logistics of a Large Range of Automotive Repair and Maintenance Items

4.1. The Context of La Poste and the End-Customer Issue

To date, eight urban warehouses have been deployed by La Poste in France, allowing it to deliver to approximately 30% of the country. The goal is to cover 100% of the country with 25 urban warehouses by 2025. The service consists of storing goods in cities to meet urgent delivery needs by offering rapid delivery solutions (in H+, D or D+1) operated by letters or packages carriers on shared routes or partner carriers, in close proximity, at an affordable cost and without carbon emissions, and with personalized order preparation services.

In order to improve the model to maintain the company's lead in the market and meet its objectives, the urban warehouse located in the eighth arrondissement of Paris, installed within a postal preparation and distribution facility for mail and parcels, was selected to be the pilot project.

The case study customer is a French group specialized in fast repair, maintenance and automotive equipment. It includes nine brands. Its objective in using La Poste's proximity

warehousing services is to have a remote stock of spare parts close to the end user in order to repair its customers' vehicles in a very short timeframe without having to worry about the management of logistics, for which La Poste ensures the availability, speed and reliability of operations. From its national stock, the urban warehouses are supplied with references studied to offer a great reactivity to the needs of garages. The first proximity storage space (urban warehouse) pilot was set up in Paris in 2019 with 3600 references stored, before opening a second one in Lille in 2021, with 4600 references stored. Two sites serving points of sale, 113 for the first, 40 for the second.

The processes currently used at La Poste to manage this customer are those traditionally found in a warehouse with manual management. This means that weekly supplies are received manually at the urban warehouse, with the stocking and picking of items to meet customer orders being done manually. The orders are prepared in reusable bins and shipped according to two solutions corresponding to the customer's needs: order closing at noon for delivery at 3 pm the same day by dedicated rounds provided by a partner carrier, or order closing at 7 pm for delivery before 10 am the next day by mail carriers' rounds.

The client's storage space currently occupies 150 square meters of floor space in the urban warehouse in the eighth arrondissement of Paris, with a total area of 600 square meters. This space has a high ceiling height (about 5 m). Consequently, mezzanines have been put in place to take maximum advantage of the available space. As a result, the effective storage space for this client is approximately 280 square meters consisting of aisles and 2 m high shelves. However, despite this configuration, the available space is far from being optimally occupied, which implies fixed storage costs that are also far from optimal.

4.2. The Methodology Followed

We chose to follow the Christine Bauer and Anind K. Dey methodology, well adapted to design intelligent systems [32]. The steps proposed in the methodology should be used as a "checklist" to guide the study process. These are represented in Figure 4 and detailed below.

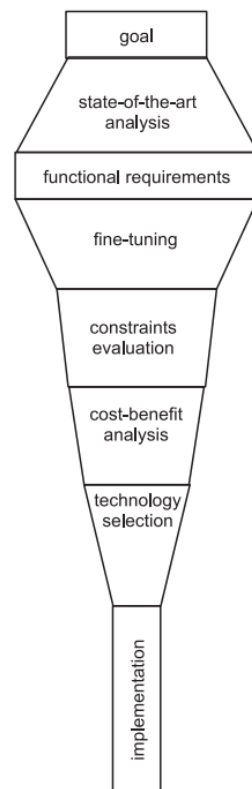


Figure 4. Study process steps of an intelligent system. Reprinted with permission from Ref. [32].

1. Define the objective of the intelligent system.

The objective must be based on the needs of the company or the user.

2. Analyze the state of the art.

This state of the art allows the characterization of the context of the study, helping to understand the solutions found for similar projects and to define the main challenges to meet the objective.

3. Define the essential functional requirements for the planned system.

The definition of the requirements considers the needs of the users.

4. Refine the contextual elements.

The aim is to eliminate options that are not relevant to the system under consideration while avoiding too radical reduction.

5. Evaluate the constraints.

This step determines whether the contextual elements presented can be considered in the project in terms of feasibility. The constraints can be technical, budgetary, temporal, legal, ethical or physical.

6. Conduct a cost-benefit analysis.

At this stage, each element of the context is evaluated according to the cost it implies to obtain the required data and its benefit in terms of its contribution to the support by the intelligent system of the whole of the desired functionalities. The analysis is performed not only in monetary (tangible) terms but also in non-monetary (intangible) terms such as image, social responsibility, sales, etc.

7. Choose the technology.

The result of this step is the decision about which technology to use to consider the relevant context elements for the system.

8. Carry out the implementation of the intelligent system.

The previous steps finally lead to the implementation of the of the intelligent system. The next section exhibits the results of the application of the previous methodology on the case study.

4.3. Application of the Methodology and Results

The steps of the methodology are successively applied and detailed.

1. Goal

As expressed previously, the objective of this study is to evaluate the adaptability of an AS/RS solution to meet the challenges encountered in urban warehouses. Despite the study of a specific customer case, with its own characteristics, this work aimed to characterize the organization eligible for the use of such an intelligent system and their limits of applicability.

2. State of the art analysis

In the current market, there are different AS/RS solutions. According to Adriane Turner [33], who recently conducted a literature review on AS/RS, there are mainly five types:





- Pallet handling systems (“AS/RS pallets” or “AS/RS unit loads”), used to store and retrieve products stored on pallets in single or double-deep racking aisles. Carts are used to transport the units from the storage location to the picking area and back. There is one cart per aisle. Once the products have been removed from the pallet, the pallet must be returned to storage. Therefore, this system is ideal for low throughput and high density or weight inventory requirements. Generally, these are systems that

require the building to be built around them and therefore cannot easily be configured within an existing building.

- Miniload systems designed for storage and retrieval of small items stored in bins or drawers. They work in the same way as an AS/RS with pallets. However, the racks can go up to four depths.
- Shuttle systems, with one or two storage depths, managing boxes or bins, and with more shuttles than aisles. These systems have a very high throughput.
- The AS/RS unit, one of the latest emerging technologies, has been introduced by the company Autostore, who are its only manufacturer. It is based on five components: an aluminum grid that holds stacked bins in which products are stored and serves as rails for robots that run on its surface driving, collecting and delivering the bins to workstations (ports) where order fulfillment and replenishment is performed. Finally, the controller is the “brain” of the system. Connected to the warehouse management system, it controls traffic, tracks inventory, controls robots, plans and schedules tasks and keeps track of everything. These systems offer unmatched storage density.
- AS/RS based on automated guided vehicles (AGVs), which move the whole racking system (with mobile shelves) or the pallets to the fixed workstation of the order picker.

Using works presenting data on this topic [33–35], the main characteristics of these solutions have been formalized in Table 2 below.

Table 2. Main AS/RS characteristics.

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

To date, in the scientific literature, no study has confirmed the advantages of these systems through a case study and qualitative and quantitative data, confirming the interest of this explorative study.

3. Functional requirements

In the case of urban warehouses, their functional requirements are drawn from the main issues of these facilities listed below:

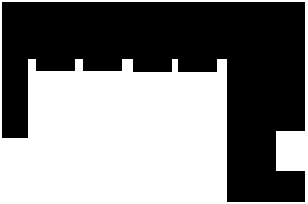
- Accommodate the maximum number of references (number, size and weight) (3),
 - Adapt to change (2),
 - Move products efficiently and accurately (4),
 - Respond to order peaks (10),
 - Allow storage and picking operations to be carried out throughout the warehouse's opening hours (11),
 - Reduce labor overhead, while increasing throughput capabilities (7),
 - Simplify product storage while improving inventory organization (5),
 - Achieve higher storage density in the warehouse footprint (1),
 - Improve warehouse and user safety through optimized material flow and improved ergonomics (8),
 - Track flow of all goods (6),
 - Provide low energy consumption or sustainability benefits (9).
4. Fine-tuning

At this stage, the functional requirements have been listed by level of relevance (see the numbering applied to each of them above) according to the challenges of urban warehouses.

5. Constraints evaluation

The customer's characteristics are the first constraints to be considered: number of references, sizes and weights of the items, output (data year 2021) (Table 3a). Then, it is necessary to consider the parameters related to the space selected to operate the system: square meters, geometry, strength of the slab (Table 3b).

Table 3. Physical constraints related to the characteristics of the client (3a) and the selected site (3b).

3a: Client physical constraints	
Number of references	5741
Average number of orders/month	762
Average number of items/order	1.3
Average weight of an item (kg)	2
Maximum weight (kg)	22.54
Minimum weight (kg)	0.001
Average dimensions (L × W × H) (mm)	248 × 138 × 73
Maximum dimensions (L × W × H) (mm)	980 × 581 × 590
Minimum dimensions (L × W × H) (mm)	10 × 1 × 1
3b: Selected site physical constraints	
Geometry	
Surface area (m ²)	98
Height under exploitable ceiling (m)	5.5
Slab resistance (kg/m ²)	600

6. Cost-benefit analysis and technology choice

In the context of this study, the technology was chosen before the analysis cost-benefit. A partnership between La Poste, Autostore and one of its French integrators, Adaméo, was initiated in 2021. Specialized in robotic technology, Autostore has developed the concept of

“automated cubic storage” (Figure 5), whose key characteristics are presented in Section 2. State-of-the-art analysis.

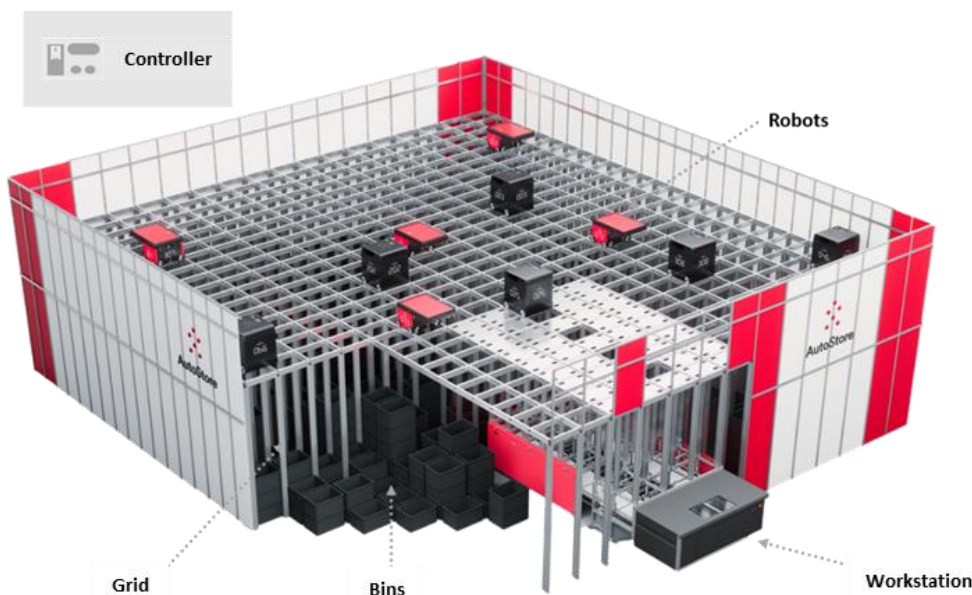


Figure 5. Autostore grid example.

The partnership consisted in setting up a demonstration of the solution within the establishment. First, it allows us to have a prototype to raise awareness in the ecosystem about the challenge of densifying stocks in small existing spaces and to showcase the capabilities of these systems. They are particularly attractive to urban logistics players because of the advantages it offers: high storage density (can reduce up to four times the required space as represented in Figure 6), ease of integration into existing buildings, flexibility of installation and very low energy consumption. Then, it permits the evaluation of whether such “Autostores” are the best kind of AS/RS to perform an efficient storage/picking process in urban warehouses, for a large number of product references of various size and kind. We evaluated the performance and economic viability of the Autostore system in our urban warehouse while comparing the model currently used to carry out the client’s services with the envisaged Autostore-based model.

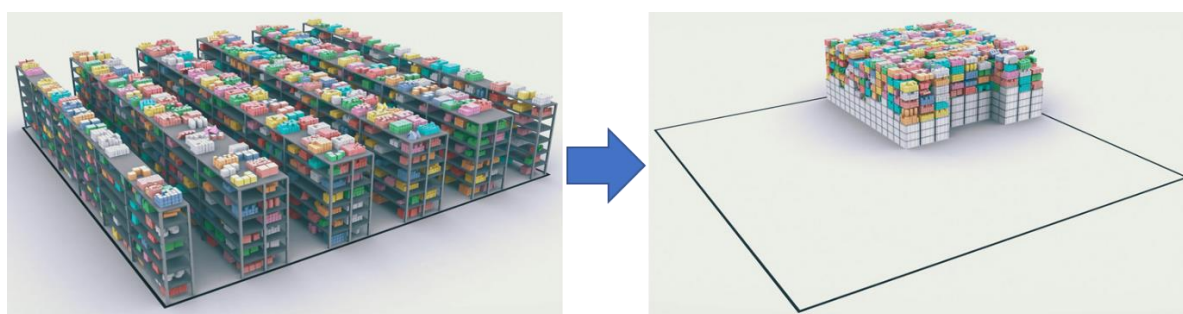


Figure 6. Space-saving representation of the Autostore systems.

A grid was modeled by the solution integrator (Adaméo), responding to the physical constraints of the space selected to operate the system. The initial characteristics of this grid are shown in Table 4. The cost-benefit analysis was conducted based on these characteristics.

Table 4. Autostore grid characteristics modeled for La Poste.

Surface area (m ²)	66
Number of bin locations	1600
Breathing coefficient	15%
Number of available bins	1360
Number of robots	5
Number of operator stations	1
Average rate (bins/h)	103
External bin dimensions (mm)	550 × 450 × 330
Inner bin dimensions (mm)	500 × 400 × 330
Max weight/bin (kg)	30
Number of possible compartments/bin	32

First of all, the analysis consisted in checking the adequacy between the characteristics of the system and those of the customer's products. The bins initially proposed had internal dimensions of 600 × 400 × 330 mm. By comparing these data with the dimensions of the 5741 references contained in the customer's article database and considering that an average of three articles are stored per reference, it was concluded that a bin height of 220 mm, another option proposed by the manufacturer, was more suitable in order to avoid "storing air". As a result, the number of bins in the system increased from 1360 to 2040. However, in spite of this increase in capacity, allowing the accommodation of more references, 1004 of them should continue to be managed outside the system, i.e., manually, for two reasons. Firstly, because the items have out-of-gauge characteristics (Table 5, line B), or secondly, because the maximum capacity of the system has been reached (Table 5, line H). A summary of these data is presented in Table 5. As a result of these findings, the space saving generated by the use of the Autostore grid could be evaluated. The number of square meters for the customer's activities is currently 320 (40 for the processing, order picking and dispatch area, in addition to the 280 for storage mentioned above). For the automated model, about 23 square meters would be necessary for the references to be managed manually outside the system, 132 (66 square meters on the ground multiplied by two because the invoicing of the exploited square meters is based on a height of 2 m) for the automated system and about 30 for the area of treatment, preparation of orders and setting in forwarding. The observed gain would therefore be 135 square meters, i.e., approximately 42% with the automated system.

Table 5. Grid physical characteristics analysis results.

	Number of References (Article Data Base)	5741
A	Number of available bins	2040
B	No. of out-of-gauge references	695
	No. of items stored/reference	3 2
C	No. of refs in bins divided in 8	1464
D	No. of refs in bins divided in 4	663
E	No. of refs in bins divided in 2	1839
F	No. of refs in bins without compartments	595 485
G = C × 8 + D × 4 + E × 2 + F	Number of needed bins	2349
H = G – A	Number of references in surplus	309
I = B + H	Number of references to manage outside the automated system	1004

The second part of the analysis consisted of modeling the economic balance of the two models (current and automated) and comparing them. First of all, it was necessary to define the remuneration model for the services provided by the automated system. The choice was made to define a price per bin movement (injection or retrieval). This price evolves according to the number of customer orders, from which the total number of movements (injection or retrieval) is calculated, and the number of years of amortization of the investment (see Table 6). This model allows La Poste to ensure the repayment of the investment and to involve the customer in meeting the announced objectives. In effect, the price per bin is adapted to the activity. The customers are “responsible”, according to their sales and the optimization of their processes, for the price they will pay. The more they ensure a high activity, the lower the price per bin they will pay.

Table 6. Example of a « price at bin movement » matrix.

Nb. of Amortization Years \ Nb. of Movements	Nb. of Movements									
	220	1099	1674	2197	3296	4394	5493	6592	8789	10,986
1	228.67 €	46.34 €	30.67 €	23.55 €	15.95 €	12.15 €	9.87 €	8.35 €	6.45 €	5.31 €
2	123.89 €	25.38 €	16.92 €	13.07 €	8.97 €	6.91 €	5.68 €	4.86 €	3.83 €	3.22 €
3	88.97 €	18.40 €	12.33 €	9.58 €	6.64 €	5.17 €	4.28 €	3.70 €	2.96 €	2.52 €
4	71.51 €	14.91 €	10.04 €	7.83 €	5.47 €	4.29 €	3.59 €	3.11 €	2.53 €	2.17 €
5	61.03 €	12.81 €	8.67 €	6.78 €	4.77 €	3.77 €	3.17 €	2.77 €	2.26 €	1.96 €
6	54.05 €	11.41 €	7.75 €	6.09 €	4.31 €	3.42 €	2.89 €	2.53 €	2.09 €	1.82 €
7	49.06 €	10.42 €	7.09 €	5.59 €	3.98 €	3.17 €	2.69 €	2.37 €	1.96 €	1.72 €
8	45.32 €	9.67 €	6.60 €	5.21 €	3.73 €	2.98 €	2.54 €	2.24 €	1.87 €	1.65 €
9	42.40 €	9.09 €	6.22 €	4.92 €	3.53 €	2.84 €	2.42 €	2.14 €	1.80 €	1.59 €
10	40.08 €	8.62 €	5.92 €	4.69 €	3.38 €	2.72 €	2.33 €	2.07 €	1.74 €	1.54 €

Figure 7 presented below shows the results of the comparison of the two economic models. The evolution of costs according to the number of orders is represented. For the automated model, several curves are simulated according to the number of years chosen to amortize the equipment investment. This comparison makes it possible to highlight the points of equilibrium between the different scenarios envisaged for the automated system and the current model. For example, the break-even point for the amounts invoiced to the customer (current situation and automated model), for an amortization of the investment over 10 years, is at 1400 orders per month, i.e., 1.84 times the current activity. Likewise, in order to consider a viable automated model with a three-year amortization of the investment, the customer must, at a minimum, realize 5600 orders per month, i.e., multiply by 7.35 times their activity. In addition, in order to achieve a 20% profit with the automated system compared to the current model, with a 10-year amortization of the installation, the client’s activity must be at least 3000 orders per month, which is about four-times higher than the current one. In any case, for all scenarios, the current model remains more advantageous for an activity lower than 1400 orders per month.

The system utilization rate was another parameter analyzed in this study. Indeed, as shown in Table 4, the modeled Autostore grid has an average processing rate of 103 bins per hour, which corresponds to the number of bins presented to the operator to perform a picking or injection operation in the stock per hour. The urban warehouse of La Poste in Paris 8 performs services for customers from 8 am to 7 pm. The automated system would therefore perform the tasks over the same time period (the hours of non-activity are dedicated to recharging the robots), implying an average processing capacity of 1133 bins per day. Figure 8 represents the system utilization rate according to the number of orders processed per month. At the order level of 1400 orders per month, the minimum that could be considered to validate the adoption of the automated system as presented above, the system utilization rate would be 13%. A discussion of the results of the study presented

in this section is developed in the following section in order to draw the first conclusions about the relevance of using these automated systems in urban warehouses.

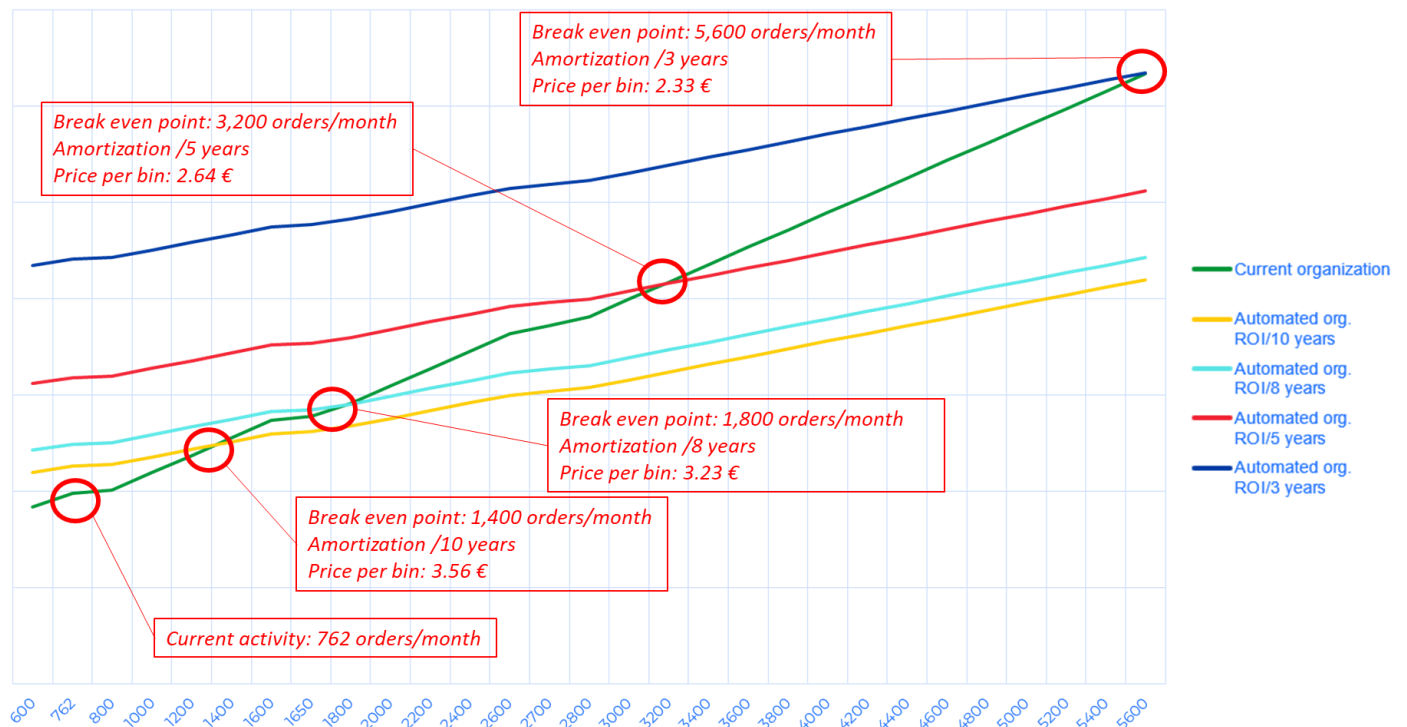


Figure 7. Trends of the amounts invoiced to the customer/month according to the number of orders and the number of years of investment amortization.

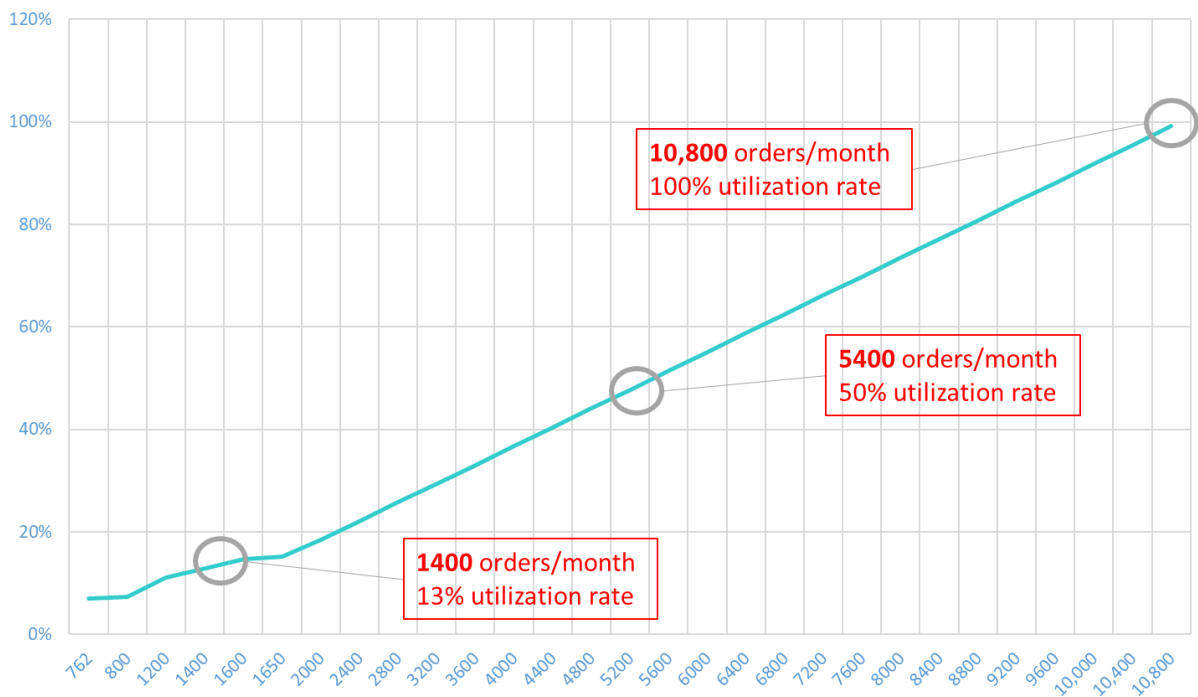


Figure 8. Automated system usage rate by number of orders processed per month.

5. Discussion

The study carried out on case of a customer using the Autostore automated storage and retrieval system allows us to make an initial assessment of these systems. The first

remark concerns the analysis of the customer's products in relation to the characteristics of the modeled grid. Determining the best configuration in order to optimize the filling allowed the addition of 680 bins to the system and to accommodate a greater number of references. This first analysis is therefore of great importance when installing an automated storage and retrieval system. A second decision was made to achieve the same goal: storing only two items for 485 of them, as their dimensions or weight did not allow for three items in one bin. This choice made it possible to avoid dedicating two bins to the same reference. Choosing to reduce the number of parts stored per reference implies studying the rate of use of each of them. Indeed, it will be preferable to store a greater number of parts for a reference that is often solicited. This parameter has not been considered in this study.

In spite of the optimization carried out in order to integrate the maximum number of references into the automated system, 309 references out of the 485 mentioned above are in excess, the maximum capacity of the system having been reached. This implies that they are processed manually and stored on shelves (current model) with the oversized items representing a total of 17.5% of the references. Without space constraints, the system adapted to the article base (5741 references) and to the customer's activity (three pieces stored per reference) would have required 3938 bins (i.e., 4529 bin locations to respect the 15% breathing space). In this configuration, there would remain 327 references, the outsize ones, to be managed manually, requiring only 14 square meters of storage on shelves. A total of 5414 references would be integrated in the automated grid with a floor space of about 80 square meters. Approximately 10 square meters would be required for the processing, order preparation and shipping area. This situation would allow a gain of more than 65% of the floor space for the customer's activities, impacting the fixed costs related to the rent of the operated space by the same amount. However, the constraints of available square meters of the space envisaged to exploit the automated solution do not allow one to reach this level of organization. The gain in floor space observed with the modeled grid is 42%.

In addition to saving space, this system is highly adaptable to the specific geometry of the room, which was difficult to design. The modeled grid allows the exploitation of all of its surface and its height. With this system, the stock is secured. The products are only accessible to the operator stations when they are required to prepare an order. This operation also guarantees "zero error" in the preparations. Each movement is recorded, ensuring better inventory management, without being equipped with complex algorithms. Indeed, for example, the management of the locations is done naturally, the bins with low rotation go down in a natural way at the bottom of pile, while the references with high rotation are positioned on the surface. This organization eliminates tedious tasks and frees up manpower, which can be assigned to other tasks.

However, the implementation of a such system requires a high investment in cost, which, depending on the activity, has a strong impact on the return on investment of such an organization. Indeed, in the case of the model presented in the client's case, it is difficult to imagine that it will be less than 10 years. Indeed, the customer's activity needs to be increased to at least 1400 orders per month to implement the automated solution. Since the customer's products fill the modeled grid entirely, making the grid a solution dedicated to this customer, its low activity cannot be compensated by another customer. This phenomenon is also valid for the low rate of use of the machine for the studied customer.

To echo the environmental issues facing urban warehouses, Autostore advocates that its solution has low energy consumption for its robots to perform their tasks. In addition, it allows the elimination of lighting and heating in the storage space. However, no data on this aspect were found during this study.

The solution studied in the customer's case allows us to understand that a minimum activity is necessary in order to make profitable the investment implied by the installation of such a system as well as its rate of treatment of the orders. Moreover, considering a multi-customer model could improve the machine utilization rate, compensate the low

activity of one customer by another and consequently reduce costs. Such a solution seems to offer the expected performances while answering the challenges of urban warehouses such as the optimization of the exploited surfaces, the ease of use and installation, the modularity, the reduction of painful tasks and subjection to musculoskeletal disorders (MSD) on the part of the operators, and the speed of treatment.

6. Conclusions

Due to the increased awareness of sustainable development issues, companies now must integrate sustainability into their practices and strategies, at the risk of otherwise seriously compromising their survival through unsustainable practices in this new socio-economic environment. These issues have been addressed through a number of research studies. These works had focused on the characterization of new forms of organization, including logistics, both in terms of flows, as well as global strategy of companies. In the field of urban logistics, this work has led to the introduction of a new model of warehouses in cities, called “urban warehouses”. Urban warehouses are a pillar of urban logistics, with specific constraints that must be addressed to make the model viable and efficient. These constraints limit the use of standard solutions. We believe that a methodical and structured use of 4.0 is a possible answer to this challenge and can respond to each part of the urban logistics processes. We have demonstrated this in this article using a case study of an AS/RS designed for the urban warehouse of an industrial partner to optimize the storage and picking processes. Following the analysis of the results of this study, the advantages of densification of the storage area, adaptability, modularity, advocated by the manufacturer of the studied solution have been confirmed. However, in the specific case of the studied customer, the modeled grid requires several changes. The rates proposed by such systems require a minimum number of orders to be processed to ensure a profitable model. Moreover, the return on investment of automated solutions is generally around three years, which is difficult to justify for this type of customer. Therefore, it is very important to define, as was done in this study, the expected components of the intelligent system and analyze the adequacy between the characteristics of the customer and the desired organization. In response to these findings, planning to study a multi-client model is a future direction to consider. Furthermore, this case study is a proof of concept that illustrated the feasibility of the designed model, though further research is needed to generalize the methodology.

Therefore, a second research perspective would be to analyze the relevance of employing other technologies from Industry 4.0 in urban warehouses. AS/RS are mostly used in the storage process. Thus, future work may investigate the perfect combination of these technologies in order to optimize all the processes of the urban warehouse and promote sustainability. This would lead to a methodology and a panel of solutions combining in a relevant and structured way the contributions of 4.0 to optimize all the steps of the logistics process in urban warehouses. Doing so will help to make a contribution toward making these essential supply chain components more efficient, viable, and environmentally sustainable.

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