Master's degree thesis

LOG950 Logistics

The Impact of Automated Storage and Retrieval Systems on Warehouse Operations

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Molde, May 2021
Amalie Nordeide and Silje Rørtveit

Abstract

Purpose: The purpose of this master thesis is to investigate how the implementation of automated storage and retrieval systems (AS/RS) affects warehouse operations for Norwegian companies of different sizes within different industries. Speed, capacity, accuracy and space utilization were all indicators investigated in the research.

Design/methodology/approach: The operational tool for collecting data was two online surveys. Data were collected over 3 weeks in March/April 2021. A total of 18 companies responded to survey 1, and 15 companies responded to survey 2.

Findings: Results from this study indicate that the implementation of AS/RS leads to increased speed and capacity in warehouse operations. There is also an indication that implementation does not necessarily eliminate the possibility for human error regarding picking mistakes. Regarding space savings, this study provides an indication that there is a high tendency for improved space and storage utilization after implementing AS/RS.

Research limitations: Lack of public overview of companies using AS/RS in their warehouses necessitate collecting the contact information of AS/RS users through companies producing and selling the system. This led to fewer responses to the surveys and limits the weight of the findings.

Originality/value: This study is one of the first empirical studies concerning how the implementation of AS/RS affects warehouse operations. The authors contributed by filling a gap in the literature by collecting empirical evidence on speed and capacity, accuracy and space utilization both before and after AS/RS implementation.

Keywords: AS/RS, automation, automated warehouse systems, order processing, warehousing, warehouse operations.

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1.0 Introduction

E-commerce orders have increased over the past years, and the COVID-19 pandemic has contributed markedly to both increases and changes in customer shopping patterns (Guthrie, Fosso-Wamba, and Arnaud 2021). Research and industry reports reveal that an accelerated trend toward e-commerce had already been observed before the pandemic struck (Kim 2020). It is thus likely that the trend will continue in the years to come.

Conventional warehousing has a major drawback: unproductive pickers walking from shelf to shelf to find products for customer's orders. E-commerce orders face requirements that include small orders, large assortments, tight delivery schedules (often next-day delivery) and varying workloads (Boysen, De Koster, and Weidinger 2019). The order-fulfillment process consists of many repetitive steps, such as printing the picking list, selecting the products from shelves by walking through aisles, and packing the order. According to Azadeh, De Koster, and Roy (2019), "warehousing systems and processes are key candidates for automation." They conclude that the advantages of automation are principally savings in space, savings in labor costs, 24/7 availability, scalability, and throughput flexibility. This is particularly suitable for the varying demand inherent to e-commerce environments. Azadeh, De Koster, and Roy (2019) reviewed new categories for automated and robotic handling systems in warehousing. A robotic handling system that has garnered significant exposure in recent years is the automated storage and retrieval system (AS/RS). The system automates the storing and retrieving of products in a warehouse. Implementation of such systems eliminates the activity of walking between aisles to pick products for a customer's order. According to Roodbergen and Vis (2009), "An automated storage and retrieval system (AS/RS) usually consist of racks served by cranes running through aisles between the racks." The processes of storing and retrieving products with AS/RS can be accomplished without the intervention of a human worker. Roodbergen and Vis (2009) also claim that the use of AS/RS offers advantages such as reduced labor costs and floor space, increased reliability, and reduced error rates. Previous literature on AS/RS uses methods such as mathematical modeling, simulation models and other analytical models to investigate AS/RS (Wang, Mou, and Wu 2016, Bipan Zou 2016, Liu, Gong, and De Koster 2018). However, our model uses empirical data to investigate the impact AS/RS have on warehouse operations.

Azadeh, De Koster, and Roy (2019) claim that, over the past several years, there has been a rapid increase in the use of robotic and automated handling systems in warehouse operations. However, there is a lack of academic literature on the subject. This study investigates the impact of AS/RS on warehouse operations through empirical data. The thesis emphasizes how AS/RS implementation has affected companies' performances by investigating speed and capacity in their order-fulfillment processes. In addition, the study investigates picking accuracy and space utilization in the warehouse.

1.1 Purpose and research questions

Previously existing literature on robotized and automated warehouse systems has addressed several interesting topics that include economic benefits, travel time of pickers, the design of automated storage and retrieval systems, and algorithms for automated warehouses (Caputo and Pelagagge 2006, Nastasi et al. 2016, Boysen, Briskorn, and Emde 2017). However, there remains a lack of literature covering the impact of AS/RS on warehouse operations. The continuous increase in e-commerce orders will likely have a significant impact on the future of warehousing. In existing literature, most papers have investigated AS/RS through the method of analytical modeling, and there is a lack of empirical evidence regarding how the system has affected their order-fulfillment process, which motivates us to remedy that deficiency. This study aims to examine:

> "The impact of automated storage and retrieval systems on warehouse operations."

The research paper in part 2 investigates the following research questions:

> *Q1: Will the implementation of automated storage and retrieval systems lead to increased warehouse productivity and capacity?*

> *Q2: Will the implementation of automated storage and retrieval systems lead to improved picking accuracy?*

> *Q3: How do automated storage and retrieval systems affect companies' space utilization?*

1.2 Delimitations

The theoretical delimitation of the thesis is that the research only covers the impact of AS/RS at the warehouse operation and order-fulfillment parts of the supply chain. The research does not investigate the impact of AS/RS on the supply chain as a whole. In addition, only one automated system is investigated (AS/RS) that covers the storage and retrieval of products at the warehouse. Whether the companies have any additional automated solutions in their warehouse is not taken into consideration.

1.3 Structure of the thesis

This thesis is written in a research paper format, including two parts. Part 1 provides an introduction to the research paper in part 2. First, chapter 2 provides a theoretical framework of conventional warehousing and its current challenges, followed by an explanation of automated warehouse solutions and AS/RS. In chapter 3 we provide a case description explaining the companies investigated in the thesis. Chapter 4 contains a thorough description of the method and data used to answer the research questions. Part 1 ends with a summary of the research paper, which is presented in part 2.

2.0 Theoretical framework

2.1 The role of warehouse operations

Warehousing is an important component of the supply chain, and is something that has become more broader, more diverse and more complex as a result of developments in society (Ackerman 1990). It is also the aspect of the logistics process that most products go through (Davarzani and Norrman 2015). Richards (2018) describes it as "a temporary place to store inventory and as a buffer in the supply chain," while Shiau and Lee (2010) describe it as "a commercial building for buffering and storage of goods." The objective of warehouse operations is, according to Stinchcomb (2012), "to satisfy customers' needs and requirements while utilizing space, equipment, and labor effectively."

Warehouse management plays an important role in the process of reaching the objective of having an efficient and productive supply chain (Won and Olafsson 2005, Zäpfel and Wasner 2006, Gu, Goetschalckx, and McGinnis 2007, Davarzani and Norrman 2015). Since warehouse operations is such a vital process in the supply chain, one needs to carefully consider the many different processes that are ongoing in a warehouse because economic efficiency is often the most important objective in warehouse literature (Davarzani and Norrman 2015). How companies store things in their warehouses affects several factors, such as time, cost and ergonomics for the warehouse workers (Azadeh, De Koster, and Roy 2019). Based on this, several processes should be considered before storing things into a warehouse. If this process is planned and completed in an effective manner, the workers will, for example, spend less time refilling goods, as well as picking the goods again at a later stage. This can also lead to a cut in some of the costs at the warehouse, such as wages, and one can avoid physical strains for the employees if efficient processes concerning such issues are determined in advance. Warehouses can, according to Davarzani and Norrman (2015) and Richards (2018), also be seen as a transshipment point because goods are being received, sorted, placed and stored, before the goods at a later point will be picked again, packed and then distributed out of the warehouse. Figure 1 illustrates the fundamental processes that normally take place in a warehouse.

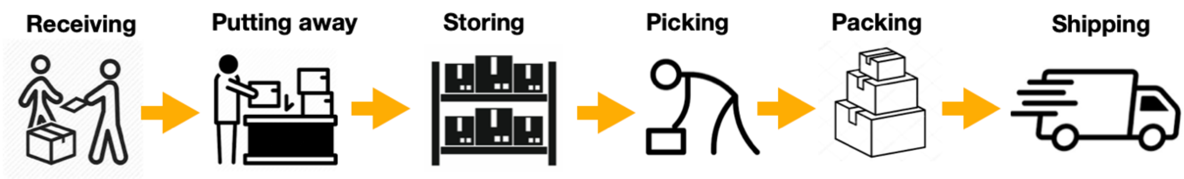

Figure 1 Processes in a warehouse

According to Koster et al (2007) and Shiau and Lee (2010), the term "warehouse" is used if the main purpose is buffering and storage, and that warehouses often involve large investments and operating costs. Although the main objective of a warehouse is to store goods, it is desirable for most companies to keep a minimum amount of inventory, as it lowers inventory costs and has a direct impact on profitability. Unfortunately, this may be difficult, as one cannot predict future demand because trends change over time (Richards 2018), particularly since demand can change quickly, rendering it difficult to forecast. Concepts such as Lean and Just in Time are well-known in logistics and supply-chain environments. These concepts encourage companies to keep a low or zero inventory while eliminating any time spent on non-value-adding activities (Phogat 2013). The reason for this is that by reducing time on non-value-adding processes, the supply chain becomes more efficient. Even though this can be the most optimal solution in certain circumstances, it is, according to Koster et al (2007), necessary in almost all supply chains to have some materials, parts and products stored or buffered to be able to respond to future demand. The process of storing goods in warehouses is therefore an important and crucial aspect of logistics (Koster et al. 2007).

2.2 Traditional warehousing and challenges

Traditional warehouses are perhaps the type of warehouse most people envision when it comes to the process of storing goods. At this type of warehouse, the employee moves around shelves and aisles in the warehouse, and physically picks items according to a picking list (Benrqya 2019, Benrqya et al. 2020). This type of storage is a widely used distribution strategy in retail supply chains (Benrqya 2019). Figure 2 illustrates what a traditional warehouse might look like.

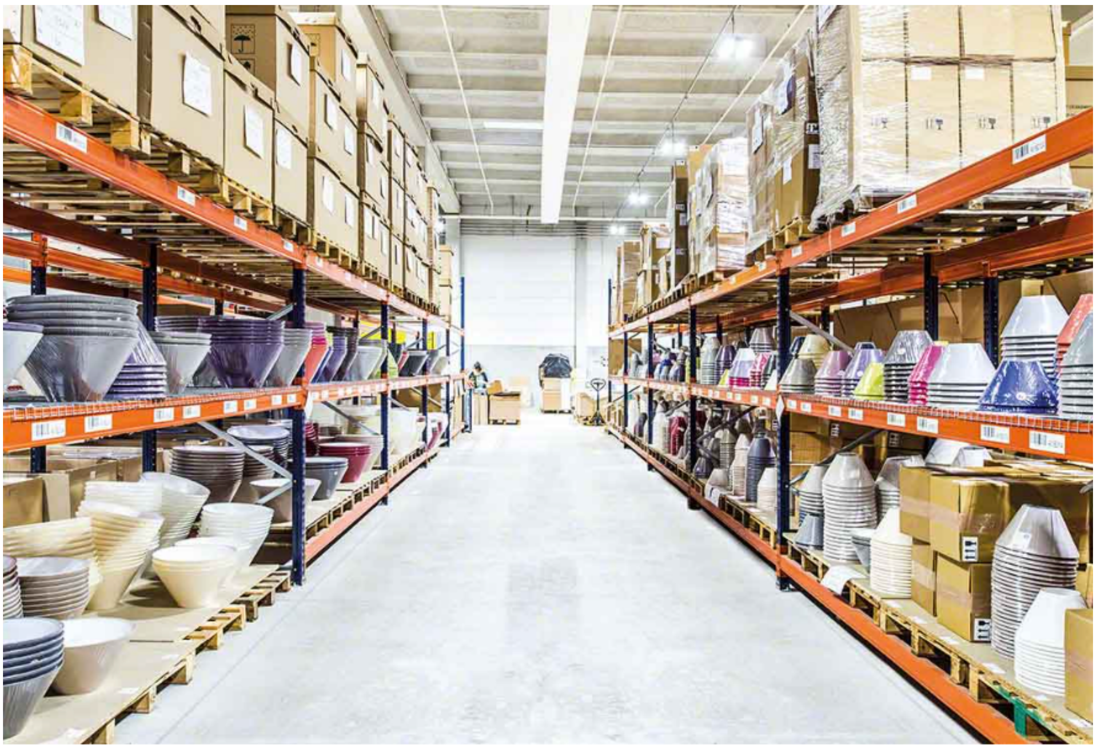

Figure 2 An example of a traditional warehouse (Mecalux 2019)

2.2.1 Challenges with traditional warehousing

There are, according to Zäpfel and Wasner (2006), several challenges related to traditional warehousing. One is the importance of optimal scheduling for all warehouse activities. According to Li et al. (2009), traditional warehousing also meets challenges in fulfilling increased customer demand, as customers today often purchase more products than previously. It can thus be important for companies to implement semi-automated solutions, such as an effective warehouse management system (WMS), which is used to maintain accurate inventory and improve efficiency in the warehouse (Shiau and Lee 2010). A WMS can be used alone or as an integrated part of an ERP-System (Richards 2018). Another challenge for traditional warehousing is order picking, which is considered the most expensive activity for every warehouse (Roodbergen and Koster 2001, Won and Olafsson 2005, Koster, Le-Duc, and Roodbergen 2007, Shiau and Lee 2010). This process is notably labor intensive at traditional or semi-automated warehouses (Koster, Le-Duc, and Roodbergen 2007). Workers at traditional warehouses must physically walk around in the warehouse and pick items according to a picking list. This can be both time consuming and physically laborious for workers. Koster, Le-Duc and Roodbergen (2007) further state that this process is considered by other warehousing professionals to be the highest-priority area for productivity improvements when wanting to become more efficient. Even though there are some challenges with traditional warehousing (Zäpfel and Wasner 2006, Li et al. 2009), there are also many possibilities. New technologies, improvements, and innovations can all be important aspects of improving traditional warehousing.

2.3 Automated warehouse solutions

In addition to traditional warehouses, there are also many warehouses that are partially or fully automated, with varying automated solutions or robots. While some activities are automated and others performed manually at a semi-automated warehouse, all activities are accomplished automatically without any form of interference from human operators at a fully automated warehouse. Semi-automated warehouses are more technologically advanced than traditional warehouses since they implement some kind of automation (Mecalux 2019). According to Custodio and Machado (2019), the term automation was already in use in 1946 and is defined as "the technology by which a process or procedure is performed without human assistance, and it integrates power, a program of instructions and a control system to carry out the instructions." Automated warehouses differ from traditional warehouses by employing more technological systems. This can, for instance, be the use of WMS systems, conveyors, cranes, and other automated picking solutions to select goods without the interference of a human worker. Speed and capacity, accuracy and space utilization can also be different between these two types of warehouses. Figure 3 illustrates an example of an automated warehouse.

Figure 3 An example of an automated warehouse (Cisco-Eagle 2021)

Despite automation having been used for decades, there has been an increase in the adoption of automated warehouse systems in recent years. Hamberg (2012) claims that the trend toward more automation at warehouses is due to the development of new technologies. Holidays and well-established shopping days such as Christmas and Black Friday could be possible explanations for investing in automation, since the numbers of orders could be too large for traditional warehouses to manage. The Covid-19 pandemic could also be a reason for the increased trend in automation because people have been obliged to change their living and shopping patterns and maintain social distancing measures. Sneader and Singhal (2020) state that the pandemic has accelerated the use of automation, particularly in e-commerce, and that this has changed well-established shopping habits. Autor and Reynolds (2020) state that the situation has resulted in what they call "automation forcing," because some companies are now forced to invest in automation to stay competitive. Custodio and Machado (2019) state that the key to having a flexible automated warehouse is to have an effective combination of equipment, data collection technologies, and management solutions.

There are many different companies that provides various types of automated systems, which are partly or fully automated. The following are some examples of automated storage systems: Goods-to-Person, Automatic Guided Vehicles, Autonomous Mobile Robots, Voice Picking and Tasking and Automated Storage and Retrieval Systems (AS/RS) (Jenkins 2020). Koster (2018) has presented a descriptive paper on automated and robotic warehouses in which he addresses several types of automated warehouse systems. He claims that if sales are increasing, there is a higher demand for efficiency and flexibility in warehouse operations, and that it is crucial to stay competitive by being able to have a rapid response to customer demand. Companies therefore need to constantly increase their capacity according to the increase in demand. However, extending a warehouse each time demand increases is costly and inefficient.

2.3.1 Automated storage and retrieval systems

The automated warehouse solution examined in this thesis is automated storage and retrieval systems (AS/RS). The storage and retrieval of goods in this system are both fully automated and have no need for human interference. The types of goods usually stored in the AS/RS are raw materials, semi-finished goods, and finished goods. Roodbergen and Vis (2009) define AS/RS as "…warehousing systems that are used for storage and retrieval of products in both distribution and production environments." The system usually consists of racks and cranes running through aisles to store goods put into the system and retrieve goods for orders. A typical AS/RS system can consist of bins, racks, robots, and ports. The bins hold the inventory, and the racks hold the bins and are used as paths for the robots to navigate on. The robots navigate on the racks to pick bins that contains products for customer's orders. They then bring the product to the port where the picking activity starts. Figure 4 illustrates an example of AS/RS with racks, bins, robots, and ports.

Figure 4 An example of a company that has implemented a type of AS/RS

The main components of any kind of AS/RS are aisles, racks, cranes, input, and output points and picking stations (Roodbergen and Vis 2009). The cranes can be any kind of automated storage and retrieval machine that allocates storage for the goods and retrieves the goods when told to. The input and output points are the locations where the goods are picked up for storage and then placed in the racks. The racks accommodate loads to be stored. The picking stations are where the operators work. At the picking stations, the operators receive the goods from the cranes (by storing and retrieving machines, e.g., robots). They pick the goods and then the cranes place the loads (e.g., pallets or bins) back into the system. Figure 5 illustrates one type of AS/RS. An AS/RS solution comes with many options for systems. The most basic version only allows one crane for each aisle, although, several systems also allow the cranes to carry two loads. These are referred to as *dual-shuttle cranes.* Cranes that can carry more than two loads are rarer.

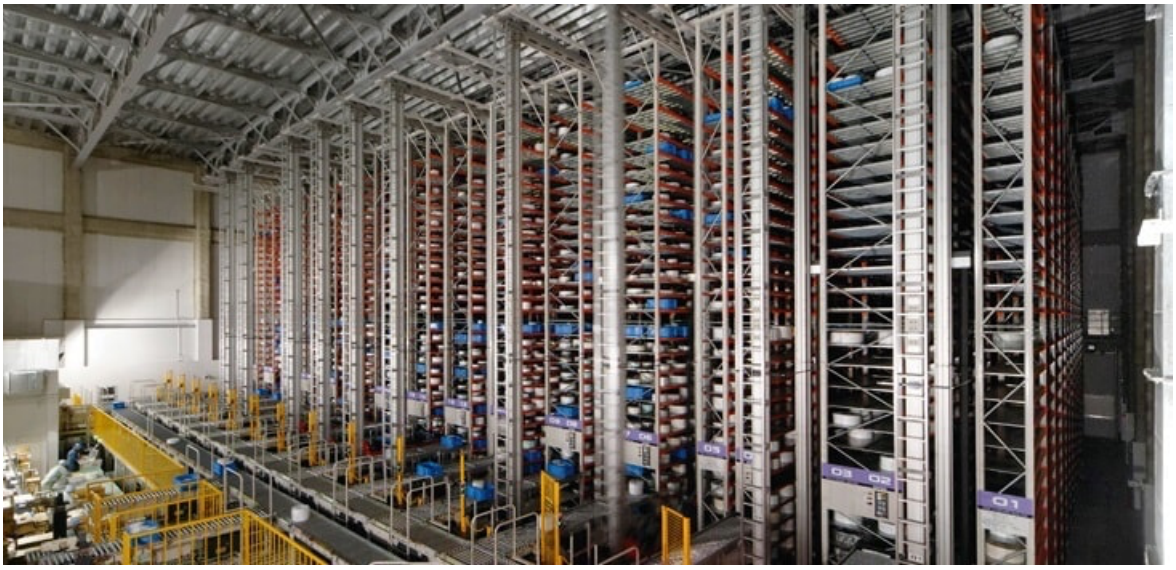
Figure 5 Example of AS/RS (Solutions 2021)

This AS/RS solution is flexible, and allows cranes to go between multiple aisles in various directions. An AS/RS can be a part of either a semi- or fully automated warehouse. In some cases, there are human workers standing at the ports to pack the orders. In that case, the AS/RS is in a semi-automated warehouse in which the automated part of the warehouse represents the AS/RS. The operator then works at a workstation where he/she picks the required amount of product from the unit-load and the robot places the bin back into the system. Literature refers to this system as an *end-of-aisle system*, and, if the pallets are placed with bins, it is usually called a *miniload AS/RS* (Roodbergen and Vis 2009). *Carousel systems* are often used when handling small and medium-sized products and are often preferred for handling typical e-commerce orders. Some warehouses have on the other hand, automated all activities. In that case there can be, for instance, a robot arms that completes the packing activity, and no activities in the warehouse are undertaken with the interference of a human operator.

System design for AS/RS

Apart from the automated storage and retrieval system, there is a need for a WMS to provide signals to the system. Without a WMS there is only an AS/RS without any commands. To give the system signals (for example, when receiving an order), the users need an integrated system to input the signals to the AS/RS. When the WMS receives orders, they give further signals to the AS/RS. The cranes then receive the message to start finding the products needed to fulfill that order. WMS' are used for both storing and retrieving goods. The system needs to be updated when the operator is placing products into the system and when products have been taken out of the system. By doing so, they obtain a real-time stock level of the inventory in the warehouse.

2.3.2 Advantages of AS/RS

According to Roodbergen and Vis (2009), Wang et.al. (2016) and Azadeh et.al (2019), implementing an AS/RS improves factors such as density, space utilization and flexibility in regard to warehouse operations. Speed and accuracy are, according to Baker and Halim (2007), also considerations which can be improved by implementing an AS/RS. Other aspects such as reduced labor requirements and improved ergonomics can constitute further advantages of AS/RS.

Density

One of the most noticeable benefits of implementing an AS/RS is space efficiency at the warehouse (Koster 2018, Azadeh, De Koster, and Roy 2019, Wang, Mou, and Wu 2016). Traditional warehouses have several shelves with isles that the workers navigate to pick products for customers' orders. An AS/RS is, however, a compact storage system that utilizes every inch it occupies with a high density. A considerable advantage of such a compact storage system is that it limits the ecological footprint, which means that it is better for the environment (Yugang Yu 2006). With some types of possible AS/RSs there are possibilities for four times the storage capacity as compared to traditional warehousing (AutoStore 2021b). Since storage space is one of the costliest aspects of warehousing, companies usually try to minimize this cost.

Flexibility and customization

According to Koster (2018), the AS/RS concept is popular because it is significantly more flexible and makes it easier to increase a warehouse's capacity. This is beneficial as companies are constantly changing, particularly within areas such as construction, strategy, capacity, core activities or key values. It is difficult to avoid such challenges from occurring given change is something companies need to go through to stay competitive and make profit. The same counts for an AS/RS. As demand increases, the company will most likely need to add extra capacity to their AS/RS**.** If it is necessary to expand the system any further, it is possible with some types of AS/RSs to expand a previously implemented system without needing to stop production, and the robots continue to operate even throughout any expansion or maintenance work on the site. Flexibility is important, as customers have different needs and demands. It is therefore beneficial that some AS/RSs can be tailored to a specific customer in accordance with the outlook of their warehouse or the types of products they carry.

Speed

Delivery time is important in the order-fulfillment process and it is crucial to keep the delivery time as low as possible, particularly given the increasing demand. Each process should be optimized and every non-value-adding activity should be reduced or eliminated. With traditional warehousing, unexpected events might occur regarding the replenishment of goods, the absence of workers, or the maintenance of a truck. These events disturb the order-fulfillment process and increase the average delivery time. An AS/RS, however, makes it possible to optimize delivery time though the use of new types of technologies (Yugang Yu 2006).

Accuracy

Order picking is, according to Koster et.al (2007), one of the most costly and labor-intensive process in most warehouses. If workers or robots make mistakes here, it can lead to ripple effects such as dissatisfied customers and higher operational costs. It is therefore vital to be accurate when executing these activities. An AS/RS can operate with a higher uptime since robots do not need breaks as human workers do, and often charge themselves during nighttime when there are no workers on site.

2.3.3 Challenges with AS/RS

In addition to being advantageous, implementing an AS/RS may also present some challenges and disadvantages. Pinkham (1999), Roodbergen and Vis (2009) and Azadeh et.al (2019) all claim that the implementation of an AS/RS represents a high investment cost, and that companies also need to face continuous costs in regard to maintenance and expansion of the system. Both Pinkham (1999) and Azadeh et.al (2019) state that an AS/RS is a considerable investment, which should be carefully considered, and that it is important to have a long-term vision when planning to implement an AS/RS.

3.0 Case description

This study investigates the implementation of AS/RS solutions on warehouse operations with regards to speed and capacity, accuracy and space utilization. This is investigated through a study on the phenomenon of automation in warehouse operations. The study investigates users of AS/RS. Due to a lack of overviews on AS/RS users, there was a need to include two companies in the study to retrieve correct data concerning AS/RS users. First, a Norwegian AS/RS producer, AutoStore, was contacted. Through the producer, their partner, Element Logic, was also contacted. The partner sells the system to the end customer (user). This study examines the end customer and the impact of AS/RS implementation in regard to speed, capacity, accuracy and space utilization.

Figure 6 illustrates the connections between the manufacturer (A), partner (B) and end customers (C). The research undertaken in this thesis is conducted on the users/customers (C) to map the impacts they have experienced in their warehouse operations after implementing an AS/RS. Further, in this chapter, the manufacturer, partner and customers are presented. In addition, a thorough explanation of the AutoStore solution is provided, and an explanation of how warehouse operations with an AS/RS typically function.

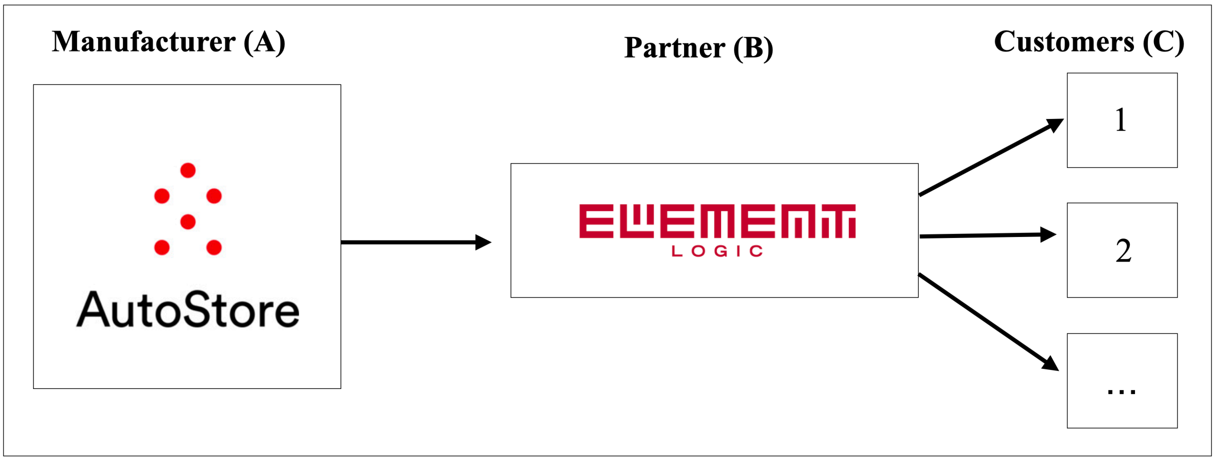

Figure 6 Illustration of the connections between the manufacturer, partner and customer

3.1 AutoStore (A)

Founded in 1996, AutoStore is a Norwegian company that is a provider of AS/RSs. Their headquarters are in Nedre Vats in Norway, and they have offices in the US, UK, Germany, Japan, Poland and Oslo (AutoStore 2021a). AutoStore is a robot technology company that focuses on optimizing software and hardware to create industry-leading order-fulfillment systems. The company provides AS/RSs globally with over 500 installations in over 30 countries across all kinds of industries that include electronic components, third-party logistics, aviation, office supplies, and textiles. Some of their customers include Best Buy, Siemens, Lufthansa, DHL, Puma and XXL (AutoStore 2021a).

AutoStore sells, distributes and services their systems through their qualified system integrators/partners, which are Alstef, AM Logistic Solutions, Bastian Solutions, Dematic, Element Logic, Fortna, Hörmann Logistik, Kuecker Logistics Group, Lalesse Logistic Solutions, LG CNS, Okamura, PULSE, Swisslog and STKSL.

3.2 Element Logic (B)

Element Logic was founded in 1985 and is a Norwegian company providing companies with automated and static warehouse solutions (ElementLogic 2021b). Element Logic is known as the original AutoStore partner. In 2003, the inventor of AutoStore, Ingvar Hognaland, and the founder of Element Logic, Kjell Blakseth, met at a tradeshow. Back then, the industry was afraid of any robotic solution, but Element Logic believed in AutoStore's solution (ElementLogic 2021c). Six months later, they built the world's first AutoStore facility. From then, they have had a strong collaboration, continuing to improve the system. Today Element Logic holds the whole of Europe as their local market. In 2019, Element Logic passed 80 million euros in turnover, and has seen exponential growth in the company since 2014.

Element Logic has, from the beginning, had technology as a huge part of their DNA. One of their most well-known assets is their software, "eManager," which allows companies to optimize their efficiency with AutoStore. The software is a WMS that enables customers to monitor their AutoStore system, as well as integrate AutoStore with their own warehouse automation system (ElementLogic 2021a).

3.3 Customers (C)

This study investigates the users of the AS/RS solution (part C from figure 6). These companies have implemented the system in their warehouse operations. The companies differ in size, manner of industry, and scope of their AS/RS solutions. All are Norwegian and operate in a wide variety of industries such as retail, e-commerce, sports, aviation, manufacturing, and electronics.

3.4 The AutoStore solution

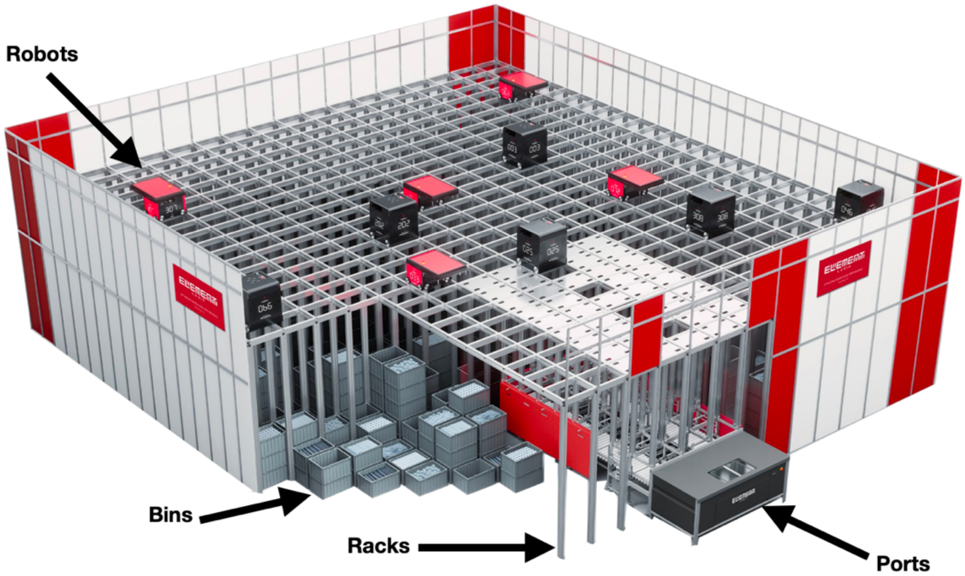

Figure 7 Example of an AutoStore AS/RS system

AutoStore is a cube-based AS/RS which contains racks, bins, robots, and ports (workstations). Figure 7 illustrates an AutoStore system with the robots maneuvering on top of the racks to store and retrieve the bins to the ports. The racks are made of an aluminum framework which holds the bins and is also a railway for the robots. The bins are stacked on top of each other, safely stored on a strong construction. All bins are standardized, and each single bin has a unique number. This number identifies the bin and is stored in the controller database, which makes the bin recognizable. The bins are available in different heights and materials and can be divided into several compartments to allow storage of multiple products in one single bin. Each bin can carry a total weight of 30 kilograms and can be delivered in different sizes.

The AutoStore command center is called “controller.” The controller provides a network connection to the customer’s infrastructure (AutoStore 2021c). The tasks of the controller are to plan and schedule tasks for the robots, provide advanced traffic control and log bin and robot positions in real time. The controller is a flexible and configurable alert system which provides service and support to the end user.

The robots have been developed over five generations, from R1 to R5, where R5 is the latest generation. Figure 8 illustrates how one of the robots looks today. The robots are directed by the controller, which gives them movement directions. It continuously makes the process smarter and more efficient and can make the robots work together to retrieve bins. If one robot is called to a service depot, the controller replaces the robot with another functioning robot.

Figure 8 One of AutoStore´s robots (AutoStore 2021)

The R5 robots work 24/7, with systems that make sure that the robots charge when necessary. The robots are energy efficient, using about 100 W, which can be compared to 1/10 of a toaster (AutoStore 2021d). The controller ensures that the robots are always assigned to the order that has the shortest route. This is done to save both time and energy for the robots.

The ports are where the human workers have access to all the bins inside the grid. This is where they receive the bins that the robots deliver to them. If the order consists of several unique products, the robots wait with the next bin at the top of the ports to be presented next. Figure 9 illustrates how a port in an AutoStore system can look. The worker is standing by the port. The WMS screen in front of the worker displays the order lines from the orders.

Figure 9 Warehouse worker standing by the AS/RS port (AutoStore 2019)

3.4.1 Warehouse operations with an AS/RS

Putting in new products

To place new products into the system, the worker asks the system for an empty bin to store the goods. The bin is then be delivered to the worker at the ports. Next, the worker scans the new items and places the items in the bin. The robots then find a storage place in the grid for the bin containing the product. When the workers put the item into the AS/RS, they give away their rights to manage that product. The AS/RS decides where the product is placed in the system. The only thing the users are in charge of is the bin the product will be put in. The WMS matches the goods to the different bins when they put in a new product or do a refill of a product. Typically, the input ports and the output ports are placed on different sides of the AutoStore grid. This is to make the input and output operations more efficient and to utilize the warehouse space. Often there are huge pallets of products to be put into the AS/RS, and by having the input on one side, it opens up more space to the worker entering the products to the system.

Order-fulfillment process

With AS/RS, the worker will display the order on the WMS screen by the port. The robots then bring the worker the bins belonging to the products needed to complete that order. There might be different products in the bins, but the WMS tells the worker which part of the bin he or she should pick from, and how many units they should pick. When the worker has picked the right quantity, he or she will confirm the number picked on the screen, and the robots put the bin back in the system. When all the products comprising the order have been delivered, the worker packs the order and the WMS brings the label belonging to that delivery.

By being able to work 24/7, the robots can start planning the orders in advance of the working day. If an order requires a bin that is placed in the bottom of the grid, the robot can start digging up that bin at nighttime to reduce time spent waiting during daytime. The controller continuously works to optimize the routes to utilize the robots in the most efficient manner possible.

Changes in demand and products

If the company faces a change in demand and needs more workers or storage, they can add more robots or bins to the grid. Some companies build their system with the ability to expand in the future and have storage ready to fit more bins when necessary. The smallest AutoStore systems hold around 2-3 robots and a few thousand bins, and some of the largest systems hold around 500 robots and 300,000-400,000 bins. The system is flexible when it comes to any change in demand, as robots can always be added to fit the current demand. The same counts if the company has any increase in the number of products. If the company needs to store more products and the AS/RS is full, they can expand the AS/RS with more grids to fit more bins.

Sequencing

As previously mentioned, the controller can always find ways to optimize the order-fulfillment process. This also includes the sequencing of orders. Products that do not have a high order frequency will eventually end up in a bin further down in the grid. The retrieval of that product usually takes more time than others and might include several robots to do the digging. If the system receives an order including that product during the evening or night, the system will start preparing for that order so that the bins are available for delivery in the daytime. This makes the order-fulfillment process more efficient during daytime and reduces the waiting time for the products.

Another kind of sequencing is that the system can be asked to bring the heaviest or less fragile products first. This reduces damage to products during transportation. As the products might be packed as they are received, this represents an advantage as it prevents time spent on repackaging if something heavier is required later in the order.

Limitations

The AutoStore has some limitations and does not fit any building. An AS/RS will fit optimally if a warehouse has a ceiling height that is a minimum of 10-12 meters. There should also be around two meters available over the AS/RS to be able to walk on the grids to conduct service work. The minimum number of bins placed on top of each other should be around four, and the most cost-effective manner of building the AS/RS is to think in terms of height rather than width.

There is a limitation on the weight of the products in the bins. The bins can carry a maximum of 30 kilograms. Products exceeding this weight should be placed outside the AS/RS.
The system also has a safety margin if something should fall out of or protrude from the bin. If a worker replenishes products and does not put the product in the bin properly, the system will not accept the bin and an error is shown on the WMS. The system has an uptime of 99.6 %, which means that the system is almost constantly running. The robots are self-diagnosing and report back to the system if they need any maintenance work (AutoStore 2021b).

4.0 Data and methods

Methods are, according to Bryman (2008), techniques researchers use to collect and analyze data, and can include questionnaires, interviews, or observations.

This chapter begins by explaining the choice of research design for this thesis in section 4.1, before information concerning the process of designing a survey is explained in section 4.2. Information about the data and how it has been collected is presented in section 4.3. Section 4.4 addresses several challenges with the choice of research design.

4.1 Research design

According to Schwartz-Shea (2011), research design refers to "the basic structure of a research project, the plan for carrying out an investigation focused on a research question that is central to the concerns of a particular epistemic community." A research method, is on the other hand, the strategy one uses to implement this specific plan (University 2018).

Multiple research designs were considered before the final choice of this thesis' design was taken; in other words, both a *quantitative* approach in which one uses the traditions of science, and a *qualitative* approach in which one employs a more reflective and explorative approach (Davies 2014). Based on previous literature and the gap in it regarding the effect of implementing an AS/RS in warehouse operations, it was beneficial to base this thesis on a *case study* that focuses on automation.

Case studies are a well-known and widely used method in scientific articles. Robert K Yin is perhaps one of the most well-known scientists to have published books on this specific method. Yin (2009) defines a case study as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context" and that the case study "relies on multiple sources of evidence." Yin further states that the need for case studies arises from the desire to understand a complex social phenomenon. Feagin (1991) states that the nature of the case study has changed from being an in-depth investigation using qualitative research methods on a single social phenomenon, to also using quantitative methods, and even a combination of these two research methods.

Furthermore, a decision was made to base this thesis on mixed methods, as it was seen to be beneficial to gather information concerning both the companies we examine that manufacture and sell the AS/RS, and the end customer's point of view. Information was gathered using varying methods to obtain a better overview of what the implementation of an AS/RS means to its users. *Mixed methods* are, according to Creswell and Clark (2011), "the type of research in which researchers or team of researchers combines elements of qualitative and quantitative research approaches for the purpose of breadth and depth of understanding and corroboration." Table 1 summarizes several differences between qualitative and quantitative research methods. The table illustrates that there are differences between these two methods regarding measurement, type of data collected, type of information, common methods, and the role of theory in relation to research.

Table 1 Overview of qualitative and quantitative research methods

	Qualitative Method	**Quantitative Method**
Uses measurement	No	Yes
Type of data:	Words and meanings	Numbers and statistics
Type of facts/information:	In-depth insight	Generalized information
Common methods	In-depth interviews with open questions, observations and literature reviews	Surveys (with closed questions), experiments and observations
Principal orientation to the role of theory in relation to research	Inductive	Deductive (testing theories)

(Bryman 2015, Smith 2020, Kenton 2020)

4.1.1 The applied method

A case study is the method that has been used during the process of writing this thesis, while the operational tool for collecting data was an online survey with anonymous respondents. This survey was the foundation for the research in this paper. In addition, one additional survey collecting empirical data and some comments from a respondent over email was received to obtain more depth in the research. Fink (2003) defines surveys as "a system for collecting information from or about people to describe, compare and explain their knowledge, attitudes, and behavior." Fink also claims that the survey system consists of several activities. A survey should set a purpose for collecting information, be valid and reliable, and be able to gather and analyze data as well as report it. Surveys can also be made in different formats, all depending on where to contact the respondents. To collect data via surveys, one usually uses the internet, phones, postal services, or a mix of these methods (Dillman 2014). Two online surveys were used in this thesis, as it was seen to be the most optimal solution regarding saving time and because it would be easier to analyze data that was already digital. Another factor that was discussed and noted was the ongoing Covid-19 situation, and that, due to this, it could be more difficult to gather the information through physical attendance. Table 2 summarizes the choice of methods used in this thesis.

Table 2 An overview over the research method used in this thesis

An overview of research methods:	
Research design	Case study
Unit of analysis	The impact of AS/RS on warehouse operations
Research approach	Mixed method
Theoretical framework	Traditional warehousing, Automated solutions, Automated Storage and Retrieval Systems, (See chapter 3.0)
Data collection	Empirical data collected with two surveys in March/April 2021. Information received over email from one respondent.

4.2 Survey design

In the process of making the two surveys, several factors were discussed: whether the questions should be general or specific, neutral, value-added, open, and the number of questions that should be asked. In addition, the use of scaling tools was considered. The questions were divided into four categories: 1. Information about the size of the AS/RS system, 2. Speed and capacity 3. Accuracy 4. Space utilization. It was further decided that the surveys should contain few rather than many questions, and that these questions should be general and employ well-known logistic concepts which should be easy to understand for people working within the field of logistics and supply-chain management. Some of the questions contained answer alternatives based on a Likert scale in which the answers were as follows: 1. Significantly fewer, 2. A little less, 3. No difference, 4. Some more and, 5. Significantly more. In addition, some of the questions were open, and the respondents could type their answers into empty boxes.

4.2.1 Survey preview

Some precautions were taken to ensure that the questions would be fully understood by the respondents. A survey preview was conducted in which the questions for survey 1 were tested on a small number of respondents. These respondents had the same prior knowledge as the respondents in the upcoming survey since they work within the field of logistics and SCM. The advantage of this is that the questions could subsequently be changed if something emerged as unclear.

After the survey preview was conducted, we received feedback on questions and adjusted them accordingly. In addition, several questions were added to the survey. The final edition of the survey was sent out to the case companies in March 2021 and data collection began.

4.3 Data collection

All data was collected as primary data. All respondents in the two surveys work in the fields or logistics and SCM (e.g., as logistics managers, operational managers, CFOs, supply-chain managers). All of them work at Norwegian companies that have implemented an AS/RS in their warehouses. The participating companies differ in several respects, such as company size, which industry they operate in, whether they use retail or e-commerce, and the sizes of their AS/RS solutions. All data from the survey are anonymous, but the respondents can be distinguished according to the size of their implemented AS/RSs since they answered questions regarding the number of bins, ports, and robots. Table 3 illustrates how the companies are categorized into the size of their AS/RSs. Questions regarding system size were asked because it would be possible to distinguish between the size of different warehouses, as well as to determine whether there are differences between companies that have implemented a small, medium or large AS/RS and how this affects warehouse operations.

Table 3 A categorization of small, medium, and large AS/RS

	Small	**Medium**	**Large**
Bins	5,000-10,999	11,000-20,999	21,000+
Robots	3-8	9-20	21+
Ports	1-4	5-7	8+

Before survey 1 was sent, an email with information on the upcoming survey was forwarded to 32 companies that have implemented AS/RSs in their warehouses. This email asked if the receivers of the email would be willing to partake in the upcoming survey. The respondents were also informed that the answers to the survey would be anonymous. Twenty consents concerning answering the upcoming survey were given. Survey 1 was sent out by email March 25th, 2021.

After receiving several replies to survey 1, whether it would be beneficial to gather some more specific information through the data collected was discussed. The answers in survey 1 were insightful, but it was necessary to collect empirical data to map the results the companies had attained from AS/RS. A short follow-up survey concerning questions about orders and order lines before and after implementing AS/RS was therefore prepared and was sent out to the same 20 respondents by email March 26th, 2021. Since all respondents were Norwegian, they received questions in Norwegian. Both surveys including all questions are attached in both Norwegian and English in Appendix 1-4.
A total number of 18 answers on survey 1 and a total of 15 answers on survey 2 were received.

4.4 Research challenges

It is always possible to encounter challenges while undertaking research. Reliability and validity were two aspects that were considered. Regarding reliability, it was necessary to consider whether the results from this study would be consistent over time, and if other researchers willing to conduct the same research later would find the same results.

Another challenge with this study was that, when collecting data, all contact information for the end customers was provided by Element Logic, which is the seller of the AS/RS to the end customers. This made the process more inconvenient than if one could base the research on users regardless of their venders.

5.0 Research summary

Warehouses are considered to be a key candidate for automation as they are both labor intensive and require large facilities for storage. Particularly concerning e-commerce, warehouses require the efficient storing of goods as they often store thousands or even millions of unique items (Azadeh, De Koster, and Roy 2019). This thesis investigates the impact AS/RSs have on warehouse operations. In the literature, there is a gap in the empirical evidence concerning the impact an AS/RS has on speed, accuracy within picking errors, and space utilization. We believe this research has contributed to the existing research undertaken on the topic by collecting empirical data on speed, accuracy and space utilization from several companies within different industries in Norway who have implemented AS/RS solutions in their warehouses. To collect data and comments from the users/companies, we conducted two surveys containing questions on speed and capacity, accuracy, and space utilization (see Appendix 1-4). Twenty Norwegian companies received the surveys. There was a total of 18 responses to survey 1 and 15 responses to survey 2.

Results from the study indicate that companies who have implemented an AS/RS in their warehouse operations have achieved increased capacity and speed in their order-fulfillment processes. For some companies, it has led to released capacity, making it possible to focus on other activities. Most companies have increased demand after implementation and are now picking significantly more order lines per day than before AS/RS implementation. Results from the study indicates that companies achieve a more efficient order-fulfillment process using AS/RS implementation.
In terms of accuracy in order picking, the study indicates that an AS/RS does not necessarily lead to the reduction or elimination of human error. Companies still struggle with picking errors such as customer orders containing wrong or missing products or incorrect quantities. Regarding space utilization, companies participating in the study have experienced significant space savings from AS/RSs. They comment that released space has been used to buffer storage, products that do not fit in the bins, pallet racks, and other purposes. Some companies also emphasize that some space is meant for further expansion of their AS/RS

solution when necessary. The responses indicate that implementing an AS/RS provides significant space savings for companies.

5.1 Managerial implications

This research is one of the first to investigate the impact of AS/RS across industries, with multiple companies participating in the study. The findings of this study provide an indication on the effects companies might achieve from implementing an AS/RS in their warehouses. For companies considering an AS/RS, it is possible to compare the size of systems used in the surveys to the company and examine the effect they have achieved. Moreover, this study can raise awareness of accuracy in terms of human error because, even though the AS/RS picks at a high accuracy rate, there is still a probability that incorrect products will be picked at the ports where the human operators work.

5.2 Limitations of the study

This study was limited by the number of respondents to the surveys. The lack of an overview of companies that have implemented AS/RSs in their warehouses rendered it necessary to contact two other companies to gather that information. This limited the study to the Norwegian AS/RS market. In addition, contact information for all companies with AS/RSs in Norway was not received, which left us with 32 Norwegian companies to contact.

5.3 Suggestions for further research

This thesis provided several interesting findings regarding the implementation of AS/RSs in warehouse operations. Our findings can form a foundation for a further understanding of the topic, and what it means for the warehouse operations for companies implementing an AS/RS.

Even though the study is conducted on Norwegian companies, it might be possible to find connections between similar companies across borders. The study also opens the possibility of further investigating whether companies in other countries and continents experience the same effects. In addition to the findings, there are also many other areas to research. For instance, conducting a study of the complexity of the inventory handled by the system in terms of temperature control, types of goods stored in the system, and variety of product range. This can be conducted to investigate whether an AS/RS is more suitable for a complex inventory. The ergonomic gain from AS/RSs would also be an interesting direction for future research, since heavy lifting and poor posture from conventional order picking is either reduced or eliminated by implementing an AS/RS. Considering how the implementation of an AS/RS affects the sustainability of a company can also be a positive approach for future research since environmental considerations are becoming increasingly important for companies worldwide.

This study was limited to 18 respondents. Therefore, for further studies, an investigation of more respondents could be beneficial. It would be interesting to ascertain whether the results were the same with a larger number of respondents.

6.0 References

Ackerman, K. B. 1990. "Warehousing - Origins, History and Development. Practical Handbook of Warehousing." *Springer Science*.

Autor, David, Reynolds, Elisabeth. 2020. "The Nature of Work after the COVID Crisis: Too Few Low-Wage Jobs." *The Hamiltion Project*.

AutoStore. 2019. "AutoStore tweet." Autostoresystem, accessed 10.05.2021. https://twitter.com/AutoStoresystem/status/1083077597788078080.

AutoStore. 2021a. "About AutoStore." AutoStore, accessed 02.02.2021. https://autostoresystem.com/about-autostore/.

AutoStore. 2021b. "Benefits." accessed 08.02.2021. https://autostoresystem.com/benefits/.

AutoStore. 2021c. "Controller." accessed 02.02.2021. https://autostoresystem.com/controller/.

AutoStore. 2021d. "The Worker." AutoStore, accessed 02.02.2021. https://autostoresystem.com/r5/.

Azadeh, Kaveh, René De Koster, and Debjit Roy. 2019. "Robotized and Automated Warehouse Systems: Review and Recent Developments." *Transportation Science* 53 (4):917-945. doi: 10.1287/trsc.2018.0873.

Baker, Peter, and Zaheed Halim. 2007. "An exploration of warehouse automation implementations: cost, service and flexibility issues." *Supply Chain Management: An International Journal* 12 (2):129-138. doi: 10.1108/13598540710737316.

Benrqya, Yassine. 2019. "Costs and benefits of using cross-docking in the retail supply chain." *International Journal of Retail & Distribution Management* 47 (4):412-432. doi: 10.1108/ijrdm-07-2018-0119.

Benrqya, Yassine, Mohamed Zied Babai, Dominique Estampe, and Bruno Vallespir. 2020. "Cross-docking or traditional warehousing: what is the right distribution strategy for your product?" *International Journal of Physical Distribution & Logistics Management* 50 (2):255-285. doi: 10.1108/ijpdlm-03-2019-0091.

Bipan Zou, Xianhao Xu, Yeming (Yale) Gong, Rene´ De Koster. 2016. "Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems." *European Journal of Operational Research* 254 (1):51-67. doi: 10.1016/j.ejor.2016.03.039.

Boysen, Nils, Dirk Briskorn, and Simon Emde. 2017. "Parts-to-picker based order processing in a rack-moving mobile robots environment." *European Journal of Operational Research* 262 (2):550-562. doi: 10.1016/j.ejor.2017.03.053.

Boysen, Nils, René De Koster, and Felix Weidinger. 2019. "Warehousing in the e-commerce area: A survey." *European Journal of Operational Research* (277):396-411. doi: https://doi.org/10.1016/j.ejor.2018.08.023.

Bryman, Alan. 2008. "Of methods and methodology." *Qualitative Research in Organizations and Management: An International Journal* 3 (2):159-168. doi: 10.1108/17465640810900568.

Bryman, Alan. Bell, Emma. 2015. *Business Research Methods*. 4 ed. Oxford, United Kingdom: Oxford University Press.

Caputo, Antonio C., and Pacifico M. Pelagagge. 2006. "Management criteria of automated order picking systems in high-rotation high-volume distribution centers." *Industrial Management & Data Systems* 106 (9):1359-1383. doi: 10.1108/02635570610712627.

Cisco-Eagle. 2021. "AS/RS Systems for Distribution and Manufacturing." accessed 27.04.2021. https://www.cisco-eagle.com/material-handling-systems/asrs-systems.

Creswell, John W., Plano Clark, Vicki L. . 2011. *Designing and Conductiong Mixed Methods Research*. 2 ed: Sage Publications.

Custodio, Larissa, and Ricardo Machado. 2019. "Flexible automated warehouse: a literature review and an innovative framework." *The International Journal of Advanced Manufacturing Technology* 106 (1-2):533-558. doi: 10.1007/s00170-019-04588-z.

Davarzani, Hoda, and Andreas Norrman. 2015. "Toward a relevant agenda for warehousing research: literature review and practitioners' input." *Logistics Research* 8 (1). doi: 10.1007/s12159-014-0120-1.

Davies, Martin Brett and Hughes, Martin Brett 2014. *Doing a Successful Research Project: Using Qualitative Or Quantitative Methods*. 2 ed: Palgrave Macmillan.

Dillman, D A., Smyth, J D., Christian, L M. 2014. *Surveys. The Tailored Design Method*. f ed: John Wiley & Sons, Incorporated.

ElementLogic. 2021a. "eManager warehouse execution, management, and control system for AutoStore." accessed 12.04.2021. https://www.elementlogic.net/solutions/software/.

ElementLogic. 2021b. "Om oss." accessed 12.04.2021. https://www.elementlogic.no/om-oss/.

ElementLogic. 2021c. "Our Story." accessed 12.04.2021. https://www.elementlogic.net/about-us/our-story/.

Feagin, Joe R., Orum, Anthony M. and Sjoberg Gideon 1991. *A case for the case study*: The Univeristy of North Carolina.

Fink, Arlene. 2003. *The Survey Handbook*. 2 ed: SAGE Publications, Inc.

Gu, Jinxiang, Marc Goetschalckx, and Leon F. McGinnis. 2007. "Research on warehouse operation: A comprehensive review." *European Journal of Operational Research* 177 (1):1-21. doi: 10.1016/j.ejor.2006.02.025.

Guthrie, Cameron, Samuel Fosso-Wamba, and Jean Brice Arnaud. 2021. "Online consumer resilience during a pandemic: An exploratory study of e-commerce behavior before, during and after a COVID-19 lockdown." *Journal of Retailing and Consumer Services* 61. doi: 10.1016/j.jretconser.2021.102570.

Hamberg, Roelof., Verriet, Jacques. 2012. *The Falcon Project: Model-Based Design of Automated Warehouses*: Springer-Verlag London.

Jenkins, Abby. 2020. "Warehouse Automation Explained: Type, Benefits and Best Practices." [Webpage], Last Modified 10 December, accessed 21 April. https://www.netsuite.com/portal/resource/articles/inventory-management/warehouse-automation.shtml.

Kenton, Will. 2020. "Quantitative Analysis." [Webpage]. Investopedia, accessed March 22 2021. https://www.investopedia.com/terms/q/quantitativeanalysis.asp.

Kim, R.Y. . 2020. "The impact on COVID-19 on consumers: preparing for digital sales." *IEEE Eng. Manag.*

Koster, René B.M. de. 2018. "Automated and Robotic Warehouses: Developments and Research Opportunities." *Logistics and transportation*:33-40. doi: 10.26411/83-1734-2015-2-38-4-18.

Koster, René de, Tho Le-Duc, and Kees Jan Roodbergen. 2007. "Design and control of warehouse order picking: A literature review." *European Journal of Operational Research* 182 (2):481-501. doi: 10.1016/j.ejor.2006.07.009.

Li, Gang, Hongjiao Yang, Linyan Sun, and Amrik S. Sohal. 2009. "The impact of IT implementation on supply chain integration and performance." *International Journal of Production Economics* 120 (1):125-138. doi: 10.1016/j.ijpe.2008.07.017.

Li, Zhengpink.   Low, Malchom Yoke Hean. Lim, Roland yan Guan. 2009. "Optimal decision making on product allocation for crossdocking and warehousing operations." *International Journal of Services Operations and Informatics* 4 (4). doi: 10.1504/IJSOI.2009.029184.

Liu, Tian, Yeming Gong, and René B. M. De Koster. 2018. "Travel time models for split-platform automated storage and retrieval systems." *International Journal of Production Economics* 197:197-214. doi: 10.1016/j.ijpe.2017.12.021.

Mecalux, Interlake. 2019. "Automated warehouse vs. Traditional warehouse." [Webpage]. Interlake Mecalux, Last Modified 26.03, accessed 20 april. https://www.interlakemecalux.com/blog/automated-traditional-warehouse.

Nastasi, Gianluca, Valentina Colla, Silvia Cateni, and Simone Campigli. 2016. "Implementation and comparison of algorithms for multi-objective optimization based on genetic algorithms applied to the management of an automated warehouse." *Journal of Intelligent Manufacturing* 29 (7):1545-1557. doi: 10.1007/s10845-016-1198-x.

Phogat, Sandeep 2013. "An intoduction to applicability of lean in warehousing." *International Journal of Latest Research in Science and Technology* 2 (5):105-109.

Pinkham, Myra. 1999. "Automated Storage & Retrieval Systems." *Metal Center News*.

Richards, Gwynne. 2018. *A complete guide to improving efficiency and minimizing costs in the modern warehouse*. 3rd ed. London: The Chartered Institute of Logistics and Transport.

Roodbergen, Kees Jan, and RenÉde Koster. 2001. "Routing methods for warehouses with multiple cross aisles." *International Journal of Production Research* 39 (9):1865-1883. doi: 10.1080/00207540110028128.

Roodbergen, Kees Jan, and Iris F. A. Vis. 2009. "A survey of literature on automated storage and retrieval systems." *European Journal of Operational Research* 194 (2):343-362. doi: 10.1016/j.ejor.2008.01.038.

Schwartz-Shea, Peregrine., Yanow, D. 2011. *Interpretive Research Design: Concepts and Processes*: Taylor & Francis Group.

Shiau, Jiun-Yan, and Ming-Chang Lee. 2010. "A warehouse management system with sequential picking for multi-container deliveries." *Computers & Industrial Engineering* 58 (3):382-392. doi: 10.1016/j.cie.2009.04.017.

Smith, Jennifer. 2020. "Smaller Is Big in New E-Commerce Warehouses; An intricate dance by robots turns tight urban spaces into 'microfulfillment' centers for online orders." *Wall Street Journal*.

Sneader, Kevin., Singhal, Shubham. 2020. "The future is not what it used to be: Thoughts on the shape of the next normal." [Webpage], Last Modified 14.04.2020, accessed 19 april. https://www.mckinsey.com/featured-insights/leadership/the-future-is-not-what-it-used-to-be-thoughts-on-the-shape-of-the-next-normal.

Solutions, Daifuku Logistics. 2021. "Miniload Automated Storage & Retrieval System (Miniload AS/RS)." Accessed 14.05.2021. https://www.daifuku-logisticssolutions.com/en/product/asrs/miniload.html.

Stinchcomb, Rick. 2012. "Warehouse Operations." [Webpage]. University of Oklahoma Press, Last Modified 23 march 2012, accessed 21 April. http://aaupwiki.princeton.edu/index.php/Warehouse_Operations.

University, Virginia Polytechnic Institute and State. 2018. "Research Methods Guide: Research Design and Method." [Webpage], Last Modified Sept 21, accessed 12 april. https://guides.lib.vt.edu/researchmethods/design-method.

Wang, Yanyan, Shandong Mou, and Yaohua Wu. 2016. "Storage assignment optimization in a multi-tier shuttle warehousing system." *Chinese Journal of Mechanical Engineering* 29 (2):421-429. doi: 10.3901/cjme.2015.1221.152.

Won, J., and S. Olafsson. 2005. "Joint order batching and order picking in warehouse operations." *International Journal of Production Research* 43 (7):1427-1442. doi: 10.1080/00207540410001733896.

Yin, Robert K. 2009. *Case Study Research: Design and Methods*. Edited by Debra J Rog Leonard Bickman. 4 ed. Vol. 5: Sage Publications Inc.

Yugang Yu, René B.M. De Koster. 2006. "Optimal Storage Rack Design for a 3d Compact AsRs with Full Turnover."34.

Zäpfel, Günther, and Michael Wasner. 2006. "Warehouse sequencing in the steel supply chain as a generalized job shop model." *International Journal of Production Economics* 104 (2):482-501. doi: 10.1016/j.ijpe.2004.10.005.

7.0 Part 2: The Research Paper

The Impact of Automated Storage and Retrieval Systems on Warehouse Operations

The Impact of Automated Storage and Retrieval Systems on Warehouse Operations

Abstract

Purpose: The purpose of this research paper is to investigate how the implementation of automated storage and retrieval systems (AS/RS) affects warehouse operations for Norwegian companies of different sizes within different industries. Speed, capacity, accuracy and space utilization were all indicators investigated in the research.

Design/methodology/approach: The operational tool for collecting data was two online surveys. Data were collected over 3 weeks in March/April 2021. A total of 18 companies responded to survey 1, and 15 companies responded to survey 2.

Findings: Results from this study indicate that the implementation of AS/RS leads to increased speed and capacity in warehouse operations. There is also an indication that implementation does not necessarily eliminate the possibility for human error regarding picking mistakes. Regarding space savings, this study provides an indication that there is a high tendency for improved space and storage utilization after implementing AS/RS.

Research limitations: Lack of public overview of companies using AS/RS in their warehouses necessitate collecting the contact information of AS/RS users through companies producing and selling the system. This led to fewer responses to the surveys and limits the weight of the findings.

Originality/value: This study is one of the first empirical studies concerning how the implementation of AS/RS affects warehouse operations. The authors contributed by filling a gap in the literature by collecting empirical evidence on speed and capacity, accuracy and space utilization both before and after AS/RS implementation.

Keywords: AS/RS, automation, automated warehouse systems, order processing, warehousing, warehouse operations.

Introduction

Automated warehouse systems and robotics have been implemented with increasing frequency in recent years. Expectations concerning decreased labor costs, improved efficiency, accuracy and space utilization have forced companies to rethink how warehouse operations are performed. According to Hao et al. (2020), these factors drive the trend toward more automated warehouses. In addition, an increase in e-commerce sales, or increased sales during official holidays and sales days such as Christmas and Black Friday, have increased challenges for warehouse operations. The ongoing Covid-19 pandemic is another example, which has resulted in end customers ordering online instead of buying items in physical stores. These customers typically have smaller orders with fewer order lines that result in more labor-intensive warehouse operations. These drivers, along with expectations of faster deliveries, represent a significant challenge for companies and may be the reason for a shift toward more automated warehousing.

There are a considerable number of different automated warehouse systems. An automated storage and retrieval system (AS/RS) is one type of automation that could be implemented in warehouses. These systems usually consist of racks holding bins and robots, which complete activities such as storing and retrieving goods for customers' orders. Roodbergen and Vis (2009) define an AS/RS as "a storage system that uses fixed-path storage and retrieval machines running on one or more rails between fixed arrays or storage racks". Previous literature on the topic has investigated the system itself, and not provided empirical evidence on how it affects warehouse operations such as the order-fulfillment process. Researchers have used methods such as simulation, analytical models, and optimization frameworks to understand these systems. There is a lack of research that uses empirical data to investigate the impact of AS/RS on warehouse operations. This research is therefore one of the first papers providing empirical data on the impact of AS/RSs on warehouse operations.

The purpose of this research is to investigate the impact of AS/RSs in warehouse operations with regard to speed, capacity, accuracy and space utilization.

Automated storage and retrieval systems

Automated warehouses can be either semi- or fully automated. At a semi-automated warehouse, there are some activities that are automated, while others are performed manually. At a fully automated warehouse, all activities are done automatically without the interference of a human operator.

An automated storage and retrieval system (AS/RS) covers the warehouse activities that include the storing and retrieval of goods. The system usually consists of racks and cranes running through aisles store goods put into the system and retrieve goods for orders. A typical AS/RS system can consist of bins, racks, robots and ports. The bins hold the inventory, while the racks hold the bins and are used as paths for the robots to navigate on. The robots navigate on the racks to pick bins that contains products for a customer's orders. Afterwards they bring the product to the port where the picking activity starts. Figure 10 illustrates an example of an AS/RS with racks, bins, robots and ports.

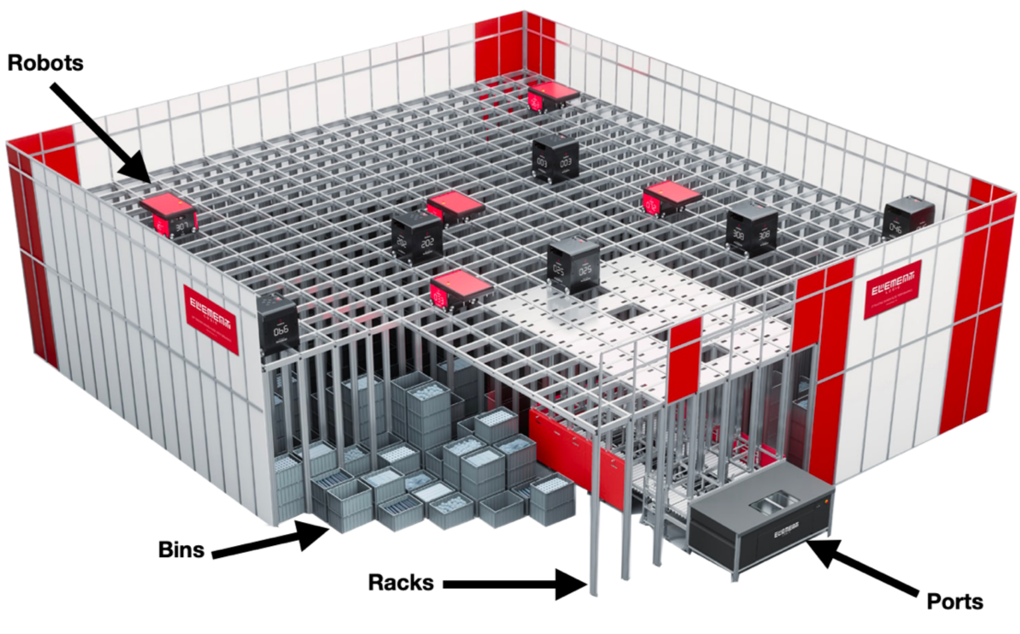

Figure 10 Example of AS/RS

An AS/RS can be part of either a semi- or fully automated warehouse. In some cases, there are human workers standing at the ports to pack the orders. In that case, an AS/RS is a semi-automated warehouse in which the automated part of the warehouse is the AS/RS. Some warehouses have automated solutions that perform all activities automatically. In that case there can be, for example, robot arms to complete the packing activity, and no activities in the warehouse are accomplished with the interference of a human operator.

According to Koster (2018), an AS/RS is flexible and makes it easy to increase the warehouse's capacity.

There are several articles that use modeling and solve optimization problems related to automated warehouse systems. Yugang Yu (2006) uses mathematical modeling to investigate how to arrange an AS/RS to be able to minimize product storage and retrieval times. Gagliardi, Renaud and Ruiz (2012) use a simulation model framework to investigate the unit-load AS/RS, which is a particular type of AS/RS in which a single storage or retrieval involves only one unit load. They found that these models must be redesigned each time a new implementation of a unit-load AS/RS is examined, which is a time-consuming process. Azadeh, Roy and De Koster (2019) investigate the differences between the features of vertical and horizontal storage and retrieval by using network optimization models. Liu, Gong, and De Koster (2018) used mathematical modeling and investigated time-travel models for split-platform AS/RSs.

Several papers have addressed different case studies in which AS/RS has been implemented (Heinrich and Willis 2014, Kovalcik and Villalobos 2019, Duong et al. 2020). As services for libraries continue to change, with increased demand for reading space and larger collections of reading materials, space efficiency is an important consideration in a library's strategies (Heinrich and Willis 2014). Heinrich and Willis (2014) conducted a case study on the Oviatt Library by using a circulation analysis, and claim that the AS/RS does not lose effectiveness when the materials are removed from the open stacks; "Just-in-time collection becomes paramount, and the demand for AS/RS increases exponentially." Duong et al. (2020) conducted a systematic literature review on robotics and autonomous systems (RAS) in the food industry from a supply-chain perspective. They found that the adoption of RAS in the food supply chain offers benefits in terms of food safety, quality, waste and supply chain efficiency.

Efficiency

Several papers address the efficiency of AS/RS by examining simulations, network models, optimization through software, case studies and literature reviews (Caputo and Pelagagge 2006, Gagliardi, Renaud, and Ruiz 2012, Wang, Mou, and Wu 2016, Bipan Zoua 2016, Atieh et al. 2016, Kovalcik and Villalobos 2019, Duong et al. 2020). In Duong et al. (2020)'s systematic literature review on automation and robotics in the food industry, they conclude that the implementation of such systems leads to supply-chain efficiency. Bipan Zou et al. (2016) and Wang et al. (2016) emphasize efficiency and flexibility at the operational level through analytical and network models. Kovalcik and Villalobos (2019) contribute to the AS/RS literature by conducting a case study on AS/RSs and the transition from storage to service at the Oviatt Library. An AS/RS solution was found to have improved operational and service efficiency at the Oviatt Library.

Accuracy

Accuracy is a challenge when it comes to manual order picking and handling. Customers demand that they receive the correct product in the quantity they ordered (Caputo and Pelagagge 2006). Caputo and Pelagagge (2006), Baker and Halim (2007) and Gagliardi, Renaud, and Ruiz (2012) have addressed AS/RS and accuracy in their papers by using the methodical approaches of a simulation model framework, a semi-structured interview and a survey questionnaire. Gagliardi et al. (2012) have used a simulation model framework to investigate AS/RSs in relation to modern distribution channels (DCs), and find that they "...provide fast, accurate and efficient material handling 24 h a day." Baker and Halim (2007) have conducted semi-structured interviews followed by survey questionnaires and conclude that automation provides throughput at a high level of speed and accuracy while maintaining costs at an acceptable level.

Space utilization

Concerning conventional warehousing and AS/RSs there are several factors, such as efficiency and accuracy, that render the operations different. In addition to these factors, there can also be a considerable difference regarding facility and space. Roodbergen and Vis (2009), Heinrich and Willis (2014), Bipan Zoua (2016), Wang et al. (2016), Koster (2018), O V Pilipenko (2019), Kovalcik and Villalobos (2019), Azadeh et al. (2019), and Wang et al. (2020) emphasize space and facilities in their papers by using methods such as literature reviews, case studies, and analytical and mathematical models. Wang et al. (2016) use network modeling to investigate multi-tier shuttle warehousing systems (MSWS), which are a variant of AS/RS solutions. One of the characteristics of this variant is that it has efficient space utilization and large storage capacity. The more effective utilization of storage space has been a key factor in the increased implementation of AS/RSs in recent years, particularly among e-commerce retailers (Bipan Zoua 2016). Azadeh et al. (2019) conclude, through employing network optimization models, that these systems are an effective fit for e-commerce operations because they require little space, have high flexibility and are able to work 24/7. In addition to saved labor costs, reduction in floor space also leads to savings in other operational costs, such as heating and lighting.

There are several papers in existing literature emphasizing the efficiency, accuracy and space utilization that AS/RSs provide. The methods used in these papers include different analytical models (network, simulation, mathematical, etc.), case studies, literature reviews, and semi-structured interviews. There is, however, a gap in the literature regarding contributions with empirical evidence on AS/RSs' efficiency, accuracy and space utilization.

Methods and data

Case description

This study investigates the effects of AS/RSs on warehouse operations with regard to speed, capacity, accuracy and space utilization. The investigation is based on a Norwegian AS/RS producer, AutoStore, and their partner, Element Logic. The partner sells the system to the end customer (user).

AutoStore is a Norwegian robot technology company that manufactures AS/RS. They have over 500 installations in over 30 countries. The system is sold through their many partners. In this research one of their partners was contacted, which was Element Logic. Element Logic is a leading Norwegian company within the technology and intralogistics industries, and one of AutoStore's partners. They provided an overview of some their Norwegian customers, which limits this study to the Norwegian market. The customers included in this study are of different sizes and are involved in various industries that include electronics, retail, e-commerce, sports, engineering, third-party logistics and manufacturing.

Figure 11 illustrates the connections between the manufacturer (A), partner (B) and customers (C). To answer the research questions, two surveys were conducted on the end customers (C) to map the impacts they have experienced in their warehouse operations after implementing AS/RSs.

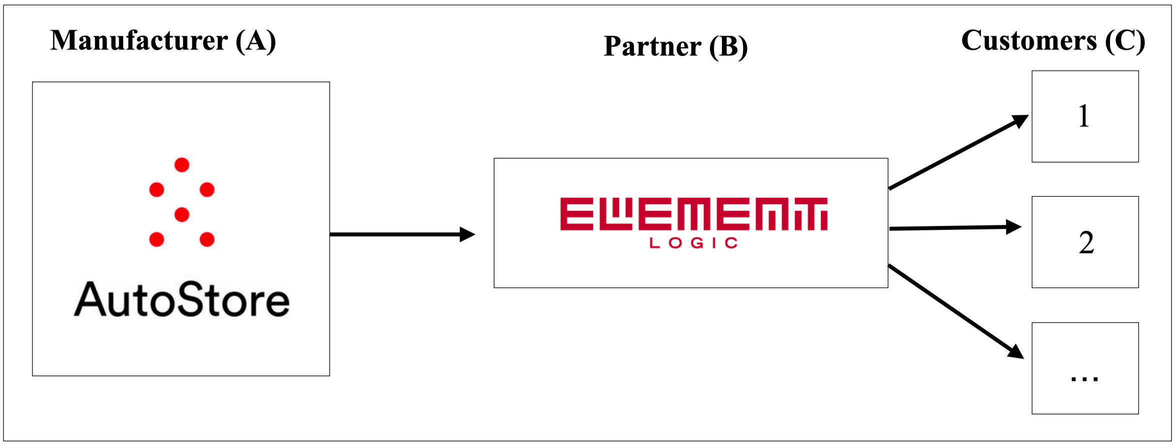

Figure 11 Illustration of the connections between manufacturer, partner and customers

Each customer is categorized based on the number of bins, ports and robots they have. Table 4 depicts how the companies are categorized based on their system size (small, medium and large).

Table 4 AS/RS system categories: small, medium, and large

	Small	**Medium**	**Large**
Bins	5,000-10,999	11,000-20,999	21,000+
Robots	3-8	9-20	21+
Ports	1-4	5-7	8+

Data collection

Data for the research was conducted through two online surveys. First, an email was sent to 32 Norwegian companies that have implemented AS/RSs in their warehouses. In the email, the receivers were informed about the subject and asked to participate in the study by answering a survey. Twenty of 32 companies consented to answering the survey, and received links to the survey via email on March 26th, 2021. A total of 18 responses for survey 1, and 15 for survey 2 were returned. Some of the questionnaires were, however, not fully completed. In both surveys, the respondents were asked to answer general questions concerning their system sizes. Questions on system size were based on the number of bins, robots and ports.

Survey 1 contained general questions regarding speed, capacity, accuracy and space utilization. Some questions had multiple answer alternatives (Likert scale), and some contained comment boxes in which the respondents could answer openly. Survey 2 was sent out due to the lack of empirical data from survey 1. The survey contained questions regarding orders and order lines.

Data analysis

Both surveys were analyzed using Microsoft Excel. Survey 1 was analyzed through the observation of answers from the Likert scales and open answers. The answers were summarized in tables to obtain a full overview of all answers. Survey 2 was analyzed through calculating the collected empirical data. Calculation was used to notice any trends in orders and order lines (e.g., if there was any increase or decrease).

Results

Both surveys included questions on the companies' system size. Three factors were considered when categorizing the systems: number of robots, number of bins and the number of ports.

Table 5 Responses to system size in survey 1

	Robots			Bins			Ports		
System size	S	M	L	S	M	L	S	M	L
Quantity	3-8	9-20	21+	5,000-10,999	11,000-20,999	21,000+	1-4	5-7	8+
Number of responses	3	7	8	3	6	9	8	2	8

Three of the respondents from survey 1 had a small system, seven had medium systems and eight had a large system. Eighteen of the respondents answered the questions on system size.

Table 6 Responses to system size in survey 2

	Robots			Bins			Ports		
System size	S	M	L	S	M	L	S	M	L
Quantity	3-8	9-20	21+	5,000-10,999	11,000-20,999	21,000+	1-4	5-7	8+
Number of responses	2	7	6	2	6	7	7	1	7

Two of the respondents from survey 2 had a small system, seven had a medium system and six had a large system. Fifteen of the respondents answered to the questions on system size. Eleven of 15 respondents completed the whole survey.

Speed and capacity

The questions covered the impact of time spent per order, picking speed for order lines and changes in employees. Survey 2 collected empirical data on orders and order lines.

Table 7 Responses to question 1.1

	No change	Small	Medium	Significantly
Time saving per order	0	0	1	16

Results from table 7 reveal that none of the respondents experienced no or small change in time spent per order. One respondent reports a medium reduction in time and 16 stated that there is a significant reduction in time spent per order. There was a total of 17 responses to time saving per order questions.

Table 8 Responses to change in order lines picked per hour after AS/RSs

	Significantly fewer	Some less	No change	Some more	Significantly more
Change in order lines	0	0	0	1	16
Change in number of employees	1	8	5	1	1

Results regarding changes in order lines from table 8 reveal that the options “significantly fewer,” “some less,” and “no change” have 0 responses. Out of 17 respondents to this question, one of them experienced some more order lines picked per hour, and 16 experienced significantly more. One respondent has significantly fewer employees after AS/RS implementation. Eight respondents some less, five respondents no change, one respondent some more and one respondent significantly more.

Table 9 Responses to questions from survey 2 on number of orders and order lines per day

		Number of orders			Number of order lines			Order lines/Order		
No.	Size	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
1	S	15	15	0,0	35	35	0,0	2,3	2,3	0,0
2	S	900	1800	100,0	1950	4000	105,1	2,2	2,2	2,6
3	S	80	110	37,5	300	410	36,7	3,8	3,7	-0,6
4	M	300	250	-16,7	2000	2500	25,0	6,7	10,0	50,0
5	M	900	950	5,6	2800	3000	7,1	3,1	3,2	1,5
6	M	100	350	250,0	400	2000	400,0	4,0	5,7	42,9
7	M	100	500	400,0	200	1000	400,0	2,0	2,0	0,0
8	L	250	250	0,0	2000	2000	0,0	8,0	8,0	0,0
9	L	225	280	24,4	500	550	10,0	2,2	2,0	-11,6
10	L	300	900	200,0	900	3500	288,9	3,0	3,9	29,6
11	L	N/A	N/A		1500	15000	900,0	-	-	
			Average	100,1		Average	197,5		Average	11,4

Results from table 9 indicate that, concerning changes in number of orders, there is an average increase of 100.1% from before and after AS/RS implementation. There are some cases in which the respondent has experienced a 0% increase (nos. one and eight) and a decrease of 16.7% (no. four). Concerning the number of order lines picked per day, there is an average increase of 197.5 %. Most companies have experienced an increase, apart from respondents one and eight. Regarding the average number of order lines per order, there is an average increase of 11.4%.

Accuracy

Results are summarized in table 10 and categorized into small (S), medium (M) and large (L) system sizes. Table 10 illustrates picking errors before and after AS/RS implementation.

Table 10 Responses on picking errors before and after AS/RS implementation

Accuracy											
Customer		Before AS/RS			After AS/RS						
Number	System Size	Wrong product	Wrong quantity	Missing product	Wrong product	Before VS after	Wrong quantity	Before VS after	Missing product	Before VS after
1	L	D	D	W	W		W		W	
2	M	W	W	W	M		M		M	
3	L	W	W	M	W		W		M	
4	L	W	W	W	W		W		W	
5	L	M	Y	Y	M		M		Y	
6	S	M	M	M	Y		Y		W	
7	L	M	M	M	M		M		M	
8	L	W	W	M	W		W		W	
9	M	D	D	D	W		W		D	
10	M	W	W	W	M		M		M	
11	L	D	W	W	M		W		M	
12	M	W	M	W	W		W		W	
13	M	M	M	M	Y		M		Y	
14	M	M	M	M	W		W		M	
15	M	W	W	M	M		W		M	
16	M	W	W	W	W		W		W	

D = Daily, W = Weekly, M = Monthly, Y = Yearly, Green color = Decrease in picking errors, Yellow Color = Unchanged number of picking errors, Red = Increase in picking errors

Results from table 10 reveal that *before* implementing AS/RS, three respondents experienced customers receiving the wrong product daily, nine of the respondents weekly, five monthly and none yearly or never. Three respondents experienced customers receiving the wrong quantity daily, eight of the respondents weekly, five monthly, one yearly and none never. One respondent experienced that there were missing products in the customer's order, eight of the respondents weekly, seven monthly, one yearly and none never.

Results from table 10 reveal that *after* AS/RS implementation, no respondents experienced customers receiving the wrong product daily, eight of the respondents weekly, six monthly, two yearly and none never. No respondents experienced customers receiving the wrong quantity daily, 10 of the respondents weekly, five monthly, one yearly and none never. One respondent experienced missing products in daily customer orders, four of the respondents weekly, eight monthly, three yearly and none never.

The table illustrates changes regarding picking errors from before and after AS/RS implementation. The changes are illustrated by the colors green, yellow and red. The results reveal 18 cases of decreases in picking errors, 24 unchanged cases and six cases of increases in picking errors.

Space utilization

Table 11 Responses to questions 3.2

	No saving	Small	Medium	Significant
Space savings from AS/RS	0	1	2	13

Results from table 11 indicate that none of the respondents had no space saving after implementing AS/RSs. One had small savings, two had medium savings and 13 had significant space savings after implementing an AS/RS. There were a total of 16 responses to this question.

Table 12 Answers to what potential released areas from an AS/RSs are currently used for

Respondent no.	What released areas from AS/RSs are currently used for.
1	Storage and dispatch.
2	Pallet racks too big for AS (AutoStore) and items that have high sales volumes and are more efficient to pick from pallets.
3	Pallet racks.
4	More items and shelf racks.
5	Can focus more on emptying containers than having a constant rush on emptying the floor.
6	Goods receipt and buffer warehouse.
7	We had to build on to make room for AS, but without AS we would have to build four times as big.
8	Manual storage, buffer and handling.
9	Some area is rented out.
10	Multiple picking locations for an item, can take in items in larger quantities than before, archiving and administration.

11	Shelves and temporary storage of goods.
12	Buffer Storage.
13	The savings are not noticeable in area, but with an upscaling you will see a greater effect.
14	Not released, but built on 400 m2 which was limited based on land etc.

Table 13 Respondents that had to move to be able to implement an AS/RS

	Yes	No
Need to move to another location to implement an AS/RS.	8	8

Results from table 13 reveal that 50% of the respondents had to move to another location to be able to implement an AS/RS. There were a total of 16 responses to this question.

Table 14 Reasons to move to another location

Respondent no.	Reason to move to another location
1	Strong growth, need to increase capacity.
2	Plot was sold and was to be demolished.
3	Difficult storage, no possibility for expansion.
4	Utilization of ceiling height and further escalation of AutoStore.
5	Expected growth. Need for large area and further expansion of AutoStore.
6	Needed to move anyway due to extreme growth. Relocation was decided long before we decided to implement AutoStore.
7	Grew out of our existing warehouse.
8	Extension.

Comment from one of the respondents after completing survey 2:

“We handle approximately the same amount or orders and order lines after AS/RS. However, we use much less time on completing these tasks after AS/RS implementation. We estimate that we use approximately half the time on picking orders, inventory count and goods receipt. This has given us the opportunity to focus on tasks that before were downgraded. In addition, we have fewer people working at the warehouse, and have achieved a higher stock accuracy”.

Discussion

The purpose of this study was to examine the impact of AS/RSs on warehouse operations. This study was conducted through two surveys covering the topics of speed, capacity, accuracy, and space utilization. First, a thorough review on literature addressing the topic of AS/RS was conducted. Existing literature contributed to building the questions for the surveys. It must be taken into consideration that the respondents might be biased, which may affect their responses in the surveys.

Speed and capacity

Baker and Halim (2007) and Duong et al. (2020) conclude that automation provides throughput at a high level of speed and leads to supply-chain efficiencies. Results from this study indicate that speed has increased for almost all companies answering the surveys, with an average increase of 197.5 %. Some companies have faced an increase in speed of as much as 400-900%. The increase interval ranges from 10% at the lowest to 900% at the highest. Some companies might have witnessed such an increase over several years of production with AS/RSs. Others might have only recently implemented AS/RSs and will, after some years of production, experience a higher increase in speed. From the results, there are two cases in which there is no change in the number of order lines picked per day. In addition, it is noticeable that the same companies have not had any change in demand. This might indicate that the companies are not handling e-commerce and retailing orders, but internal orders for manufacturing. One of the respondents informed us that, while his/her company has not had an increase in the number of orders or order lines after implementing an AS/RS, their time spent on completing the orders they do have has decreased significantly. They estimate that the time they spend completing warehouse activities such as placing items in the system, completing orders, and inventory control, has decreased by 50%. In addition, the respondent informed us that they now have more time to focus on activities that were previously downgraded. This company had fewer employees working at the warehouse after the implementation, and has achieved a higher stock accuracy. The results also indicate that the investigated companies experience a growth in demand, with an average increase of 100.1%. There is an increased interval of 5.6% at the lowest to 400% at the highest. There are two companies with no increase, and one company with a demand decrease of 16.7 % (respondent 4) which, at the same time, has an increase in order lines picked by 25 %. Results indicate that companies implementing AS/RSs experience a growth in demand. However, as discussed with order lines, some companies might handle orders for manufacturing and do not have the objective to increase demand.

Responses from the survey indicates that implementing AS/RSs provides the opportunity to release capacity. As demand and workload increase, there is no longer the same need to hire new employees because companies can add an extra robot to the system instead.

Accuracy

From literature, researchers find that AS/RS lead to accurate and efficient material handling 24h a day (Gagliardi, Renaud, and Ruiz 2012). This research paper investigates how the implementation of AS/RS affects accuracy in regard to human error. Results indicates that it does not eliminate human error such as picking the wrong product, wrong quantity, or missing order lines. In some cases, there has been no change, others decreased the number of errors and others experienced an increase in mistakes. There is no information if the increase in mistakes correlates with the increase in total order lines picked per day. However, the study indicates that even though the system itself has a high level of accuracy, there is still opportunity of human error when placing products into the system and picking products at the ports.

Space utilization

Wang, Mou, and Wu (2016) claim that an AS/RS has efficient space utilization and a large storage capacity. They also emphasize that the high utilization of space is one of the reasons for the increased implementation of AS/RSs in companies in recent years. From the research, 13 out of 16 respondents experienced significant space savings after implementing AS/RSs. The three other respondents experienced small or medium space savings. This indicates that AS/RS offers a significant opportunity for increased space utilization and further expansion within the same facility. The sales manager at Element Logic stated that, as a general calculation, it can be said that 10,000 bins in an AS/RS (the AutoStore system) correspond to 750 full pallets of $1m^3$ (overstock pallets). This is equivalent to 1,500 picking pallets when a pallet, on average, is 50% full at its picking location. This refers to an average warehouse facility with 8-9 meters of ceiling height. With 10,000 bins, there is an opportunity to save 1,000 m^2 of floor area. The sales manager also informed us that, with conventional picking racks that are typical for e-commerce, there is a use of 0.8 cubic meters per square meter of floor space. With an AS/RS there are 5 cubic meters per square meter. An AS/RS is thus 5-7 times more space efficient than the typical picking rack. This calculation is based on an AS/RS facility of 10,000-15,000 bins (see Appendix 5 for the complete calculation). The space savings will increase exponentially with the size of the facility.

Previous literature, responses from the survey, and calculations from Element Logic indicate that there is a considerable opportunity for improved space utilization with AS/RSs.

Conclusion and suggestions for further research

The focus of this paper has been on the effect AS/RSs have on warehouse operations. Data were collected through two online surveys to answer the research question regarding speed, capacity, accuracy and space utilization. A total of 18 Norwegian companies which have implemented AS/RSs contributed to the study. Results from the research indicate that an AS/RS leads to increased efficiency with higher speed and released capacity in warehouse operations. There is also an indication that the implementation does not necessarily eliminate the possibility of human error regarding picking items for the orders. Concerning space utilization, the study indicates that there is a high tendency for significant space savings and improved storage utilization.

After completing the research, we find that there are several directions to take for future research. From analyzing the results of the survey, it could be possible to conduct a study on the complexity of the inventory handled by the system in relation to, for example, temperature control, types of goods that are stored in the system and variety of product range. It is also possible for future researchers to either examine how AS/RS affects sustainability or consider the ergonomic gain derived from implementing an AS/RS, given heavy lifting and poor posture from conventional picking is reduced or eliminated.

References

Atieh, Anas M., Hazem Kaylani, Yousef Al-abdallat, Abeer Qaderi, Luma Ghoul, Lina Jaradat, and Iman Hdairis. 2016. "Performance Improvement of Inventory Management System Processes by an Automated Warehouse Management System." *Procedia CIRP* 41:568-572. doi: 10.1016/j.procir.2015.12.122.

Azadeh, Kaveh, René De Koster, and Debjit Roy. 2019. "Robotized and Automated Warehouse Systems: Review and Recent Developments." *Transportation Science* 53 (4):917-945. doi: 10.1287/trsc.2018.0873.

Baker, Peter, and Zaheed Halim. 2007. "An exploration of warehouse automation implementations: cost, service and flexibility issues." *Supply Chain Management: An International Journal* 12 (2):129-138. doi: 10.1108/13598540710737316.

Bipan Zoua, Ren´e De Kosterb, Xianhao Xu. 2016. "Evaluating dedicated and shared storage policies in robot-based compact storage and retrieval systems."

Caputo, Antonio C., and Pacifico M. Pelagagge. 2006. "Management criteria of automated order picking systems in high-rotation high-volume distribution centers." *Industrial Management & Data Systems* 106 (9):1359-1383. doi: 10.1108/02635570610712627.

Duong, Linh N. K., Mohammed Al-Fadhli, Sandeep Jagtap, Farah Bader, Wayne Martindale, Mark Swainson, and Andrea Paoli. 2020. "A review of robotics and autonomous systems in the food industry: From the supply chains perspective." *Trends in Food Science & Technology* 106:355-364. doi: 10.1016/j.tifs.2020.10.028.

Gagliardi, Jean-Philippe, Jacques Renaud, and Angel Ruiz. 2012. "A simulation modeling framework for multiple-aisle automated storage and retrieval systems." *Journal of Intelligent Manufacturing* 25 (1):193-207. doi: 10.1007/s10845-012-0686-x.

Hao, Jingjing, Haoming Shi, Victor Shi, and Chenchen Yang. 2020. "Adoption of Automatic Warehousing Systems in Logistics Firms: A Technology–Organization–Environment Framework." *Sustainability* 12 (12). doi: 10.3390/su12125185.

Heinrich, Helen, and Eric Willis. 2014. "Automated storage and retrieval system: a time-tested innovation." *Library Management* 35 (6/7):444-453. doi: 10.1108/lm-09-2013-0086.

Kovalcik, Justin, and Mike Villalobos. 2019. "Automated Storage & Retrieval System." *Information Technology and Libraries* 38 (4):114-124. doi: 10.6017/ital.v38i4.11273.

Liu, Tian, Yeming Gong, and René B. M. De Koster. 2018. "Travel time models for split-platform automated storage and retrieval systems." *International Journal of Production Economics* 197:197-214. doi: 10.1016/j.ijpe.2017.12.021.

O V Pilipenko, E N Provotorova., S M Sergeev., and O V Rodionov. 2019. "Automation engineering of adaptive industrial warehouse." *Journal of Physics: Conference Series*.

Roodbergen, Kees Jan, and Iris F. A. Vis. 2009. "A survey of literature on automated storage and retrieval systems." *European Journal of Operational Research* 194 (2):343-362. doi: 10.1016/j.ejor.2008.01.038.

Wang, Yanyan, Rongjun Man, Xiaofeng Zhao, and Hui Liu. 2020. "Modeling of Parallel Movement for Deep-Lane Unit Load Autonomous Shuttle and Stacker Crane Warehousing Systems." *Processes* 8 (1). doi: 10.3390/pr8010080.

Wang, Yanyan, Shandong Mou, and Yaohua Wu. 2016. "Storage assignment optimization in a multi-tier shuttle warehousing system." *Chinese Journal of Mechanical Engineering* 29 (2):421-429. doi: 10.3901/cjme.2015.1221.152.

Yugang Yu, René B.M. De Koster. 2006. "Optimal Storage Rack Design for a 3d Compact AsRs with Full Turnover."34.

Appendix

Attachment 1. Survey 1 (English)

System design

Q1: How many robots do your AutoStore system consist of?

- 3-8
- 9-20
- 20 +

Q2: How many bins do your AutoStore system consist of?

- 5000-10000
- 11000-20000
- 21000+

Q3: How many ports do your AutoStore system consist of?

- 1-4
- 5-7
- 8+

Speed and capacity

Q4. To what extent do you agree that the time to complete one order has decreased significantly?

- No impact
- little
- medium
- significantly

Q5: Do you experience any difference in order lines picked per hour after implementing AutoStore?

- Significantly fewer lines picked
- A little less
- No difference
- Some more
- Significantly more

Q6: Do you see any change in number of employees after implementing AutoStore?

- Significantly fewer
- A little less
- No difference
- Some more

- Significantly more

Accuracy

Before implementation:

Q7: How often did you experience that the customer received the wrong product?

- Daily
- Weekly
- Monthly
- Yearly
- Never

Q8: How often did you experience that the customer received the wrong quantity?

- Daily
- Weekly
- Monthly
- Yearly
- Never

Q9: How often did you experience that there was a missing product in the customer's order?

- Daily
- Weekly
- Monthly
- Yearly
- Never

After implementing AutoStore:

Q10: How often do you experience that the customer receives the wrong product?

- Daily
- Weekly
- Monthly
- Yearly
- Never

Q11: How often do you experience that the customer receives the wrong quantity?

- Daily
- Weekly
- Monthly
- Yearly
- Never

Q12: How often do you experience that there is a missing product in the customer's order?

- Daily
- Weekly
- Monthly
- Yearly
- Never

Space utilization

Q13: Did you have to move to another warehouse/location to implement AutoStore?

- Yes
- No

Q13.1 If yes: Why did you have to move?

- Open answer

Q14: How much space saving would you estimate that you have achieved by implementing AutoStore?

- No savings
- Small
- Medium
- Significant

Q14.1: If you have achieved any space savings, what is the released space used for today?

- Open answer

Attachment 2. Survey 1 (Norwegian)

System design

Q1: Hvor mange roboter består deres AutoStore system av?

- 3-8
- 9-20
- 21+

Q2: Hvor mange kasser (bins) består deres AutoStore system av?

- 5000-10999
- 11000-20999
- 21000+

Q3: Hvor mange porter (conveyor eller carousel) består deres AutoStore system av?

- 1-4
- 5-7
- 8+

Hastighet og kapasitet

Q4. Til hvilken grad er dere enig i at tid brukt per ordre har blitt redusert?

- Ingen endring
- Liten
- Medium
- Betydelig

Q5: Opplever dere noen forskjell i antall ordrelinjer plukket per time etter AutoStore implementering?

- Betydelig færre
- Litt færre
- Ingen forskjell
- Litt flere
- Betydelig flere

Q6: Har dere noen endring i antall ansatte etter AutoStore implementering?

- Betydelig færre
- Litt færre
- Ingen endring
- Noen flere
- Betydelig flere

Nøyaktighet

Før implementering av AutoStore:

Q7: Hvor ofte opplevde dere at kunder mottok feil produkt i gjennomsnitt?

- Daglig
- Ukentlig
- Månedlig
- Årlig
- Aldri

Q8: Hvor ofte opplevde dere at kunder mottok feil antall produkt i gjennomsnitt?

- Daglig
- Ukentlig
- Månedlig
- Årlig
- Aldri

Q9: Hvor ofte opplevde dere at det manglet produkter i kundens ordre i gjennomsnitt?

- Daglig

- Ukentlig
- Månedlig
- Årlig
- Aldri

Etter implementering av AutoStore:

Q10: Hvor ofte opplever dere at kunder mottar feil produkt i gjennomsnitt?

- Daglig
- Ukentlig
- Månedlig
- Årlig
- Aldri

Q11: Hvor ofte opplever dere at kunder mottar feil antall produkt i gjennomsnitt?

- Daglig
- Ukentlig
- Månedlig
- Årlig
- Aldri

Q12: Hvor ofte opplever dere at det mangler produkter i kunders ordre i gjennomsnitt?

- Daglig
- Ukentlig
- Månedlig
- Årlig
- Aldri

Plassutnyttelse

Q13: Hadde dere behov for å flytte til et annet lager for å kunne implementere AutoStore?

- Ja
- Nei

Q13.1 Hvis ja: Hvorfor måtte dere flytte?

- Åpent svar

Q14: Hvor stor arealbesparelse vil dere anslå at dere har oppnådd etter å ha implementert AutoStore?

- Ingen besparelse
- Liten
- Medium
- Betydelig

Q14.1 Dersom dere har opplevd arealbesparelse, hva brukes frigitt areal til i dag?

- Åpent svar

Attachment 3. Survey 2 (English)

System design (to be able to categorize the customers)

Q1: How many robots do your AutoStore system consist of?

- 3-8
- 9-20
- 20 +

Q2: How many bins do your AutoStore system consist of?

- 5000-10000
- 11000-20000
- 21000+

Q3: How many ports do your AutoStore system consist of?

- 1-4
- 5-7
- 8+

Q4: How many orders did you deliver approximately every day BEFORE implementing AutoStore?

- Open answer

Q5: How many orders did you deliver approximately every day AFTER implementing AutoStore?

- Open answer

Q6: How many order lines did you pick approximately every day BEFORE implementing AutoStore?

- Open answer

Q7: How many order lines did you pick approximately every day AFTER implementing AutoStore?

- Open answer

Attachment 4. Survey 2 (Norwegian)

Oppfølgingsspørsmål

System design

Q1: Hvor mange roboter består deres AutoStore system av?

- 3-8
- 9-20
- 21+

Q2: Hvor mange kasser (bins) består deres AutoStore system av?

- 5000-10999
- 11000-20999
- 21000+

Q3: Hvor mange porter (conveyor eller carousel) består deres AutoStore system av?

- 1-4
- 5-7
- 8+

Q4: Hvor mange ordrer leverte dere omtrentlig hver dag FØR implementering av AutoStore?

- Åpent svar

Q5: Hvor mange ordrer leverte dere omtrentlig hver dag ETTER implementering av AutoStore

- Åpent svar

Q6: Hvor mange ordrelinjer plukket dere ca. hver dag FØR implementeringen av AutoStore?

- Åpent svar

Q7: Hvor mange ordrelinjer plukket dere ca. hver dag ETTER implementeringen av AutoStore?

- Åpent svar

Attachment 5. Calculation on space utilization

Mail from Niklas Poulsen – Sales Manager Element Logic

Translated to English.

“Before/Traditional: I will say that before 2010 there were built many warehouses with customized ceiling height for the end user. That is to say 6-7-8-9 meters. After this we see that there have been more professional builders and real estate companies that are speculating in logistics property.
That is to say they think less on the end user, but more on the life cycle of the building. Then should also fit well with the next tenant. It does not cost “much” to increase ceiling height from 10 to 12 meter, so we see more and more companies doing so.
Generally, for warehouse buildings I will say that 8-10 meters of ceiling height is average, but the average height is increasing each year because most builders build 11,3 meters of indoor ceiling height. For AutoStore we see that users building wise get good utilization with an AutoStore with between 4 to 13 meters ceiling height. This is not any absolute number when there are many ways AutoStore can be built in several heights.

The average ceiling height with AutoStore is 7-9 meter on warehouses with AutoStore today. Notice that there are customers who build AutoStore in warehouses with 4-6 meters ceiling height who lower the average, and some that build AutoStore with ceiling height of 11-12 meters who bring the average up. With other words, it spans a little up and down.

When it comes to stock compression it really depends on the solution the customer has in advance. Space-wise AutoStore is at least 4x denser than warehouse vending machines (this depends on how many bins a customer need. The bigger the need for more bins, the bigger, both relatively and marginal, the space saving is). With a need of 10 000 bins, you save 3-4 times the space, but with a need of 100 000 bins, you save significantly more, maybe 10x the space.
For manual warehouses, the calculation is even better, but it really depends on the solution and need for the customer.

In a 12 meters warehouse there is no lack for pallet racks, but rather picking locations. Every location in the AutoStore is picking stations. Picking locations for racks demand significant floorspace.

As a foundation for a calculation, we can say that 10 000 bins in AutoStore is equivalent to 750 100% full pallets of 1m3 (overstock pallets). This is equivalent to 1500 (the double) of picking pallets when a pallet on average is 50% full at its location.
This fits for an average warehouse with 8-9 meters of ceiling height.
With 20 000 bins, you easily save 2000 m2 floor space, and with 10 000 bins, on average 1000 m2. This is a very general claim, when it depends on the customer, ceiling height, pallet type, pallet height, number of levels in height on a pallet rack, etc.

For shelf racks/shelves for e-commerce, 1 shelf is equivalent for ca. 1 AutoStore bin. Normal for e.g., e-commerce, we see that there is used average 5-6 shelves per section who take 0,6 m2. As you might be aware of, we can build AutoStore in several different heights. The usual is the bin which is 330mm with 16 bins in height. For this the calculation is 16*0,6*0,4=3,8 square meter storage space on 0,24 square meter floor space. But this only tells half the truth. Cubic meter/m3 is more relevant!
On a shelf rack with 6 shelves in height = 0,6 x 0,965 m x 0,41 (shelf dimensions) x 6 shelves = 1,4 cubic (m3) per 0,6 m2 floor space = 2,3 cubic per 1m2 floor space, without the need for aisles. If we add the need for aisles, we will have to divide the number by 3. Ca. 0,7-0,9 cubic per 1m2.

Lineup will be as follows:

- Picking racks: 0,6 cubic per m2
- AutoStore: 5 cubic per m2. Therefore, 5-7 times more space efficient than picking shelves.

This is calculated with a base of a 10-15000 bins system. For bigger systems the space savings will increase exponentially".