



WAREHOUSE AUTOMATION SELECTION FRAMEWORK								
Qualifying factors	Item characteristics		Investment budget		Size limitations		Warehouse capacity	
Comparable factors	Space utilization $p_1 \times W_1$	Scalability $p_2 \times W_2$	Ergonomics $p_3 \times W_3$	Sustainability $p_4 \times W_4$	CAPEX $p_5 \times W_5$	OPEX $p_6 \times W_6$	Versatility $p_7 \times W_7$	Robustness $p_8 \times W_8$
Total score for a solution	<p>Total score of qualified solution</p> $S = \sum_{i=1}^8 p_i \times W_i$							

Selecting the Right Warehouse Automation Solution

A Decision-Making Framework Based on Qualifying and Comparable Factors

Master's thesis in Supply and Operations Management

HAMPUS JOHANSSON
ALEX PERSSON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se
Report No. E2023:077

REPORT NO. E2023:077

Selecting the Right Warehouse Automation Solution

A Decision-Making Framework Based on Qualifying and
Comparable Factors

HAMPUS JOHANSSON
ALEX PERSSON

Department of Technology Management and Economics
Division of Supply and Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

Selecting the Right Warehouse Automation Solution
A Decision-Making Framework Based on Qualifying and Comparable Factors
HAMPUS JOHANSSON
ALEX PERSSON

© HAMPUS JOHANSSON, 2023.
© ALEX PERSSON, 2023.

Report no. E2023:077
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: The warehouse automation selection framework developed in the study which aims to guide decision-makers toward solutions that align with their requirements. Development and further elaboration are found in chapter 5.

Gothenburg, Sweden 2023

Selecting the Right Warehouse Automation Solution

A Decision-Making Framework Based on Qualifying and Comparable Factors

HAMPUS JOHANSSON
ALEX PERSSON

Department of Technology Management and Economics
Chalmers University of Technology

SUMMARY

The importance of warehouse automation is increasing, and it is essential to choose the right solution to meet business requirements. The purpose of this research is to identify critical factors that should be considered when selecting a warehouse automation solution. This study utilized semi-structured interviews to identify four qualifying and eight comparable factors. Based on these factors, a decision-making framework was developed to guide decision-makers towards physical automation solutions that align with their requirements. The proposed framework utilizes the Best-worst method (BWM) to help decision-makers prioritize automation solution features and select the most suitable solution. This research contributes to the existing literature by providing a decision-making framework that can be utilized to support organizations in selecting warehouse automation solutions that align with their unique requirements.

Keywords: Warehouse automation, Decision-making framework, Multi-criteria decision-making, Best-worst method, Solution selection

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the following individuals and groups who have been instrumental in the completion of our thesis:

First and foremost, we would like to extend our heartfelt appreciation to our supervisors, Robin Hanson from Chalmers and Robin de Richelieu from Triathlon Group. Their guidance, expertise, and encouragement throughout the entire process have been invaluable.

We are deeply grateful to all the respondents who generously shared their time and insights with us. Their contributions have been instrumental in shaping our research and conclusions.

We would also like to acknowledge the opposing group, Adam and Linn, for their insightful feedback and constructive criticism. Their input has helped us to refine our ideas and arguments.

We extend our sincere thanks to all the supportive colleagues at the Triathlon Group who welcomed us and showed interest in our work. Their encouragement and feedback have been tremendously valuable. A special thanks to Peter Bengtsson and Patricia Hesselgren, who believed in us and trusted us to write our thesis at Triathlon Group.

Lastly, we would like to express our heartfelt gratitude to all our friends, family and loved ones, who have supported us throughout this journey. Their encouragement and moral support have played a key role in keeping us motivated and focused.

Thank you all for your invaluable contributions to our thesis.

1. Introduction	4
1.1 Background.....	4
1.2 Purpose.....	5
1.3 Limitations.....	5
2. Theoretical framework	7
2.1 <i>The fundamentals of warehousing</i>	7
2.1.1 The warehouse's role in the supply chain.....	7
2.1.2 Processes within the warehouse activity.....	8
2.1.3 Warehouse management systems.....	9
2.2 <i>Context</i>	10
2.2.1 Item characteristics.....	10
2.2.2 Supply- and demand characteristics.....	10
2.3 <i>Performance</i>	11
2.3.1 Benefits and risks of automation.....	11
2.3.2 Key performance indicators for the warehouse activity.....	12
2.3.3 Warehouse capacity performance measurements.....	12
2.3.4 Environmental sustainability performance.....	13
2.3.5 Ergonomics within the warehouse activity.....	14
2.4 <i>Design</i>	14
2.4.1 Operation principles within the warehouse activity.....	15
2.4.2 Order picking systems.....	16
2.4.3 Automated order picking systems.....	17
3. Methodology	21
3.1 <i>Research design</i>	21
3.2 <i>Literature study</i>	21
3.3 <i>Interview study</i>	21
3.3.1 Interview methodology.....	21
3.3.2 Interview respondent selection.....	22
3.3.3 Development of interview guides.....	23
3.4 <i>Analysis process</i>	24
3.5 <i>Multi-criteria decision-making</i>	24
3.5.1 Best-worst multi-criteria decision-making.....	25
4. Empirical data	27
4.1 <i>Supplier respondents</i>	27
4.1.1 Supplier respondent 1 [S1].....	27
4.1.2 Supplier respondent 2 [S2].....	28
4.1.3 Supplier respondent 3 [S3].....	29
4.2 <i>Industry respondents</i>	30
4.2.1 Industry respondent 1 [I1].....	30
4.2.2 Industry respondent 2 [I2].....	31
4.2.3 Industry respondent 3 [I3].....	32
4.2.4 Industry respondent 4 [I4].....	33
4.2.5 Industry respondent 5 [I5].....	34
5. Identification of critical factors and framework development	36
5.1 <i>Analysis and selection of critical factors</i>	36
5.1.1 Qualifying factors.....	36
5.1.2 Comparable factors.....	38

5.2	<i>Warehouse automation selection framework</i>	42
6.	Discussion	44
6.1	<i>Discussion of the framework</i>	44
6.2	<i>Research methodology criticism</i>	44
6.3	<i>Using the proposed framework in a general setting</i>	45
6.4	<i>Research contributions</i>	45
7.	Conclusions and future research	47
	References	I
	Appendix A: Industry interview framework	V
	Appendix B: Automation supplier interview framework	VI

1. Introduction

This chapter aims to facilitate the background, purpose, and limitations of the study. The background describes the vantage point of the study by introducing the concept of supply chain management and the purpose of warehousing within supply chain management. The problem is later in the background formulated which produces a purpose of the study, and finally, the limitations surrounding the study are stated and argued for.

1.1 Background

The development towards a global market in the late 20th century increased the competition which companies responded to by e.g., optimizing costs through increased focus on core competences, and outsourcing of activities outside of the companies' core competences (Jonsson & Mattsson, 2019). Cost optimizations, increased focus on core competences, and outsourcing of activities expanded the locus of logistics and forced the introduction of a new, and wider concept, namely Supply Chain Management (SCM; Jonsson & Mattsson, 2019) which according to The Council of Supply Chain Management (CSCMP) incorporates “[...] the planning and environment of all activities involved in sourcing and procurement, conversion, and all logistics management activities.” (Jonsson & Mattsson, 2019, pp. 21).

Warehousing constitutes one of the critical activities in supply chain management (SCM; Jonsson & Mattsson, 2019; Baker & Halim, 2007), which is highlighted by the fact that warehousing generates approximately 20% of the total logistics costs in any given value chain (Baker & Halim, 2007; de Koster et al., 2007). Warehouses are in simple terms a dedicated space for storage and handling (Kusrini et al., 2018) with the purpose to manage the flow of goods and storage of raw materials, semi-finished goods, finished goods, and wholesale or retail inventory (Brewer et al., 2001) and ultimately facilitate utility (Jonsson & Mattsson, 2019). To manage the flow of goods in an efficient manner, warehousing is commonly divided into four sequential and interdependent processes namely put-away, storage, order-picking, and shipping preparation (Kusrini et al., 2018; Brewer et al., 2001; van Gils et al., 2018). Kusrini et al. (2018) differentiates between supply- and demand-driven warehousing, where the first refers to upstream warehousing, i.e., warehousing holding stock to supply internal customers, e.g., manufacturing and production. Demand-driven warehousing, however, refers to downstream warehousing, i.e., storage of products to fulfill the demand and needs of external customers (Kusrini et al., 2018). How the different types of warehousing are managed depends on each specific supply chain context, and other factors such as warehouse design, and prioritized key performance indicators (KPIs; Jonsson & Mattsson, 2019). The warehousing activity has an extensive history of optimization through the minimization of storage-, handling-, and warehousing costs by achieving high rate of utilization and low operating costs (Jonsson & Mattsson, 2019). The processes within the warehouse activity have previously been performed by human operators, however, the warehousing industry is facing challenges concerning the availability of

qualified staff (Hamberg & Verriet, 2012). Warehouse automation can according to Hamberg and Verriet (2012) address the challenge of qualified staff scarcity and has the potential to reduce operational costs. Warehouse automation solutions, such as storage, retrieval, and sortation systems have become common in large warehouses and were present in more than a third of large warehouses already in 2007 (Baker & Halim, 2007). Baker and Halim (2007, pp. 129) define warehouse automation as “[T]he direct control of handling equipment producing movement and storage of loads without the need for operators or drivers”.

Material handling systems (MHSs) are utilized to facilitate the processes within a warehouse by incorporating everything that refers to any handling and movement of goods (Jonsson & Mattsson, 2019). Handling material is defined as a non-value adding activity, however, the material handling activity generally generates between 20% to 70% of a product’s costs which emphasizes its importance (Caputo & Peagagge, 2008). Current globalized and turbulent markets put a requirement of flexibility on material handling systems in order to achieve efficient and effective production systems (Caputo & Peagagge, 2008). Technological advancements have generated automated material handling systems (AMHSs), constituting physical warehouse automation, which is increasingly adopted as a viable option to improve the operations within the warehouse activity. An automated material handling system offers several different benefits, including the increase of customer service through order accuracy, high space utilization and consequently reduced space requirements, control of inventory, and ultimately flexibility (Baker & Halim, 2007).

Order picking systems (OPSs) are utilized to facilitate the order picking process by consolidating the process of retrieving products for internal- and external customers (de Koster et al., 2007; van Gils et al., 2018; Jonsson & Mattsson, 2019). Order picking systems have been subject to academic and industrial scrutiny for many years due to their criticality within supply chain management, leading to the development of several different order picking systems and methods (de Koster et al., 2007). However, all order picking systems utilize material handling systems to fulfill their purpose. The emerging automation of material handling systems, in consequence, offers the possibility to automate the order picking process, allowing companies to improve the flexibility, efficiency, and effectiveness of the critical process.

It is evident that the technological advancements that enable automation of warehouse processes offer several benefits that can improve flexibility, efficiency, and effectiveness in a global, ever-changing, turbulent and competitive environment. However, existing literature on the topic does not highlight the critical factors to consider upon selection of a warehouse automation solution. Consequently, companies are faced with a plethora of technological possibilities without the structure of making decisions which ultimately leads to suboptimization of organizational, and societal, resources.

1.2 Purpose

The purpose of this research is to identify the critical factors when selecting a warehouse automation solution, and utilize these factors in the development of a decision-making framework. The framework aims to direct decision-makers toward the physical automation solution(s) that aligns with their requirements.

1.3 Limitations

As aforementioned, Kusriani et al. (2018) divides the warehouse activity in different processes, which includes put-away, storage, order-picking, and shipping preparation. However, to fulfill the purpose of this study, the shipping preparation process is excluded from the study to the benefit of in-depth analysis of subprocesses within the put-away, storage, and order-picking processes. The warehouse processes described by Kusriani et al (2018) can be divided into several subprocesses, whereas each to some extent can be automated. The main scope of this research solely includes the placement of material in the designated storage location, i.e., put on shelf, in the put-away process, storage assignment and storage of material in the storage process, locating the article in the warehouse, and retrieval from storage in the order-picking process, which is visualized in Figure 1.1.

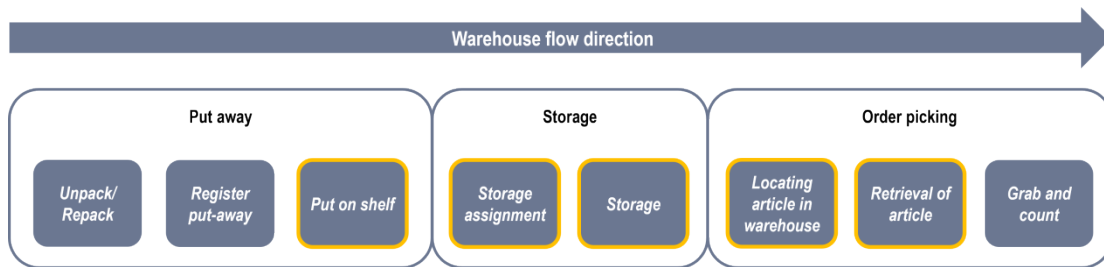


Figure 1.1: A visualization of the scope of the study with the main processes as described by Kusrini et al. (2018). The figure visualizes the focus on the three main processes, namely put-away, storage, and order-picking, including subprocesses. The subprocesses that are relevant for the purpose of the study are outlined in yellow, and includes put on shelf, storage assignment, storage, locating article in warehouse, and retrieval of article.

2. Theoretical framework

The theoretical framework aims to support the analysis while facilitating a basic understanding of the subject for the reader. The first part, 2.1 Warehousing, will elaborate on what warehousing is and what the key activities and functions can be found in the warehouse operations.

The following sub-chapters are built upon a framework consisting of three dimensions that impact the selection of a warehouse automation solution, namely context, performance, and design. See Figure 2.1 for a visualization of the interactions between dimensions.

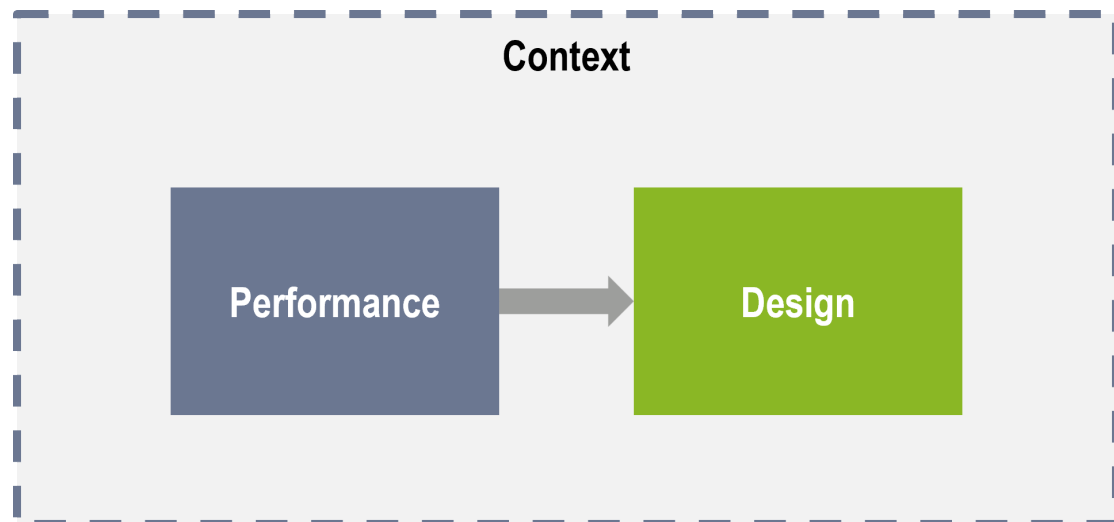


Figure 2.1: Visualization of the three different dimensions utilized to support the analysis of the report. The figure visualizes how the context influences both the performance and design, however, the system configuration, i.e., design, are influenced by the performance goals that are prioritized.

In chapter 2.2 the contextual dimension will be elaborated. The context refers to the factors and conditions that affect the desired objectives and functioning of a system or process. In regard to the selection of warehouse automation, the context determines what designs are possible as well as what performance goals are significant, which is visualized in Figure 2.1.

In chapter 2.3 the performance dimension will be elaborated. Performance refers to what objectives the company wants to achieve. The objectives are based on specific requirements, future goals and context that the company finds itself in. It is the performance objectives of the warehouse automation system that determines what design that should be selected as visualized in Figure 2.1.

Finally, in chapter 2.4 the design dimension will be elaborated. Design refers to the selection and configuration of a system. As seen in Figure 2.1, the selection of a warehouse automation solution is influenced by the performance goals of the company as well as the context in which the system operates. The design dimension includes understanding the possibilities and options as well as the design factors that might affect the selection.

2.1 The fundamentals of warehousing

In this chapter the role of warehouses in supply chains is elaborated as well as the relevant warehousing activities and systems. This is to provide a background to how warehouses are used and what activities can be automated.

2.1.1 The warehouse's role in the supply chain

Warehouses are according to Kusriani et al. (2018) a dedicated space for storage and handling. Brewer et al. (2001) argue that the ultimate purpose of warehousing is to manage the flow of goods and storage of raw material, semi-finished goods, finished goods, and wholesale or retail inventory.

Higginson and Bookbinder (2005) explain how warehouses and distribution centers can perform many different roles in the supply chain and propose seven different functions of warehouses. Firstly, it can act as a make-bulk/break-bulk consolidation center. A make-bulk consolidation center combines small quantities of several products in fewer, larger assortments, while a break-bulk facility de-aggregates large incoming loads for product mixing and to create consolidated outbound shipments (Higginson & Bookbinder, 2005). Both types of consolidation centers play a crucial role in supply chain management by improving efficiency, reducing transportation costs, and creating consolidated shipments that are easier to manage (Higginson & Bookbinder, 2005).

The second function that a warehouse can perform according to Higginson and Bookbinder (2005) is as a cross-dock. Cross-docking is a distribution strategy where products are received, sorted, consolidated, and shipped immediately, without being stored long-term (Higginson & Bookbinder, 2005). This method eliminates the need for activities like storage, picking, and put away, reducing handling, and increasing efficiency. Cross-docking requires complex planning and coordination to work effectively and may not be suitable for all products (Higginson & Bookbinder, 2005). The use of a CD can provide greater control over delivery schedules and is well suited for just-in-time manufacturing environments. (Higginson & Bookbinder, 2005).

The third function a warehouse can perform according to Higginson and Bookbinder (2005) is as a transshipment facility. The traditional function of a distribution center is transshipment, which involves taking an item or shipment out of one vehicle and loading it onto another (Higginson & Bookbinder, 2005). Transshipment may occur when there is a good reason to change transportation modes or vehicle type, and it can be used during the final delivery stage to manage time-of-day constraints or weight restrictions.

The fourth function according to Higginson and Bookbinder (2005) is as an assembly facility. A warehouse can act as an assembly facility by delaying item-differentiation, packaging, and labelling until later stages of the supply chain, which can improve product allocation (Higginson & Bookbinder, 2005). Using a distribution center for final assembly activities also allows for "product localization" and the ability to configure an item in each market area to better reflect the needs and characteristics of that market (Higginson & Bookbinder, 2005).

The fifth function that Higginson and Bookbinder (2005) propose is that the warehouse act as a product-fulfilment center. A warehouse can act as a product-fulfilment center by directly responding to product orders from final consumers and shipping those items directly to them (Higginson & Bookbinder, 2005). Further Higginson and Bookbinder (2005) explain that the sixth function that a warehouse can perform is as a returned goods depot. A warehouse can act as a returned goods depot where returned products are inspected, separated, and processed to minimize costs and quickly get the returned product back into the forward distribution channel (Higginson & Bookbinder, 2005). Higginson and Bookbinder (2005) do as well propose, except for the previously mentioned function, that the role of a warehouse or distribution center (DC) can extend beyond traditional inventory storage and shipment. It can also serve as a center for additional activities such as repairs, customer support and factory outlets, and even a depot for trucks or drivers.

2.1.2 Processes within the warehouse activity

As previously mentioned, warehousing generally incorporates four different processes, namely put-away, storage, order-picking, and shipping, as visualized in Figure 2.2 (Kusrini et al., 2018; Brewer et al., 2001; van Gils et al., 2018).



Figure 2.2: Visualization of the four warehouse processes (Kusrini et al., 2018; Brewer et al., 2001; van Gils et al., 2018), restructured from Kusrini et al. (2018). The four processes visualized facilitate the warehouse activity and include put-away storage, order-picking, and shipping preparation.

The put-away process concerns the placement of products or material in the warehouse (Kusrini et al., 2018). The put-away process includes material handling activities such as verification, location and placement of product material (Kusrini et al., 2018). Karasak (2013) argues that the put-away process requires several different transfers from the receiving gate to the storage location and therefore generate costs amounting to approximately 15% of the total warehouse operating costs.

The following process is storage, which includes activities such as movement from the unloading area to its designated place (Kusrini et al., 2018). The storage process is according to Gu et al. (2007) concerned with the organization of parts held in a warehouse with the aim to facilitate efficient order handling as well as high space utilization. The storage process can be organized differently, depending on the specific organization's prioritizations (Gu et al., 2007). Examples of prioritizations can according to Gu et al. (2007) be customer service and material handling considerations to obtain fast picking.

The order picking process is regarded as one of the most important processes within the warehouse activity since it is labor-intensive (Kusrini et al., 2018; Azadeh et al., 2019; van Gils et al., 2018; de Koster et al., 2007). The order picking process includes clustering and scheduling of customer orders, assigning stock on locations to order lines, releasing orders to the floor, picking the articles from storage locations, as well as disposal of picker products (de Koster et al., 2007).

Shipping preparation is the fourth and final warehouse process as defined by Kusrini et al. (2018). The shipping preparation process includes scheduling and assignment of transportation to and from docks, packing after the picking process, and the loading of trucks (Kusrini et al., 2018). The shipping preparation process is not included in the scope of this report however it is relevant to the warehousing process in general.

2.1.3 Warehouse management systems

Yong (2009) emphasizes the importance of information management systems (IMS) in order to obtain efficient communication and control. One example of IMS is warehouse management system (WMS) which utilizes information technology to manage operations and processes within a warehouse with the aim to enhance the warehouse efficiency (Yong, 2009; Jonsson & Mattsson, 2019). Technological solutions for data collection enable a connection between the shop floor and enterprise resource planning (ERP) software, facilitating effective, efficient, and flexible warehouse management (Yong, 2009). Common functionalities of WMS presented by Jonsson and Mattsson (2019), and supported by Yong (2009), are presented in Table 2.1.

Table 2.1: Common functionalities of WMS presented by Jonsson and Mattsson (2019).

Functionality	Description
Goods reception	Registration of incoming goods
Storage	Information regarding placement
Warehouse administration	Update of inventory balance
Order receipt and picking	Generation of picking order
Transportation documentation	Printing of labels
Material management	Order point calculations

Yong (2009) conducted an analysis of the performance enhancement generated by the implementation of WMS in a warehouse and concluded that the IMS has a positive impact on operational warehousing

KPIs and argues for IMSs criticality for successful competition against rivals on the market. Benefits found by Yong (2009) included reduced labor costs, increased productivity, improved accuracy of inventory data, improved customer satisfaction, reduced lead times, and reduced human errors.

2.2 Context

The context refers to the external factors and conditions that affect the functioning of a system or process. Hanson et al. (2018) emphasize that contextual influence can have a significant impact on the performance of automated systems in a warehouse. Contextual factors further explained in this chapter includes item characteristics, and supply- and demand characteristics.

2.2.1 Item characteristics

During a study on kit preparation, which can be viewed as a type of order picking, Hanson and Medbo (2019) found several item characteristics within the contextual dimension. The characteristics that Hanson and Medbo (2019) found included component weight, size, and the number of picks per order.

Marchet et al. (2015) conducted a study on the automation of the ordering-picking process. In their findings, Marchet et al. (2015) highlighted item characteristics and operating policies as critical considerations when automating warehousing processes. The combination of item characteristics and operating policies are according to Jonsson and Mattsson (2019) important to consider, since they ultimately impact the warehousing process, e.g., if the items are included in kitting, batching, or are directly delivered to the customer.

When selecting a warehousing system, item characteristics can also include the load carrier (Jonsson and Mattsson, 2019). The carrier of the load itself has certain characteristics, and if the load carrier constitutes the storage keeping unit in the warehousing system, it needs to be taken into consideration when selecting warehousing systems (Jonsson and Mattsson, 2019). One common load carrier that is utilized in warehousing systems is pallets (Jonsson and Mattsson, 2019). Type of load carriers and storage keeping units are often decided by the context in which a company is present within and are therefore included in the contextual dimension.

2.2.2 Supply- and demand characteristics

The differentiation between supply- and demand-driven warehousing constitutes contextual factors which impact the prioritized performance and thus the design of the warehouse operations. Kusrini et al. (2018) differentiates between supply- and demand-driven warehousing, where the first refers to warehouses that hold stocks to supply internal customers, e.g., production system such as takt time production system. Demand-driven warehousing, however, refers to warehouses that store products to fulfill the demand and needs of external customers (Kusrini et al., 2018), i.e., order fulfillment.

2.2.2.1 *Takt time production system*

Production systems are a contextual factor that ultimately influences the selection of in-production warehouse strategy, hence, the selection of warehouse automation solution. One production system, widely adopted since the beginning of the 20th century is takt time production system (Haghsheno et al., 2016). In its industrial adoption, takt time enabled a 50% reduction of throughput times compared to traditional production systems (Haghsheno et al., 2016). Today, the takt time production system is central in the management strategy just-in-time (JIT; Haghsheno et al., 2016).

Takt time refers to the speed at which products are produced by ultimately defining the time available to produce one part (Cochran, 1999). The takt time is, hence, calculated by dividing the overall available production time during a chosen time period by the overall forecasted customer demand for that time period (Cochran, 1999; Haghsheno et al., 2016). The definition is as follows (Haghsheno et al., 2016):

$$\text{Customer takt (production)} = \frac{\text{Available net working time}}{\text{Average customer demand}}$$

The takt time production system is according to Cochran (1999) related to system goals and performance measurements, e.g., reduction of mean product delivery time by achieving a balanced and leveled production systems, and consequently derives requirements for investment decisions. The takt time production system, hence, comprises a contextual factor for the selection of automated warehouse solutions.

2.2.2.2 Order fulfillment

Companies performing retail warehousing, e.g., third-party logistics providers, are located further down in the supply chain and consequently influenced by other contextual factors. One contextual factor surrounding retail warehousing is order fulfillment to external customers, rather than order fulfillment to internal customers which is the case for in-production warehousing. Nguyen et al. (2017) propose product assortment, inventory management, last-mile delivery, and returns management as contextual factors that impact the order fulfillment to external customers. Order fulfillment is according to Nguyen et al. (2017) influenced by customer behavior, which is a contextual factor that needs to be considered when automating warehouse operations, and that ultimately can drive growth of sales.

In their study, Nguyen et al. (2017) proposes an integrative framework of order fulfillment and consumer behavior in online retailing. The integrative framework developed by Nguyen et al. (2017) includes the order fulfillment processes inventory management, last-mile delivery, and returns management. The inventory management includes e.g., the selection of production assortment, and product availability (Nguyen et al., 2017). The last-mile delivery process includes delivery information and options, shipping and handling charges, delivery, and order tracking (Nguyen et al., 2017). The returns management includes e.g., returns procedure, returns options, and returns handling (Nguyen et al., 2017). Order fulfillment, hence, becomes a contextual factor to consider when selecting warehouse automation solutions, since aforementioned order fulfillment processes are requirements from external customers.

2.3 Performance

Performance refers to the effectiveness and efficiency of the warehouse automation system in achieving its objectives. When making the decision to automate, there are a multitude of productivity improvements that might be desired by the company. There will also be other performance factors or benefits that can be achieved, but as in every business decision, there are risks involved as well. This section will cover what possible performance improvements can be achieved with automation as well as the possible risks with an implementation. The chapter will also cover what key performance indicators are and how companies use them to measure the performance in the warehousing operations.

2.3.1 Benefits and risks of automation

The availability of human operators in warehouse operations is a growing concern due to various issues, including health and safety concerns, night-time working hours, hard and uninspiring work, and low wages (Hamberg & Verriet, 2012). Simultaneously, the pressure to reduce operational costs is increasing in warehouse activities (Hamberg & Verriet, 2012). To address these concerns, Hamberg and Verriet (2012) suggest that the automation of warehouse operations is a viable solution. Hashemi-Petroodi et al. (2020) argue that a high ergonomic level can enhance the system's performance by improving the workers well-being which in turn decreases human errors. A low level of ergonomics, however, may impact the worker's safety and cause injuries, absenteeism, fatigue, and ultimately reduce the productivity of the system (Hashemi-Petroodi et al., 2020). The adoption of automated warehouse solution generates several possible benefits, including reduced labor costs and reduced rates of error (Roodenberg & Vis, 2008).

According to Baker and Halim (2007), the primary reasons for automation in warehouses include accommodating growth, reducing costs, and improving service. Automation can also improve productivity, order accuracy, reduce space requirements, increase volume capacity, and enable better control of inventory (Baker and Halim, 2007), i.e., improve the reliability (Roodenberg & Vis, 2008).

Despite the numerous benefits of warehouse automation, Baker and Halim (2007) identify some risks associated with automation. One of the risks is over-investment, leading to significant costs without sufficient benefits. However, the risk of over-investment can be mitigated by taking an incremental and

flexible approach to automation, allowing organizations to evaluate the benefits of new technologies before investing further. Another risk according to Baker and Halim (2007) is the potential loss of flexibility and adaptability of the chosen solution to changes in the business. To be able to adapt to changes in business (e.g., expansion of operations) without major disruptions or inefficiencies, it is important to consider scalability when selecting a warehouse automation system (Döllinger & Larsson, 2017). High-tech installations should be based on long-term demand forecasts, and over-capacity to handle peak demand should be included in costed marketing and supply chain plans (Baker & Halim, 2007).

2.3.2 Key performance indicators for the warehouse activity

Kusrini et al. (2018) argue that a high warehouse performance has the possibility to improve the quality, delivery time, customer satisfaction, and reduce costs in the logistics system. Warehouse key performance indicators are, according to Kusrini et al. (2018) utilized to measure the performance of warehouses in the logistics system and are commonly divided into four categories, namely input, output, efficiency, and effectiveness. There are many ways to classify KPIs, however, according to Kusrini et al. (2018) the most common classification for warehouse KPIs are soft and hard metrics, i.e., qualitative, and quantitative metrics.

Soft warehouse KPIs, i.e., soft metrics, are qualitative measures, e.g., managers perception of customer satisfaction and loyalty (Kusrini et al., 2018). Ergonomics and safety constitute two additional soft metrics where ergonomics refers to the workers interaction with their working environment (Hashemi-Petroodi et al., 2020).

Hard warehouse KPIs, i.e., hard metrics, are according to Kusrini et al. (2018) quantitative measures. There has not been an agreement among researchers regarding which hard KPIs are suitable for warehouses, however, Kusrini et al. (2018) proposes 20 KPIs in relation to the four processes of warehouses (see Figure 2.2) which are presented in Table 2.2. Additional important performance measures for manual warehouse operations are according to de Koster et al. (2007) travel time, and distance. Travel time is a function of the travel distance, which emphasizes the importance of travel distance in the warehouse design (de Koster et al., 2007). However, most of the warehouse automation solutions relevant for this study, limits the travel distance compared to manual operations, hence, constitutes an important performance KPI to consider when selecting between different warehouse automation solutions.

Table 2.2: Suggested KPIs by Kusrini et al. (2018) for the four warehouse processes. The KPIs are segmented into put-away, storage, order-picking, and shipping, i.e., the four different warehouse processes as proposed by Kusrini et al. (2018).

	Financial	Productivity	Utilization	Quality	Cycle time
Put-away	Put-away cost per order line	Put-aways per person-hour	% Utilization of put-away labor and equipment	% Perfect put-aways	Put-aways cycle time (per put-away)
Storage	Storage space cost per order line	Inventory per area unit	% Locations and cubes occupied	% Locations without inventory discrepancies	Inventory days on hand
Order-picking	Picking cost per order line	Order lines picked per person-hour	% Utilization of picking labor and equipment	% Perfect picking lines	Order picking cycle time (per order)
Shipping	Shipping cost per customer order	Orders prepared for shipment per person-hour	% Utilization of shipping docks	% Perfect shipments	Warehouse order cycle time

2.3.3 Warehouse capacity performance measurements

The sizing and dimensioning of a warehouse can significantly affect various expenses such as construction, inventory management and replenishment, as well as material handling (Gu et al., 2010).

According to Gu et al. (2010) the company needs to determine the number of cranes and aisles as well as the storage rack dimension when configuring a warehouse automation solution, i.e., the two capacity considerations are storage space and throughput. These capacity demands need to be balanced towards minimizing costs and maximizing equipment utilization.

In the study by Hanson et al. (2018) both the storage capacity as well as the throughput capacity of a warehouse automation solution is discussed. Hanson et al. (2018) presents two ways of adapting the throughput of a robot-based warehouse automation solution. The first option is to increase the number of robots, resulting in more articles being presented to the picker. The second option is to increase the number of picking stations.

Döllinger and Larsson (2017) did consider both the picking and the storage performance in their study where they selected an automation solution. The order picking performance consisted of three considerations, the picking productivity, the peak demand of the business and the picking accuracy i.e., the throughput capacity and accuracy. Döllinger and Larsson (2017) took space utilization, flexibility in product, and maximum number of SKUs into consideration when evaluating the storage performance. The maximum number of SKUs refers to the total number of products that can be stored in the warehouse, which is determined by the number of available storage locations. Meanwhile, the flexibility of the storage location itself is defined by its ability to accommodate goods of various sizes.

When selecting a warehouse automation solution, it is important to consider the physical limitations of the building, as the capacity of the system must fit within the available space. Once the capacity requirements have been determined, it is crucial to consider space utilization to ensure optimal usage of the available space. Space utilization was one of the measures for storage performance in the study by Döllinger and Larsson (2017). Gu et al. (2010) did consider the space utilization when determining the warehouse design and layout. Hanson et al. (2018) did as well consider the space utilization when evaluating a warehouse automation solution where the utilization of ceiling height was the main discussion point.

2.3.4 Environmental sustainability performance

Sustainable supply chain management is according to Tan et al. (2009, pp. n.a.) the “Management of raw materials and services from suppliers to manufacturer/service provider to customer and back with improvement of the social and environmental impacts explicitly considered”. Tan et al. (2009) states that companies utilizing warehouses commonly disregard the environmental impacts of their actions, which ultimately becomes a problem for the sustainability of the supply chain.

Shevtshenko et al. (2012) addressed the issues of warehousing sustainability when researching sustainable designs of material handling equipment within the warehousing activity. Shevtshenko et al. (2012) suggest that one possible approach to improve the sustainability of the warehousing activity is to make material handling equipment sustainable by making it reconfigurable, reusable, and reliable. With this approach, Shevtshenko et al. (2012) derived a table that presents the differences between conventional and more sustainable design for material handling equipment, which is presented in Table 2.3 in this study.

Table 2.3: Presentation of the differences between conventional and more sustainable material handling equipment (Shevtshenko et al., 2012).

Conventional material handling equipment	Sustainable material handling equipment
Product design is fixed	Dynamic product design
Product disposed when requirements change	Product reconfigured when requirements change
Features selected at the moment of purchase	New features can be added to the product
Product life cycle is fixed	Product life cycle has potential to get increased

To summarize the sustainable approach suggested by Shevtshenko et al. (2012), the material handling equipment utilized in the warehouse activity should be selected with the considerations of predicted requirements of the future. Sustainable material handling equipment should therefore be able to be reconfigured without considerable investments.

Additional sustainability measures to consider in the warehousing activity are energy consumption of the material handling equipment. According to Carli et al. (2020), material handling equipment may impact energy consumption, which therefore needs to be considered in order to improve the sustainability of the warehousing activity. Examples of material handling equipment generating energy consumption while conducting direct movement of items in the warehouse are automated material handling equipment (Carli et al., 2020).

2.3.5 Ergonomics within the warehouse activity

According to Gruchmann et al. (2020) ergonomics is the science linking human and automated work and the objective should be to optimize the working conditions while considering human abilities. Grosse et al. (2015) developed a framework considering four aspects of ergonomics affecting three main performance metrics for order picking. The first aspect that Grosse et al. (2015) use in their framework is the perceptual aspect, i.e., how the worker perceives the information that the order picking system provides. The second aspect is the mental aspect, where Grosse et al. (2015) takes the mental load into consideration. The third consideration is the physical aspect, since order picking involves physical activities, such as walking, lifting and carrying for example. The final aspect is the psychosocial aspect that, according to Grosse et al. (2015), includes motivation, stress, workload, boredom, structure of workforce, and work assignment. All of the aspects will affect the order picking performance, the order picking quality as well as the worker's health.

The employer should conduct risk assessment continuously in a workplace (AFS:2012). Assessments that should be made include assessing the risks of strain injuries during manual handling, the risks of repetitive work, the possibilities for employees to influence the layout and implementation of their work, the need for knowledge and information about working positions, movements, technical equipment and aids, as well as early signs of joint and muscle overload (AFS:2012).

Döllinger and Larsson (2017) used ergonomics as a criterion for selecting a warehouse automation solution. They considered the walking distance, the ease of pick as well as the working environment to assess what solution is most suitable for the company.

2.4 Design

Design refers to the selection of a system and the configuration of the system, typically with the goal of achieving a specific set of objectives or requirements. Warehouse design is according to Hamberg and Verriet (2012) a challenging task, where trends such as warehouse automation are increasing the complexity. Hamberg and Verriet (2012) express that the effort of designing a warehouse includes several decisions to be made on different levels and propose three different levels for decision-making, namely operational, tactical, and strategic. These levels address short-term, medium-term, and long-term decisions respectively. Hamberg and Verriet (2012) presents five types of decisions that are made at the tactical and strategic level, which includes: (1) overall structure of the warehouse to determine and define the functional areas, (2) sizing and dimensioning to identify capacities of the functional areas, (3) layout to define the physical arrangement, (4) specification of the material handling equipment to be deployed, and (5) operational strategy to define the high-level operational strategies. In this study, the fourth decision, i.e., specification of the material handling equipment to be deployed, constitutes the main focus while the other decisions remain important for the context.

Aforementioned decisions presented by Hamberg and Verriet (2012) are complex due to interdependency between the different levels and the fact that no warehouse meets all requirements (Hamberg & Verriet, 2012). While there are many different models for different aspects of warehouse design, Hamberg and Verriet (2012) argue that there exists little supportive literature concerning integrated warehouse design.

In this chapter, various elements of warehouse design will be explored, including operation principles, related to the first, third and fifth type of decision-making according to Hamberg and Verriet (2012). Secondly an overview of common order picking systems, and automated order picking systems related to the fourth type of decisions presented by Hamberg and Verriet (2012).

2.4.1 Operation principles within the warehouse activity

In the following subchapters some operational principles will be further elaborated. Firstly, principles of storage assignment will be explained, followed by the principles of routing and an overview of picking principles. This is being done to facilitate an understanding of some general ideas to consider in the warehouse design.

2.4.1.1 *Storage assignment*

When designing a warehouse, the storage assignment of articles is a crucial aspect that requires careful consideration. Most approaches can be divided into either dedicated or random storage (Malmborg, 1996). Dedicated storage involves assigning a specific location for each item, while random storage entails placing items where space is available. Hausman et al. (1976) provides insight into three distinct approaches to storage assignment: random storage, full turnover-based storage (FTB), and class-based storage (CB) where FTB and CB would according to Malmborg (1996) be seen as dedicated storage. FTB is where the article with the highest turnover is placed closest to the in- and output. CB is where the articles are divided into classes based on their turnover rate and placing them in the designated area for their respective class. The class with the highest turnover rate is placed closest to the in- and output. These methods can be employed to maximize the efficiency of storage assignment in various settings (Hausman et al., 1976).

Generally, random storage is preferred as it minimizes space requirements by allowing all items to be placed anywhere, however, this approach is not very efficient for item retrieval (Malmborg, 1996). In contrast, dedicated storage is less space-efficient since it reserves specific spots for items, even when there is no item in stock, nevertheless, this approach is more efficient in the retrieval process (Malmborg, 1996).

2.4.1.2 *Routing*

Efficient picking operations have substantial impact on the warehouse management performance, and therefore impact the costs as well as service level (Cano et al., 2017) of the warehouse activity. Traditionally, picking operations, such as transport and travel time, consume approximately 50% of the order processing time (Cano et al., 2017). Enhanced efficiency in order picking operations can substantially reduce storage costs which, according to Cano et al. (2017) is done through order picking routing planning.

Routing planning generally includes deciding the most efficient sequence for a picker to retrieve articles throughout a warehouse in order to fulfill one, or several, orders (Cano et al., 2017). The industry commonly utilizes different approaches to routing planning, such as routing policies, routing strategies, heuristics, metaheuristics, and other similar solutions (Cano et al., 2017). The choice of routing planning approach depends on the conditions for the specific company's context and prioritized KPIs. However, the ultimate goal with routing planning is to improve the warehouse management efficiency by reducing the transport and travel time for order pickers (Cano et al., 2017).

2.4.1.3 *Picking principles*

This chapter outlines three different principles that can be applied separately, or in combination, within the warehouse activity, however, for different causes and desired results. The three principles outlined in the following sections are batching, kitting, and zoning. Depending on the context and performance objectives, an implementation of either, or a combination of, these three picking principles can be done.

Batching is a picking principle used to minimize the travel distance of pickers by batching together orders of similar picking location (Ho et al., 2008; Yu & de Koster, 2008). According to Yu and de Koster (2008), there are two types of batching: static batching and dynamic batching. Static batching is where the number of order lines are known at the beginning of the planning horizon, while in dynamic batching the order information is considered as it becomes available.

Kitting is when parts are delivered and presented to the assembly operation in pre-sorted kits, where every kit contains parts for one assembly object (Hanson & Brolin, 2013). If the kit is presented to one assembly station it is classified as stationary while if it follows along and contains parts for multiple assembly stations it is classified as traveling (Hanson & Brolin, 2013). In mixed model assembly, where variants are assembled in a mix, different variants require kits to include different parts (Hanson & Brolin, 2013).

Zoning is dividing the picking area into several smaller areas or zones (Jonsson & Mattsson, 2019; Yu & de Koster, 2008). There are multiple ways of dividing the warehouse into zones such as based on picking frequency, product type, or if special equipment is needed (Jonsson & Mattsson, 2019).

2.4.2 Order picking systems

Order picking consolidates the process of retrieving products for internal- or external customers and is the most labor-intensive process of the warehouse processes in manually operated warehouses (de Koster et al., 2007; van Gils et al., 2018; Jonsson & Mattsson, 2019), and capital-intensive in automated warehouses (de Koster et al., 2007). De Koster et al. (2007) emphasizes the importance of choosing a fitting order picking system to facilitate quality warehouse operations.

There are many ways order picking systems (OPSs) can be classified. Marchet et al. (2015) suggests two ways. The first is to classify into three main classes, picker-to-parts, parts-to-picker, and picker-less systems. The second way is to classify based on four factors: who picks the part, who moves inside the picking area, if conveyors are used between the picking zones, and what picking policy is employed. From these four factors, Marchet et al. (2015) identified five main classes of OPSs ranging from least to most automated: picker-to-parts, parts-to-picker, pick-to-box, pick-and-sort, and completely automated picking. Jaghbeer et al. (2020) classifies OPSs, into three main types: human picker, robot picker and picker-less. Human picker includes picker-to-parts and parts-to-picker systems, robot picker includes robot-to-parts and parts-to-robot systems, and an example of a picker-less systems is dispensers.

In picker-to-parts systems the order picker moves along aisles to pick internal- or external customer order requests (de Koster et al., 2007). De Koster et al. (2007) differentiates between two picker-to-parts systems, namely low-level, and high-level picking. In the low-level picker-to-parts-systems the order picker picks products from storage racks or bins while moving along the aisles, while in the high-level picker-to-parts-systems the picker moves along the aisles onboard a lift truck or crane that supports the pickers vertical operations (de Koster et al., 2007).

According to de Koster et al. (2007) the picker-to-parts systems consists of several different processes, including travel, search, pick, and setup. The time distribution of these processes within a given picker-to-parts system is visualized in Figure 2.3.

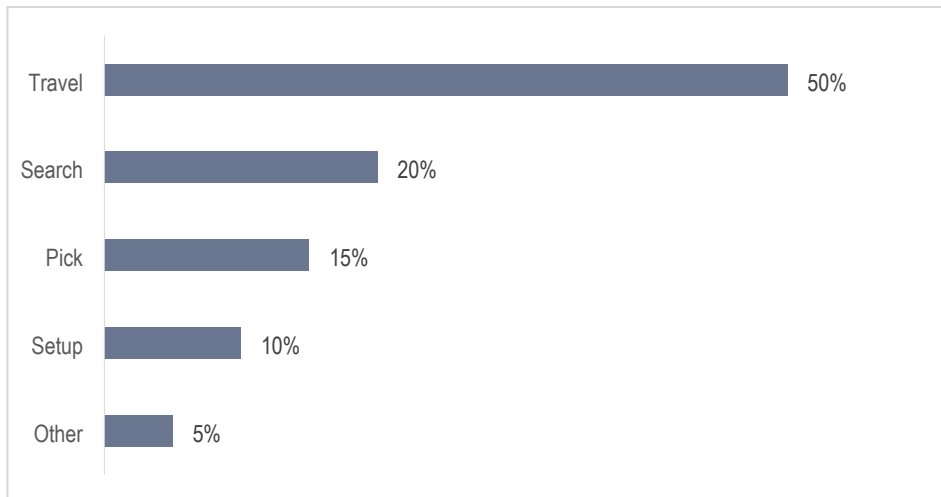


Figure 2.3: Figure visualizing the distribution of an order-picker's time in a picker-to-parts system (de Koster et al., 2007).

Parts-to-picker systems consists of order-picking that brings the parts to the picker (de Koster et al., 2007; Jonsson & Mattsson, 2019; Rushton et al., 2017). The parts-to-picker systems are according to Jonsson and Mattsson (2019) suitable for warehousing contexts when there is frequent picking of few order lines per order. Rushton et al. (2017) adds that part-to-picker systems oftentimes are computerized to ensure accurate order picking in the correct sequence.

There are often several different order-picking systems employed within one warehouse and there is usually a differentiation between systems that utilize humans for order picking and OPSs that are automated (de Koster et al., 2007). OPSs that utilize humans for order-picking are most common, and among these picker-to-parts are the most common.

2.4.3 Automated order picking systems

Order picking is, as aforementioned, one of the most labor-intensive processes in a manually operated warehouse (de Koster et al., 2007; van Gils et al., 2018; Jonsson & Mattsson, 2019). Order picking processes and order picking systems have been subject to academic and industrial scrutiny for many years due to its impact on the supply chain performance, leading to the development of different picking methods and advanced emerging technologies to ensure productivity and efficiency (de Koster et al., 2007). The technological developments have generated automated order-picking equipment such as AS/RS, AGVs, automated cranes, automated lifts, automated carousels, dispenser system, A-frame, and other robotic fulfillment systems (de Koster et al., 2007; Jonsson & Mattsson, 2019; van Gils et al., 2007). The choice of order picking system is one of the key decisions for a company as it has a significant impact on the performance of the warehouse (Marchet et al., 2015). This chapter provides elaboration on some of the automated order picking systems considered relevant for the study, including general automated storage and retrieval systems (AS/RS).

Automated storage and retrieval systems (AS/RS) have according to Roodenberg and Vis (2008) been utilized in distribution and manufacturing contexts since the 1950s. AS/RS are able to both store and retrieve loads in both supply- and demand-driven warehousing settings without the interaction of an operator and therefore constitutes an automated order picking system (Roodenberg & Vis, 2008).

Upon designing an AS/RS there are multiple important aspects to consider (Roodenberg & Vis, 2008; Jonsson & Mattsson, 2019). Roodenberg and Vis (2008) emphasizes the importance of considering current and future capacity demands when designing a specific AS/RS for a particular warehouse setting. It is also important to consider the interfaces to other systems utilized in the warehouse, as AS/RS often only constitutes one of several systems in an automated warehouse (Roodenberg & Vis, 2008). The performance of the AS/RS is consequently influenced by the other system's operational performances (Roodenberg & Vis, 2008).

One of AS/RS primary functions is storage of loads in racks, which according to Roodenberg and Vis (2008), can be designed in diverse ways, e.g., dedicated storage assignment, random storage assignment, closest open location storage assignment, full-turnover-based storage assignment, and class-based storage assignment, which are further elaborated in 2.4.1.1.

2.4.3.1 Robot-based Compact Storage and Retrieval System (RCSRS)

A Robot-based compact storage and retrieval system (RCSRS) is an automated order picking system where the inventories are stored in bins that are in a grid (Zou et al., 2016). In the grid, bins are stored on top of each other creating a storage stack. Robots travel on top of the grid and have the possibility to lift the bins vertically and can transfer bins between storage stacks and picking stations (Zou et al., 2016).

The popularity of the automated storage and retrieval system can be attributed to various reasons, according to Zou et al. (2016). Firstly, the system boasts a flexible and modular structure, allowing companies to begin with a small grid that can be constructed within their existing warehouse and expand over time Zou et al. (2016). Secondly, the system offers flexible throughput capacity (Zou et al., 2016). This means that by adding more robots and workstations, the capacity can be increased even over a short period. Moreover, the system utilizes compact storage space by placing bins on top of each other, and the robots transport them on the grid roof, thereby eliminating travel aisles (Zou et al., 2016). This feature allows for efficient use of warehouse space. Lastly, the system's robots can move flexibly in x- and y-directions, using the shortest paths between locations with very little to no congestion resulting in short response times (Zou et al., 2016).

2.4.3.2 Robotic Mobile Fulfillment System (RMFS)

A Robotic Mobile Fulfillment System (RMFS) is a type of automated storage and part-to-picker order picking system (Lamballais et al., 2017). A RMFS typically consists of three components: Autonomous Mobile Robots (AMRs), mobile racks, and workstations (Tutam, 2021). The solution works in the way that the AMR transfers the rack to the workstation, meaning that the picker is stationary, eliminating the walk distance (Tutam, 2021). When the pick has been conducted, the AMR returns the shelf to an empty storage location (Tutam, 2021).

The racks are not required to be in a fixed position, enabling the system to move the highest runners closest to the outbound area continuously, even when there is a high fluctuation in demand, according to Lamballais et al. (2017). The layout of the warehouse is not static and can therefore be changed relatively quickly (Lamballais et al., 2017). If storage capacity becomes insufficient, it is possible to easily change the layout or the number of shelves and if a higher picking capacity is needed it is possible to increase the number of workers in each workstation (Lamballais et al., 2017).

2.4.3.3 Unit load AS/RS

Unit load AS/RS, also called high-rise storage, is a AS/RS that automatically store and retrieve standardized unit loads, e.g., pallets, from multiple-level high-rise storage racks utilizing a storage and retrieval crane that can move in horizontal and vertical directions simultaneously (Takakuwa, 1996). When the storage and retrieval crane is positioned at a designated location, the operations needed to pick/place the specific unit load are performed, e.g., dropping/picking the item and pulling the shuttle on the crane back (Takakuwa, 1996). Unit load AS/RS are according to Takakuwa (1996) commonly linked to other systems through conveyor and AGV systems. Unit load AS/RS can work in single-, or dual command cycles (Roodenberg & Vis, 2008; de Koster et al., 2007). Single command cycles mean, according to Roodenberg and Vis (2008), that the crane(s) performs either a single storage or retrieval request at a time, while dual command cycles means that the crane(s) performs both a storage and retrieval request at a time. The number of command cycles impacts the cycle time, productivity, and efficiency and should therefore be included in considerations upon implementation of a unit load AS/RS (Roodenberg & Vis, 2008).

Compared to a manual warehouse, a unit load AS/RS requires much less space for a given volume of storage (Cooksey, 1985). Additional benefits of a unit load AS/RS system include reduced need of

workers, reduced operational expenditures (OPEX), and improved productivity performance (Cooksey, 1985). Possible drawbacks of the system are high investment costs due to expensive facilities, and difficulty to meet new conditions by modifying the system, i.e., low level of flexibility and scalability (Cooksey, 1985; Zmic et al., 1992).

2.4.3.4 Mini load AS/RS

Mini load AS/RS handles smaller units, i.e., mini loads. According to Lerher et al. (2013), mini load AS/RS are widely used in a wide variety of fields, e.g., automotive, chemical and pharmaceutical industries. The mini load AS/RS generally consists of three entities, namely a picking aisle with storage racks on both sides, a storage and retrieval machine, as well as one or several input and output (I/O) locations. The storage and retrieval machine can generally perform multiple-cycle operations, which increases the efficiency of the systems, and therefore constitutes an important system configuration decision (Lerher et al., 2013). Moving from single-command cycles to multiple-command cycles has, according to Lerher et al. (2013) proven to increase the throughput with up to 50%.

There are several benefits of a mini load AS/RS, primarily efficient utilization of warehouse space, reduction of damage and loss of goods and decreased number of required warehouse workers (Lerher et al., 2013). The mini load AS/RS can according to Lerher et al. (2013) reach high velocities which enables fast storage and retrieval operations.

However, one drawback of the system is high initial investment costs, which according to Lerher et al. (2013) is one critical factor that customers consider when procuring warehouse automation solutions. In addition to high investment costs, the mini load AS/RS tends to be inflexible in regard to meeting future demands which limits the adaptability of the system (Lerher et al., 2013). Another drawback of the mini load AS/RS is high energy consumption, which is generated from high engine power utilized for high velocity storage and retrieval operations (Lehrer et al., 2013).

2.4.3.5 Robotic shuttle-based AS/RS

Robotic shuttle-based AS/RS has emerged on the market of warehouse automation solutions as a more efficient configuration compared to traditional AS/RS (e.g., unit load AS/RS; Azadeh et al., 2019). Azadeh et al. (2019) states that these systems utilize racks with aisles and deploy autonomous shuttles (i.e., robots) that operate at each level in the aisle. The systems are oftentimes classified on the basis of three categories, which depend on the movement of the robots in the system, e.g., horizontal, vertical, and diagonal systems (Azadeh et al., 2019). E.g., a horizontal robotic shuttle-based AS/RS, allows robots to move products horizontally through rails while lifts move the shuttles vertically (İyigün & Görçün, 2022). To remove the need for lifts, it is possible to allow the robots to move both vertically and horizontally (Azadeh et al., 2019). Recent developments have also enabled diagonal movement, i.e., simultaneous vertical and horizontal movement (İyigün & Görçün, 2022).

Manufacturers of robotic shuttle-based AS/RS (e.g., KNAPP, Swisslog, and Vanderlande) argue that there are several benefits with the system compared to a traditional AS/RS, including minimization of running costs, and low energy consumption (Lerher et al., 2013), reduction of storage costs, increase of throughput capacity to handle peak demands efficiently (by increasing the robotic fleet), increase of picking quality, and enhanced flexibility (İyigün & Görçün, 2022).

The solution is, however, associated with drawbacks despite the emerging technological advancements. One of the primary drawbacks with robotic shuttle-based AS/RS compared to e.g., mini load AS/RS, is the investment costs, which commonly are relatively high (Lerher et al., 2013).

2.4.3.6 Carousel-based AS/RS

Carousel-based AS/RS are according to Park et al. (2003) economical and efficient automated storage and retrieval systems utilized for storing and retrieving different articles. The system has become increasingly adopted in different industrial applications, primarily due to the systems generally being less expensive than other alternatives, e.g., mini load AS/RS. Carousel-based AS/RS are primarily classified in two different types, namely horizontal, and vertical (Park et al., 2013). A horizontal carousel is simply

a lined series of storage baskets or bins with a drive mechanism that rotates carriers horizontally, while a vertical instead rotates vertically (Park et al., 2003). Some carousels are according to Park et al. (2003) unidirectional, i.e., can only rotate in one direction, while others are bidirectional, meaning that they can move in two directions. According to Park et al. (2003) it is not uncommon that a worker, e.g., picker, operates several carousels at the same time.

The benefits of vertical carousel-based AS/RS are several according to Buley and Knott (1986), including utilization of unused air space while minimizing the floor space it occupies, and good ergonomics as the pickers picking activity can be adapted.

According to Đukić and Gajsek (2021), the horizontal carousel-based AS/RS is associated with numerous benefits. By utilizing a single employee for several carousels simultaneously, waiting time for the operator is reduced, and further eliminated which enables high picking productivity (Đukić & Gajsek, 2021). Additional benefits with the horizontal carousel-based AS/RS are, according to Đukić and Gajsek (2021), improved space utilization compared to traditional storage systems and enhanced ergonomic performance.

The carousel AS/RS has some drawbacks which, according to Đukić et al. (2015), include a dangerous working environment due to loads being in continuous movement. Additionally, the investment costs of a carousel AS/RS are according to Đukić et al. (2015) high, compared to vertical lift modules.

2.4.3.7 Vertical Lift Modules (VLM)

Vertical lift modules (VLM) are according to Calzavara et al. (2019) parts-to-picker AS/RS utilized for high-density storage and retrieval of small items. A VLM can be viewed as a system consisting of three basic columns, namely front and rear columns, equipped with brackets that function as shelves to support trays and totes, which are utilized for storage (Đukić et al., 2015). The third column, i.e., the center column, is utilized for an insertion/extraction device which operates within front and rear columns in vertical motion, to store or retrieve trays by order. The system solution allows for small items composed of several trays that are delivered in front of a picker when demanded (Calzavara et al., 2019). The vertical lift modules AS/RS are increasingly adopted due to increased pressure on picking productivity, space savings, and ergonomics (Đukić et al., 2015).

The system is associated with several different benefits, including improved productivity due to the system allowing for dual operations, e.g., where the operator can handle a tray while the system can independently store previous trays (Calzavara et al., 2019). Đukić et al (2015) adds additional benefits, including space savings, increased picker productivity, batching techniques with pre-sorted and organized pick lists, as well as improved ergonomics for the picker as the system eliminates the need for reach, bend, or climb to store or retrieve articles.

However, the drawbacks with the VLM are similar to other parts-to-picker AS/RS, which includes high investment costs compared to traditional storage systems, reconfiguration difficulties, and high maintenance costs (Đukić et al., 2015). Although, companies that have installed VLMs have reported a positive ROI within the first nine to 18 months, according to Đukić et al. (2015). Additionally, compared to a carousel AS/RS, the VLM AS/RS are slower (Đukić et al. 2015).

3. Methodology

This chapter presents the research design, including a detailed explanation of the data collection method, which involves a combination of a literature study and interview study. Additionally, the chapter will describe the data analysis techniques and explain how the information obtained was utilized to develop a framework for decision-making.

3.1 Research design

According to Blomkvist and Hallin (2015), a deductive study formulates a hypothesis based on theories and designs the study to verify or falsify it. An inductive approach, on the other hand, uses theory to understand a problem and empirical data to potentially form new theories. The abductive approach, as described by Blomkvist and Hallin (2015), is a research approach that combines aspects of both deductive and inductive methods. It allows for the integration of theoretical and empirical data to form a more comprehensive understanding of the phenomenon being studied (Blomkvist & Hallin, 2015). The abductive approach is where the understanding of the empirical data influences the understanding of the literature and vice versa.

This study intended to uncover the critical factors impacting the adoption and implementation of physical warehouse automation and develop a decision-making framework. Given the objective of discovering new insights and the interplay between theoretical and empirical data, the abductive approach was deemed an appropriate method for this study.

The study started with an initial literature review to assemble a theoretical framework and to create an interview guide. To gain preliminary insights into key facets of warehouse automation, a visit to an automated warehouse was conducted at a workwear manufacturer in the south of Sweden. During the visit, an interview with the logistics manager was held, as well as firsthand observations of the automated warehouse. The empirical data gathered at the workwear manufacturer proved to be scientifically rigorous and was therefore included in the study. The study proceeded with the gathering of empirical data through interviews with additional respondents of relevance. The theoretical framework was then supplemented based on new findings from the interviews. The empirical data was together with the theoretical framework analyzed to identify the critical factors which provided the basis for developing a decision-framework.

3.2 Literature study

The goal of the literature study was to build a theoretical framework to use as a base for the interview guide as well as for the analysis. The literature study was conducted by searching databases on the internet. The databases included Google Scholar, ResearchGate, Emerald, and Chalmers library. When doing searches, it is important to have a clear search strategy and to maintain a record of what has been searched (Wholey et al., 2010). All searches were therefore held on record and organized by search engine (database) and the keywords that have been searched for, in order to reduce the time of doing the same search multiple times and assisted the process of locating already read articles.

Most of the literature review were initiated at the beginning of the study period with the aim of establishing a foundational understanding of relevant subjects. As the study progressed, additional literature was examined, and the theoretical framework was enhanced and augmented with new insights acquired throughout the course of the study.

3.3 Interview study

When directly collecting data from people, the unstructured extreme is engaging in fluid and open questions for discussion according to Wholey et al. (2010). The structured extreme is asking the same questions, which are closed-ended, to all participants. Semi-structured interview technique is in turn a middle ground between structured and unstructured interview techniques and was consequently the chosen interview technique utilized in the interview study, which is further elaborated in this chapter.

3.3.1 Interview methodology

Semi-structured interviews are, according to Wholey et al. (2010), suitable when the interviewers wish to identify significant issues by utilizing probing follow-up questions. With the arguments stated by Wholey et al. (2010), the authors chose the semi-structured interview method to fulfill the purpose of this study.

During a semi-structured interview, a mix of closed- and open-ended questions are asked and followed up by how- and why questions (Blomkvist & Hallin, 2015; Wholey et al., 2010). Wholey et al. (2010) suggest that some closed-ended questions are useful to open the conversation while open-ended questions ensure that the conversation continues. Based on the aforementioned arguments, the authors utilized a mix of closed- and open-ended questions to maintain a dynamic and progressive discussion during the interviews. The interview guide should not be too extensive (Blomkvist & Hallin, 2015) and having a priority of topics is a good way to make sure the most important topics are covered first (Wholey et al., 2010). However, flexibility and being able to swerve from the original plan is important to extract as much information as possible (Blomkvist & Hallin, 2015; Wholey et al., 2010). By assigning each question a priority, the authors of this study ensured that important topics were covered in a structured and flexible manner.

To ensure traceability of statements, the sound from all interviews were recorded, and this was done with the approval of the respondent. During the interviews one of the authors conducted the interview while the other was taking notes, making sure that the most significant information was captured. Each respondent was in later stages provided with the opportunity to read through, adjust misinterpretations, and ultimately confirm the use of statements in the report. The language used was Swedish and the interviews were held either physically or online depending on the respondents' preference. The duration of the interviews ranged between 45 and 70 minutes.

3.3.2 Interview respondent selection

The first selection criteria for the respondents were that the person should be working in an industry that utilizes physical warehouses or at a supplier of warehouse automation solutions. The second criterion was that they should have insight into the decisions regarding warehouse investments.

The respondents in this research are presented in Table 3.1, together with the industry of which the company is present within, as well as the position of the respondent, how the interview was conducted (face-to-face or video meeting), the duration of the interview and the date of the interview. Each respondent was asked if they knew anyone that could provide the study with additional information, which is a method called snowball sampling (Wholey et al., 2010). Utilizing snowball sampling ultimately led to the acquirement of an additional interview respondent working at a supplier of automation solutions, further referred to as [S3], see Table 3.1. Additional initiations evolved from the snowball sampling; however, these did not lead to additional interviews nor sources of information and are therefore not further elaborated.

Table 3.1: Table presenting the respondents' industry, position within the organization, duration of interview as well as date of interview. The industries represented in this report are workwear, third-party logistics, automotive, as well as suppliers of warehouse automation solutions. The interviews occurred between February and March in early 2023 and the duration varied between 45 – 70 minutes.

Respond.	Industry	Position	Format	Duration	Date
[S1]	Supplier of automation solutions 1	Managing director	Video meeting	65 min	2023-03-03
[S2]	Supplier of automation solutions 2	Process designer	Video meeting	60 min	2023-03-29
[S3]	Supplier of automation solutions 3	Solution Design Manager Automation	Video meeting	30 min	2023-04-17
[I1]	Workwear	Logistics manager	Face-to-face	45 min	2023-02-23
[I2]	3PL	Business development manager	Face-to-face	60 min	2023-03-01
[I3]	Automotive OEM 1	Logistics engineer	Video meeting	60 min	2023-03-08
[I4]	Automotive OEM 2	Logistics developer	Video meeting	70 min	2023-03-09
[I5]	Automotive OEM 3	Lean Transformation Global Leader In-plant Logistics	Video meeting	60 min	2023-03-31

There is no purpose of disclosing the specific companies that the interview respondents represented, however, the industry in which the company operates as well as the interview respondents' position is of relevance as it sets the company in a context and ensures that the interview respondent had insight into the decisions regarding warehouse investments, respectively. The company name, as well as the name of the interview respondents, are anonymized to allow the respondents to speak freely.

3.3.3 Development of interview guides

The interview guides utilized for the semi-structured interviews were developed following the initial data gathering and establishment of the theoretical framework, i.e., the literature study. This was done in order to add substance to the interviews by ensuring that the questions were relevant and that the authors were prepared and able to understand and capture subject- and industry-specific terminology and nuances.

Due to the different characteristics of the interview respondents (see Table 3.1), it was evident that two different interview guides were necessary. Hence, two different interview guides were developed, one for the suppliers of warehouse automation solutions, and another for the customers of warehouse automation solutions, i.e., the industry.

The interview guide for the suppliers of warehouse automation solutions was designed to understand their different solutions, how the suppliers support their customers in the selection of a warehouse automation solution, as well as what factors are critical for customers when selecting a warehouse automation solution. The interview guide for suppliers of warehouse automation solutions is presented in Appendix A.

The interview guide for the industry, i.e., the (current and potential) users of warehouse automation solutions, however, was designed to understand the reasoning of their current- and desired future state. Additional questions outlined in the interview guide were developed with the aim of facilitating a dynamic discussion where critical factors for selection of warehouse automation solutions were possible to identify. The interview guide for the industry is presented in Appendix B.

3.4 Analysis process

The purpose of this study was to find critical factors and to use those in a framework to support decision-makers when selecting a warehouse automation solution. The word *critical* can be defined in several different ways for different applications. However, the Oxford English Dictionary (OED; 2023) defines the word *critical* as “of decisive importance with regard to the outcome of a situation”, which is the definition that was utilized in this specific research.

The analysis process was developed with the aim to provide prerequisites for progressive analysis. In the theoretical framework, three different dimensions; context, performance, and design, were utilized to understand the impact of the selection of a warehouse automation solution. These dimensions were used as well when conducting the analysis of the literature and empirical data. The context dimension contributed to understanding the respondent’s context and what performance factors were critical in what context and is as well the dimension that sets limits to what solutions are viable. The performance dimension is the main focus of the analysis and contributes to selecting critical factors. The design dimension helped to understand the possibilities in warehouse automation solutions.

The data obtained from the combination of a literature review and semi-structured interviews was analyzed using a qualitative research methodology, with a specific focus on thematic analysis. According to Blomkvist and Hallin (2015), thematic analysis involves the identification of categories within the data, which are then organized into themes. These categories were not pre-determined, but rather derived from the interview material. In this study, the themes represent the factors deemed important by the respondents when considering the implementation of an automation solution.

Moreover, the analysis aimed to identify any potential gaps or areas where additional information was required in order to formulate a comprehensive decision-making framework. To address these gaps, supplementary data collection methods such as additional literature review or further interviews were employed.

3.5 Multi-criteria decision-making

The decision-making framework developed as part of the study’s purpose is a multi-criteria decision-making framework. Multi-criteria decision-making (MCDM) is, according to Liang (2021), a well-known branch of decision-making due to its capacity to handle problems with a multitude of objectives. Multi-criteria decision-making can according to Liang (2021) be divided into two different categories, continuous MCDM, and discrete MCDM. In this study, a discrete MCDM is utilized to select, and rank a finite number of alternatives based on a number of critical criteria that are identified in the literature and interview study.

A typical discrete MCDM problem looks according to Rezaei (2015) like this:

$$A = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ \begin{matrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{matrix} & \begin{pmatrix} p_{11} & p_{21} & \dots & p_{n1} \\ p_{12} & p_{22} & \dots & p_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1m} & p_{2m} & \dots & p_{nm} \end{pmatrix} \end{matrix}$$

Where $\{C_1, C_2, \dots, C_n\}$ is the criteria and $\{t_1, t_2, \dots, t_m\}$ is the alternatives, in this study this would be the different technologies. The performance score (p_{ij}) is how well technology i (t_i) performs in that criterion j (C_j).

There are according to Liang (2021), commonly two phases within a multi-criteria decision-making process, firstly an evaluation of alternatives with respect to the selected criteria, i.e., assigning the performance score (p_{ij}). Secondly an aggregation of the evaluations into an overall score for each alternative. The overall score for technology i (S_i) is calculated by multiplying each performance score (p_{ij})

) with the criteria weight (w_j) and summarize the weighted performance score ($p_{ij}w_j$) from all criteria as expressed here:

$$S_i = \sum_{j=1}^n p_{ij}w_j$$

In this study, the criteria refer to the critical factors that are identified in the literature and interview study, while the alternatives refer to the different types of physical automation configurations and solutions. To obtain the weights for each criteria the best-worst method (BWM) was utilized. BWM was selected since it requires less comparison data and is more consistent compared to other MCDM methods (Rezaei, 2015).

3.5.1 Best-worst multi-criteria decision-making

Best-worst multi-criteria decision-making has according to Liang (2021) been widely adopted in a wide variety of different industries, e.g., supply chains, energy, technology, tourism, and manufacturing, due to its aforementioned benefits.

The basic procedure of the best-worst multi-criteria decision-making method is defined by five different steps, which can be summarized as follows (Rezaei, 2015):

Step 1: A set of criteria $\{C_1, C_2, \dots, C_n\}$ is determined.

Step 2: The most important criteria is selected by the decision-maker; this is in the model called the best criteria (C_B). The least important criteria are subsequently selected and, in the model, this is labeled as the worst (C_W) criteria. These two criteria are utilized in step 3 and 4 for conducting pairwise comparisons.

Step 3: The preference of the best, over all, other criteria, is determined by a decision-maker by assigning an integer between 1-9 comparing the best criteria to all others where 1 means "equally important" and 9 means "extremely less important". By comparing the best (C_B) to all other criteria, the Best-to-Other vector would be:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn}),$$

where a_{Bj} indicates the preference of the best criterion (C_B) over criterion j (C_j). It is clear that $a_{BB} = 1$.

Step 4: The preference of the worst, over all, other criteria, is determined by a decision-maker by assigning an integer between 1-9 comparing the worst criteria to all other where 1 means "equally important" and 9 means "extremely more important". By comparing the worst (C_W) to all other criteria, the Worst-to-Other vector would be:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW}),$$

where a_{jW} indicates the preference of criterion j (C_j) over the worst criterion (C_W). It is clear that $a_{WW} = 1$.

Step 5: The optimal weights (w_1, w_2, \dots, w_n) are determined by solving the following model:

$$\begin{aligned} &\text{Minimize } \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\}, \\ &\text{Subject to } \begin{cases} w_1 + \dots + w_n = 1, \\ w_j > 0, \quad j = 1, 2, \dots, n. \end{cases} \end{aligned}$$

The BWM method is utilized in the framework developed in this study. Since the study's purpose is to identify critical factors and use them to develop the decision-making framework, the criteria will be identified and selected. However, the user of the framework will select the best and the worst as well as conduct comparisons of the criteria.

4. Empirical data

In this chapter the data from the interview study is presented. Due to the different characteristics of the interviews depending on if the respondent is a supplier of automation systems or an industry respondent, the chapter is divided into 4.1 Supplier respondents and 4.2 Industry respondents.

4.1 Supplier respondents

During the study, three suppliers of warehouse automation solutions were interviewed, supplier respondent 1 [S1], supplier respondent 2 [S2], and supplier respondent 3 [S3]. The suppliers provided knowledge about the demand from their customers and could pinpoint the factors that are the most critical when they supply the automated warehouse solutions.

4.1.1 Supplier respondent 1 [S1]

[S1] is an executive at a supplier of RCSRS solutions. The supplier sells and configures the hardware and software of automated solutions. The focus of the interview was on the sales process and demand gathering of when they sell systems to their customers and the factors that are considered. A share of the interview was also dedicated to provide [S1] with the opportunity to compare their solution to the competition and explain what factors are making their customers choose them.

[S1] discusses various drivers that push their customers towards automation. One of the main drivers is the need to lower OPEX. The second driver is the lack of available personnel, especially since logistics companies tend to be clustered in areas, leading to high competition for workers. Automation can also save space, which is another reason companies opt for it. Additionally, when conducting an automation project, there is a significant value in analyzing the company's data and processes to improve the overall business. Another driver that [S1] mentions is the change in demand, especially in the retail sector. With the shift towards e-commerce, central warehouses now handle a much larger volume of smaller orders, which creates a bigger need for workers, a resource that is expensive and difficult to find. Consequently, the e-commerce transition has been driving the demand for light goods warehouse automation. Lastly, [S1] highlights that improvements in ergonomics and safety are also important considerations when selecting an automation solution.

The flexibility and scalability of automation solutions are essential factors in the selection of their automation solution, according to [S1]. [S1] highlights that they are selling to growing customers that require scalability and flexibility. According to [S1] their RCSRS solution offers a modular solution that allows for small-scale installations that can be expanded over time, both the storage and the throughput capacity.

[S1] also provided insights into system types provided by the competition. Shuttles, for example, are competitors that connect each robot to an aisle, where the robot represents throughput capacity, and the racks represent storage capacity. Increasing either the throughput or storage capacity in shuttle systems can also increase the other, creating challenges for customers.

When asked to compare an RMFS solution with the RCSRS they sell, [S1] highlights the floor space and ceiling height requirements as differentiation between the solutions. RCSRS needs more ceiling height than the RMFS but instead can utilize the volume of a warehouse in a better way. [S1] also comments on the hardware complexity that the fixed grid that is utilized in an RCSRS is not as easily moved as the shelves in a RMFS solution.

[S1] was asked how their solutions would suit the automotive industry and according to [S1], it would be suitable in kitting applications since the order fulfillment looks similar to e-commerce or retail orders. However, when the user of the system wants to store larger volumes of the product, for example in pallets, an RCSRS solution would not be suitable.

The biggest limiting factor for a RCSRS is according to [S1] the size of the articles. However larger items and items with a high volume are usually stored outside of the RCSRS. Another factor regarding articles is that dangerous goods cannot be stored in a cubic solution.

[S1] explains that when they are gathering the requirements for the customer, they look at normal demand, peak demand, and extreme peak demand. When making the requirements they take into consideration the customer promise and how they can meet that demand. The amount of running hours per day is one key consideration since the robots need time to charge.

The company is taking future scenarios into consideration, but according to [S1] they are not making any long-term projections or analysis since it drives complexity and risk. This is due to the scalability of the system, since it is possible to start small and build when the company grows, instead of building a solution for a future scenario that might not happen. But the future potential is considered in the design, so the system is not built into a corner where it is no longer possible to expand.

There is of course a larger freedom when working with a green field compared to a brown field, according to [S1]. However, the RCSRS has the strength of having a high adaptability to current warehouses, since it does not have to be built in any certain shape. The customer wants to avoid moving the warehouse and then RCSRS is a good solution since it is adaptable.

[S1] wants to add that fire protection is a factor that needs to be considered. The bins in the RCSRS solution that [S1] provides are not perforated leading to less airflow in case of fire. Then the sprinkler system can more easily put out the fire. These are factors that both insurance companies and fire protection engineers are asking suppliers to consider.

[S1] works with a standardized product both regarding hardware and software. Some customization can be done for specific customers but this is avoided as much as possible since customization can lead to increased complexity, which can create significant risks for the project. Due to the standardization, the customers tend to expect continuous software updates making the system better and better, something that [S1] admits being a challenge.

On the theme of standardization, [S1] explains that the logistics automation industry has traditionally been a very engineering-focused industry with customization being very important for customers. However, there is currently a much higher pace of change at companies, leading to less customization and more standardization to achieve flexibility and scalability. So rather than purchasing an expensive custom solution that no one has, customers tend to choose cheap standardized solutions that many actors have to stay flexible, especially regarding software.

Regarding the performance of the solution, the main factor is the efficiency in the order picking process while the efficiency for the put away process is secondary, according to [S1].

4.1.2 Supplier respondent 2 [S2]

[S2] works at a large provider of automated warehouse solutions and holds the position of process designer where [S2] primarily works with understanding the business process of the customers and translates it to technological possibilities. The company provides several different technologies, including AS/RS, piece and picking robotics, robotic (de)palletizers, conveyors, sorters, automated carton handling, and mobile robotics as well as additional services. The company's AS/RS and mobile robotics are the two technologies that are within the scope of this report, whereas the company e.g., provides robotic shuttle AS/RS and mini load AS/RS.

When asked regarding the company's process of developing an automated warehouse solution for the customers, [S2] states that the initial assessment includes understanding and mapping of activities, processes, and the strategy of the customer. Questions commonly asked are "What goods are handled?" "How many transactions are handled?" which ultimately guides the company towards a fitting solution for the customer. Subsequently are levels of capacity analyzed and adapted to the customer's needs.

[S2] further elaborated on the importance of the customer's strategy. Customers' business strategies are different, which ultimately impacts the warehouse activity and consequently the prioritized key performance indicators that [S2] looks at when designing an automated warehouse solution. One important key performance indicator regarding strategy is according to [S2] inventory turnover rate. The customer's desired inventory turnover rate strategy will ultimately impact [S2]'s choice of solution and design. Two industries that have different inventory turnover strategies are e.g., grocery and fashion, whereof the first has a higher inventory turnover rate than the other.

When asked regarding the choice of industries of which [S2] serves, standardized processes are mentioned as a key aspect. The majority of the company's customers have standardized processes with goods that can easily be handled. Grocery and fashion are prime examples of industries that have easily handled products with standardized products. Automotive, however, has a wide product variation with articles of different sizes and shapes, which ultimately increases the complexity of automated warehouse solutions.

While discussing the automotive industry, [S2] states that the risks associated with stopping the production line are too high for automated warehouse solution suppliers to engage in such affairs and deliver system solutions. The company does serve the automotive industry, however, primarily with parts or with equipment that the automotive customer installs themselves. Thereby [S2]'s company does not have to promise the uptime, rather the automotive company internalizes the risks. Warehousing and distribution of spare parts in the automotive industry is according to [S2] a fitting process to automate, however, different sizes and shapes increase the complexity of developing a solution that meets the requirements of the customer.

Concerning operational and capital expenditures, [S2] states that there naturally exists a trade-off between the two. Reducing operational expenditures is usually a driver to automate, however, the operational expenditures commonly reduces when the capital expenditures increase. Each customer is therefore forced to calculate the total cost of ownership to choose the solution that best fulfills their specific needs and requirements.

Additionally, [S2] mentioned some emerging trends within the industries of which [S2] serves, which includes increased focus on e-commerce, specifically directly towards consumers. This in turn impacts the characteristics of the average order, which e.g., are reduced in size which increases the number of orders.

4.1.3 Supplier respondent 3 [S3]

[S3] works at a global supplier of warehouse automation solutions, primarily with sales and as a designer of automated warehouse solutions. The supplier that [S3] works at provides a wide variety of warehouse automation solutions, including several of the AS/RS solutions presented in the literature study, e.g., unit load AS/RS, mini load AS/RS, robotic-shuttle based AS/RS, and VLM. With their wide portfolio, the supplier provides customized solutions for up- and downstream warehouse operations for several different industries.

When asked regarding the critical factors when selecting a warehouse automation solution for their customers, [S3] states article characteristics and order structure as critical factors. [S3] exemplifies by stating that different systems have different capabilities to handle various order sizes, and different systems have different limitations in regards of size and weight, which ultimately includes or excludes solutions, respectively.

In a discussion regarding industries that the supplier serves, [S3] argues that their ability to customize their solutions enables them to serve a large variety of industries. However, one industry that the supplier has historically avoided is the automotive industry. According to [S3], there are no technological constraints of automating the warehouse operations in the automotive industry, however, the

characteristics of the industry with e.g., just-in-time, puts such high requirements on the suppliers that the risks outweigh the possible gains.

Other critical factors that [S3] states include investment size, OPEX, and the desired amount of workers. [S3] argues that the investment size is crucial, however, the operations expenditures are more critical in the long-term perspective. [S3] further argues that operations expenditures are an important warehouse key performance indicator, which oftentimes are utilized to calculate a business case. Ultimately, [S3] states that automation of warehouse operations has the potential of reducing the number of workers performing manual labor, which subsequently becomes a critical factor when selecting between different warehouse automation solutions.

A final critical factor that [S3] states is sustainability. Decision-makers demand footprint data of the different warehouse automation solutions, which is something that the supplier, including [S3], calculates and provides for all of their solutions. The footprint, i.e., sustainability of a solution, therefore, becomes a critical factor when selecting between different warehouse automation solutions.

4.2 Industry respondents

During the study, five actors from the industry were interviewed, these are respondents [I1], [I2], [I3], [I4], and [I5]. The industry respondents provided their view about what factors are important when they are looking to select an automated warehouse solution.

4.2.1 Industry respondent 1 [I1]

[I1] holds the position of Logistics manager at a large workwear manufacturer headquartered in the south of Sweden. The company is a global provider of workwear and is a prominent actor in a highly competitive landscape. The workwear provider has during the last years experienced impressive growth. On their growth journey the manufacturer encountered size limitations in their distribution warehouse, which was the starting point for the company's automation development. Since then, the company has installed an RCSRS, and later expanded the warehouse with additional grids and robots. As of today, the workwear manufacturer is looking to automate beyond storage, and are looking at e.g., automated depalletization solutions.

According to [I1], the main reason for automation was, as aforementioned, existing size limitations. During a fair, representatives from the company met personnel from the supplier, who seemed to have a picture perfect RCSRS solution that was adapted to the workwear manufacturer's operations by default. One example of this is that the manufacturer's packaging was 1:1 to the bins utilized in the specific RCSRS – which proved to be a critical factor for the selection of automation solution.

Additionally, [I1] states that ergonomics was very important for the company when selecting an automation solution. The packaging with workwear articles is very heavy and it was very demanding for the personnel to manage day-to-day operations. By implementing an RCSRS, it was possible to reduce the workload and improve the ergonomics for the workers. The implementation of RCSRS also meant a reduction in the number of forklifts utilized in the warehouse. This in turn enhanced the perceived and actual safety for the warehouse workers.

The scalability provided by the RCSRS is according to [I1] one of the main drivers for choosing the specific solution. This has proven to be a suitable choice, as the growth of the company induced another expansion of the automated warehouse solution, adding additional storage locations and robots without interrupting the day-to-day operations.

The manufacturer is positioned in a highly competitive landscape of global providers of workwear, according to [I1]. Additionally, the industry has high demand for delivery accuracy. This has in turn led the manufacturer to maintain delivery accuracy as one of their prioritized key performance indicators. By maintaining a high delivery accuracy, the manufacturer is able to compete against competitors better located e.g., in Germany.

Other critical factors for the workwear manufacturer according to [11] are dimensions of the articles due to the limitations of the specific RCSRS bins, as well as order picking performance.

Near to the distribution warehouse that is operated by an RCSRS solution, the manufacturer has a buffer warehouse, where no fully automatic solution is installed. The warehouse consists of long and very tall racks where forklifts operate in the aisles. The forklifts are semi-automated, meaning that the operator puts in what product they are looking for and the forklift drives itself to the location. The operator is still needed to perform the pick but is assisted by the system and the forklift. The reason the buffer warehouse does not have a fully automated solution is due to several factors according to [11]. Firstly, the warehouse is not owned by the manufacturer. This means that it is not certain that they can be there for as long as they want. An automation solution is complicated and expensive to relocate, so to make such an investment, they need to own the warehouse. Another reason is the fact that the racks were newly purchased, so to reconfigure the warehouse once again would not be good for the company so they adapted to current resources.

4.2.2 Industry respondent 2 [12]

As a background, the industry respondent [12] is Business development manager at a 3PL provider. The 3PL provider is currently using two different automation solutions in Sweden. The first one being an RMFS solution, and the second a RCSRS. Both solutions are used as distribution warehouses, i.e., demand-driven warehouses, but the 3PL provider does also have supply driven warehouses. However, they do only have fully manual warehouses for supply-driven warehouses. The reason they have not automated the supply-driven warehouses is mainly due to the amount of order lines per put away, and the limit is about four order lines per put away according to [12]. When looking at for example pallet warehouses, where there is a full pallet in and a full pallet out, the volume needs to be very large for an automation solution to be profitable.

[12] mentions that for them as a 3PL provider, due to the contract length of typically three to five years and a depreciation time of an automation solution of about ten to twelve years, it is very important that the solution is generic. What is meant by generic is that it is standardized and will be a suitable solution for a vast range of potential customers. The investment cannot be customized for any one application, since there is always a risk that the customer will leave. Both solutions they have are quite generic solutions.

[12] mentions the importance of simple hardware. Both solutions that they currently use have a simple hardware layout with only a few key components. This is important in cases where the system is moved, resold, or repurposed in any way. This further emphasizes the importance of generic solutions for 3PL providers.

Regarding the operation capacity, [12] mentions that in the 3PL business model, they are selling a guarantee of capacity, something that is of importance. This makes the flexibility of capacity a key factor in their selection of a solution. In both solutions they have selected, there is the possibility of adding and removing both storage and picking capacity. Flexibility in storage capacity is not as easy but can be done by adding or removing racks/shelves without any large reconfigurations. The flexibility in picking capacity is a bit simpler and can be done by adding/removing robots, however, there is a limitation in the number of picking stations. This is a factor that [12] mentions as a major drawback, that even if the systems they currently are using are considered flexible, they still have a capacity limit built into them. A factor that is critical for [12] is the uptime reliability and highlights that in both solutions they have, even if one robot fails, the system can keep on running at almost full capacity.

When asked the reasons why they chose the two different systems, and not used the same type in both locations, [12] said that the RMFS solution would potentially work in both applications, but that the bins for the specific RCSRS solution were too small for the articles of the customer that they have in the RMFS. However, the selection of the RCSRS was based on the fact that the total cost of the RMFS solution was higher due to the use of more space since it does not use the height in an effective way. They also

considered a robotic shuttle based AS/RS in both cases, but due to the lower flexibility and higher initial cost, they chose the aforementioned solutions.

Getting workers is also something that drives towards automation according to [I2]. They do get more applications when they have automated solutions. This is due to both the working environment and the future ambitions of the company. The profile of the work is also changing from someone who works fast and is flexible to someone who is consistent.

Human errors are important to consider according to [I2]. When comparing RCSRS and RMFS the difference is that the RCSRS presents one article number at a time while RMFS presents 16. This means there is a higher risk of human errors with the RMFS. However, other systems such as light indicators assist the picker.

[I2] continue to briefly comment on other factors that are important to consider. For example, warehouse buildings currently in Sweden are not built for automation. Ergonomics and safety are key concerns. Economy is a driver. The productivity is much higher with automation and much less space is required. Flexibility is very important. Changes in storage and throughput capacity are key concerns. Engineering degree of the supplier is a consideration. Some suppliers only deliver standardized solutions while some really can adapt everything. Implementation time is important. The productivity aspect of picking per time unit is not as simple as faster is better. Some solutions have some waiting time, but this means that workers can do other tasks such as packing as well.

4.2.3 Industry respondent 3 [I3]

Industry respondent 3 [I3] works with logistics development and internal material handling at a large automotive original equipment manufacturer (OEM), labeled as Automotive OEM 1. At this specific production plant there are three different business units, the first being engine assembly, the second being foundry of parts, and lastly processing, according to [I3]. The first business unit handles a broad portfolio with a vast number of variants and high volumes whereas each article has different needs and requirements while the second business unit is characterized by few variants and high volumes.

[I3] states that their desire is to primarily automate the operations that handle many variants with high volumes, i.e., the engine assembly rather than the foundry of parts. As of today, Automotive OEM 1 has an automated unit load configuration, in proximity to the assembly line. The unit load presently works as buffer storage and safety stock to the assembly line. The output, i.e., retrieval, from the storage are complete pallets. Picking is not conducted regularly, however, happens when necessary.

[I3] states that one of the primary critical factors for their automation is accessibility to each article at any time. Accessibility allows them to reach any article at any time, which enables adaptability and therefore flexibility.

Another critical factor that [I3] mentions is the current structures, resources, and set-ups utilized in the warehouse. The current automated unit load system utilized at the plant was installed in the 1980s according to [I3]. Historically, Automotive OEM 1 had a larger automatic unit load system with higher capacity to handle full pallets, however, emerging trends require smaller unit loads due to higher degree of product variants. Recently, the operations have become increasingly manual, due to the OEM's desire to separate the flow of pallets from the flow of smaller units, whereof the flow of smaller units are manually operated to leverage the turnover efficiently.

According to [I3], Automotive OEM 1's production is in a period of transformation and a new warehouse facility is established, where needs and requirements can be set from the start without the consideration of any historical decisions. In this transformation, [I3] states that they are utilizing the article characteristics, e.g., size, number of variants, packaging sizes, and order characteristics, e.g., order volume, as vantage point. Another important consideration, i.e., critical factor, for the OEM is according to [I3] volume efficiency, which in this case has resulted in more options of automation solutions. An

additional driver is according to [13] safety, whereof a forklift-free warehouse is prioritized due to organizational policies.

When asked about which technologies and automation solutions Automotive OEM 1 are looking at in the transformation period, [13] states that arrangements and contracts are work in progress and can therefore not be discussed at this stage. But what they primarily consider are flexibility, scalability, safety, OPEX, and volume utilization. However, one of their most critical factors is technological maturity. Many of the innovative automation solutions on the market are provided by startups that do not have the technological maturity to deliver a system that meets the high requirements on uptime of a large automotive OEM, which in this case limits the options for [13] when selecting automation solution.

When comparing the automotive industry with other industries, [13] emphasizes the criticality of uptime. The core of the automotive industry is the assembly line which are producing based on a takt time, which is an aspect of uptime that other industries does not have to consider. Takt time increases the risk and complexity for the automotive industry.

[13] argues that many of the automation solutions are adapted to other industries, and therefore requires adaptation when implemented in the automotive industry. Characteristics that are taken into consideration here are number of picks per order line, takt time, continuous flow etc. This in turn, generates other investment costs, and capital expenditures (CAPEX) which is something that [13] has to consider when making decisions.

4.2.4 Industry respondent 4 [14]

Industry interview respondent 4 [14] has been working at Automotive OEM 2 for many years and has especially worked with logistics development. Presently, [14] is working with smart factories and are looking at different technologies and how they can be adopted to enhance their production.

Historically, Automotive OEM 2 had approximately four automated unit load storage systems in Europe. One of the automated unit load storage systems was for spare parts, the others were for chassis and other unit load storage. However, Automotive OEM 2 encountered capacity constraints from the automated unit load storage systems according to [14]. The systems were installed and adopted in the 1970s and started to lose functionality. When the automated storage systems started to lose functionality, top management decided that they should not utilize automated unit load systems and were therefore exchanged for manual warehouse operations.

Presently, Automotive OEM 2 is building a new factory for the production of batteries, and at that production plant, the warehouse operations will be automated. The automated warehouse system utilized at the new plant is according to [14] unit load storage systems that stores pallets, while automated guided vehicles are utilized to transport the pallets to the production line. In this particular unit load system, three different sizes of pallets are utilized according to [14].

When asked what factors are the most critical for the selection of automated storage systems, [14] emphasizes the importance of space utilization, and automation ambition, i.e., the attitude towards automation. When selecting a solution for an already existing building, the possibility to utilize the full volume becomes more important since the limitations and boundaries are already set according to [14].

Another critical factor for Automotive OEM 2 is according to [14] flexibility. Since the industry is ever-changing, especially present developments toward electrification, changes the conditions for automation which puts a demand on flexibility of the systems. This will in turn impact the capacity according to [14]. An additional critical factor according to [14] is the production pace, i.e., demand pattern, in the automotive industry, where the production is forecasted, planned and initiated based on a takt time, which is very different from other industries.

When discussing how article characteristics impact the selection of automated storage system, [14] emphasizes the packaging as the most critical, however, also notes that size, and article sensitivity is

important to consider. For the warehouses discussed regarding Automotive OEM 2, there is never any re-packing of pallets, and articles stay in the original packaging, which increases its criticality for adoption in an automated storage system.

[14] also emphasized important KPIs to consider, such as number of put-aways per time unit, cycle time for put-aways, and other productivity measurements for order picking. Other important factors to consider are accessibility to articles at all time, according to [14].

During the final minutes of the interview, [14] highlighted sustainability in regards of energy efficiency as a critical factor to consider when selecting between different warehouse automation solutions. [14] stated that this might not have been as important historically, however, in recent development where the cost for energy has skyrocketed. Therefore, it will become increasingly important to consider energy efficiency in the future.

4.2.5 Industry respondent 5 [15]

Industry respondent 5 [15] works for a large automotive manufacturer, further labeled as Automotive OEM 3. [15] is responsible for Lean Transformation globally and is the process owner of the in-plant logistics from receipt of material to delivery to the assembly line.

[15] starts by explaining the purpose of warehouses in an automotive manufacturing supply chain. The industry is in a context where the production planning is very precise, and every car that is manufactured has been planned for a long time. This means that the manufacturer is very aware of each flow of material. However, due to fluctuations in the lead times and other disturbances, the material flows are not always in perfect sync with production, meaning that the manufacturer needs to store the material that arrives before it is needed. This has been very apparent according to [15] when there has been a component shortage leading to shut down of the manufacturing, however, many of the material flows are not possible to shut off, meaning a lot of material comes to the factory, but will not be used until the materials missing are coming. Traditionally manufacturers in the automotive industry have solved these issues by building large warehouses according to [15]. The warehouse basically acts as a synchronizer of flows. So according to [15], the situation where investing in an automation solution could be a good idea is when the plant has suppliers with a very long lead time on many parts, for example a factory located in Europe with many suppliers in Asia.

Automotive OEM 3 formerly utilized automated high-rise pallet warehouses according to [15]. However, these have been phased out for a few reasons. Firstly, due to process improvements, the need for large warehouses has decreased. Secondly, there have been instances when an automatic warehouse malfunctioned, resulting in the stop of the entire production flow. Using forklifts with human operators reduces the risk of a total shutdown. Uptime was highlighted multiple times during the interview as a very critical factor according to [15]. The automotive industry is so sensitive to stops since a standstill is extremely expensive.

[15] explained that the automotive company has no plans to invest in any warehouse automation solutions in the production flow. When asked why, [15] stated several reasons. Firstly, investing in a solution that will be in use for 30 years or more is challenging, as it is difficult to predict whether the conditions that the system was purchased during will persist. Specifically, the business case may be sound when the warehouse automation solution is initially purchased during a volatile market period, but if the market subsequently becomes less volatile or resourcing is done leading to less lead time deviations, the warehouse may be oversized, resulting in an expensive solution. Moreover, article characteristics such as size, weight, hazardous materials, or packaging changes may make the selected solution obsolete, which is another risk highlighted by [15].

According to [15], Automotive OEM 3 only handles palletized unit loads in the production flow, so as it looks right now, only high-rise automatic pallet solutions would fit the context. [15] was asked where an automation solution for non-palletized unit loads would fit in the production logistics, and the interviewer suggested that the kitting process would be a suitable operation where the material flow to the picker

could be automated and compared the operation with e-commerce picking. [15], however, thought that first of all, e-commerce has a completely different delivery requirements since stops in the e-commerce leads to late deliveries and annoyed customers, but it is not close to as expensive as in a lean manufacturing context where in the end the whole production might stop.

At Automotive OEM 3, the kitting stations are located close to the assembly line, meaning that it would be hard to get efficient automation when the kitting stations are spread out in the plant according to [15]. [15] did, however, point to another manufacturer which had a central kitting warehouse from where the kits were delivered to assembly, in that kind of layout an automation solution might be suitable for kitting.

Still [15] sees a big challenge with applying automation to a kitting operation, which is that there is such a big variation on the different parts, so finding a solution that would suit all parts is difficult.

[15] explained that in an automotive manufacturing plant the production planning is crucial. Therefore, an automatic warehouse solution has to be able to work with the production plan and even out the in- and outflow from the warehouse. This is also important in the configuration of the capacity of the warehouse; however, this is crucial for both automatic and manual warehouses.

5. Identification of critical factors and framework development

In chapter 5.1 the empirical data and literature are analyzed to identify and select critical factors that are utilized in the development of the warehouse automation selection framework, that ultimately aims to support decision-makers when selecting a warehouse automation solution. The framework is presented in chapter 5.2 along with the process of applying and utilizing the framework.

5.1 Analysis and selection of critical factors

By conducting a thematic analysis of the empirical data and the literature, several factors have been identified that are considered when selecting a warehouse automation solution. Two different types of factors have been identified. The first type is labeled as *Qualifying factors* by the authors. These factors highlight the contextual limitations that determine feasible solutions for the company. The second type has by the authors been labeled as *Comparable factors*. These are factors that are taken into consideration, but where the importance of each factor, i.e., the weight, will differ between companies depending on the context and thereby is comparable to one another. Comparable factors will be weighted using multi-criteria decision-making.

In this chapter, the two types of factors will be further elaborated. The specific factors that have been selected will be argued for based on the findings in the empirical data and the theoretical framework. An overview of the identified factors can be found in Table 5.1.

Table 5.1: All identified factors with type, name, definition, and abbreviation.

Type	Factor name	Definition	
Qualifier	Item characteristics	The limitations in terms of size, weight, and other characteristics imposed on the storage location itself.	Q1
	Investment budget	The limit in monetary terms that can be invested in an automation solution.	Q2
	Size limitations	The physical limitations of the warehouse building.	Q3
	Warehouse capacity	The required throughput and storage capacity.	Q4
Comparable	Space utilization	How well the solution utilizes the available space.	C1
	Scalability	The possibility to change the capacity, both regarding throughput and storage capacity, in an efficient way.	C2
	Ergonomics	How ergonomically suitable the solution is.	C3
	Sustainability	The environmental aspects include how resources are used considering both resources used in operation as well as resources used to produce the automation solution.	C4
	OPEX	How much savings in OPEX the solution can facilitate.	C5
	CAPEX	The cost of the solution.	C6
	Versatility	The ability of a solution to be flexible and adaptable in order to effectively handle a wide range of applications, different types of customers, changing industry characteristics, and forthcoming changes.	C7
	Robustness	That the solution has a high uptime, a low fail rate, and can be relied on.	C8

5.1.1 Qualifying factors

From the empirical data and the literature, four distinct areas of qualifying factors, Q1-Q4, have been identified and can be seen in Table 5.1. These will be further elaborated and argued for in the following subchapters.

5.1.1.1 Item characteristics (Q1)

The first qualifying factor identified is labeled item characteristics. This factor includes the limitations in terms of size, weight, and other characteristics imposed on the storage location itself. Contextual factors

play a significant role in determining the limiting factor. For instance, in a warehouse dedicated to order fulfillment with one-piece picking operations, the individual items would be the constraining factor. Conversely, in companies dealing with pallets, such as Automotive OEM 1-3, as indicated by [13], [14], and [15], the pallets determine the dimensions of the storage location. Jonsson and Mattson (2019) supported the arguments of [13], [14], and [15] by arguing that it is important to consider the load carriers characteristics, as well as the characteristics of chosen storage keeping unit.

[S1] highlighted item characteristics as a critical factor and explained that the biggest limiting factor when selecting their RCSRS solution is the size of the items that will be stored. [S2] did as well say that the goods that are handled guides the decision of warehouse automation solution. [I1] highlighted that the solution the workwear company selected, had an almost perfect one to one fit with their packaging, so they did not need to repack to fit their packaging in the solution. [I2] also mentions the size of the storage location as a limiting factor when discussing the RCSRS solution the 3PL are using.

Weight of the item is also a limiting factor since all solutions have a weight limit of the items in storage. This was mentioned by [S3] and [I5] as limiting factors. Hanson et al. (2018) supported the arguments of [S3] and [I5] by stating that item characteristics such as weight and size are important factors to consider when evaluating different order picking systems.

Additional characteristics found are that some solutions are not suitable for dangerous goods, which was highlighted by [S1] when talking about RCSRS solutions. [I5] supported the arguments of [S1] and emphasized the importance of considering compatibility when selecting between different warehouse automation solutions. Đukić et al. (2015) in turn supported the arguments of [S1] and [I5] when describing that carousel based AS/RS solutions are not suitable for dangerous goods.

5.1.1.2 Investment budget (Q2)

The second qualifying factor is the investment budget. For all investment decisions there is a budget and this factor will qualify the solutions that are within the budget for the decision-making company. The factor regarding investment size has been found in both the empirical data as well as the literature.

Investment size was a critical key performance indicator that was discussed several times during the interview with [I2]. Initial costs, i.e., investment costs, was according to [I2] one of the reasons that they did not select a robotic shuttle based AS/RS, since their proposed robotic shuttle based AS/RS induced higher investment costs, compared to the solutions they selected, i.e., RCSRS, and RMFS. The arguments stated by [I2] therefore motivate investment costs as a critical factor when selecting automated warehouse solutions. [I3] supported the arguments of [I2] by reiterating the criticality of investment size when selecting between different automated warehouse solutions.

When describing different systems, Zrnica et al. (1992), Lerher et al. (2013), and Đukić et al. (2015) all have investment cost as a consideration. Baker and Halim (2007) stated that one benefit of automating warehouse operations can reduce costs, however, there is a risk of over-investing in automation without realizing any benefits.

5.1.1.3 Size limitations (Q3)

The third qualifying factor found is size limitations. This factor includes the physical limitations of the warehouse building itself such as the ceiling height of the building, the floor space available, and the shape of the building.

This factor becomes less of an issue when establishing a green field warehouse, whereas it rather becomes a question about investment cost of the building itself. In contrast, when fitting a warehouse automation solution into an already established warehouse, there are inherent limitations that increase the complexity of implementation, whereas utilization of space becomes more important according to [I4].

The ceiling height of buildings was brought up as a contextual factor by Hanson et al. (2018) when analyzing warehouse automation solutions. [S1] and [S3] highlighted that ceiling height and floor space requirement differs between systems, such as RCSRS and RMFS.

5.1.1.4 Warehouse capacity (Q4)

The fourth and final qualifying factor is the warehouse capacity. There are a multitude of ways of measuring the warehouse capacity. It is however evident from the result and the literature that two measurements stand out for warehouse capacity in the context of warehouse automation, those are throughput and storage capacity.

All supplier respondent mentioned throughput capacity. [S1], [S2], and [S3] said that they look at the order demand of the customer when gathering requirements. [S1] said they gather data on the average, peak, and extreme peak of order lines per hour and scale the system accordingly. [S2] said that one of the primary things they look at is how many transactions are handled. [S3] stated that the order structure is something they look at when suggesting solutions. The throughput was as well discussed as a capacity measurement in the studies by Hanson et al. (2018) and Gu et al. (2010). This indicates that the throughput of the system is a key consideration when selecting automation solutions. It is also clear that this is a qualifying factor since a company will not invest in a solution that cannot handle the number of order lines that the company requires.

Storage capacity was mentioned in the literature. Hanson et al. (2018) did take the number of SKUs in storage into consideration when analyzing warehouse automation solutions. Döllinger and Larsson (2017) did also use the number of SKUs as a criterion when selecting a warehouse automation solution. Finally, Gu et al. (2010) also mentions the storage capacity as a measurement and says that it has to be balanced to the throughput capacity when configuring an automation solution. This indicates that storage capacity is a key consideration when selecting automation solutions. It is also evident that this is a qualifying factor, since a company will not invest in a solution that cannot store the amount of SKUs they require.

5.1.2 Comparable factors

Eight comparable factors, C1-C8, have been identified from the empirical data and the theoretical framework. Though every one of these are important, tradeoffs are always made in large investments. These factors will be utilized to differentiate between suitable solutions to find the solution that aligns with the requirements of the decision-making company.

5.1.2.1 Space utilization (C1)

In all warehouses, space is a resource that should be utilized in a proper way. Most automation solutions are able to use the space better than a manual warehouse due to less space between shelves for example. However, this factor is more or less important for a company depending on contextual factors such as a high opportunity cost on the space. This factor differs from the qualifying factor Q3 since it considers how well the solution utilizes the space and not how much space is available.

This factor was clearly found both in the empirical data and the literature. Firstly, the workwear company that [I1] represents encountered size limitations in their distribution warehouse, which was the starting point for the company's automation development. By installing a RCSRS, the workwear company was able to utilize the available space more efficiently. The space utilization of a specific warehouse automation solution can therefore be considered critical when selecting a warehouse automation solution. [I3] also highlights the importance of space utilization, by stating that it is one of the most critical factors when they select warehouse automation solutions.

[I4] supported the arguments of [I1] and [I3] and stated that one of their most critical factors when selecting a warehouse automation solution is the space utilization of a specific warehouse automation solution. Further on, [I4] stated that the space utilization of a specific solution becomes more critical when the solution is implemented in an existing building, due to the fact that the limitations boundaries are set.

[S1] in turn stated that automating warehouse operations can save space, which commonly is a reason for warehouse automation. The importance of space and volume utilization when selecting between different warehouse automation solutions was reiterated by [S1] during a discussion where [S1] compared different systems of which [S1] were familiar with.

Baker and Halim (2007) stated that automation has the potential to reduce space requirements and increase volume capacity, which ultimately is about space utilization. The space utilization of a specific warehouse automation solution therefore becomes a critical factor when selecting between different warehouse automation solutions. Gu et al. (2010), Hanson et al. (2018), and Döllinger and Larsson (2017) all included space utilization as a consideration in their studies.

Kusrini et al. (2018) in turn proposed several different key performance indicators for the different warehouse processes. The utilization of storage space generated a key performance indicator that measures the percentage of occupied storage locations in a warehouse. This key performance indicator proposed by Kusrini et al. (2018) can therefore be viable to evaluate space utilization and space requirements.

Hamberg and Verriet (2012) proposed five important decisions that need to be taken at tactical and strategic levels, which included sizing and dimensioning to identify capacities of the functional areas. The arguments from [I1], [I3], [I4], and [S1] combined with the literature, motivate the criticality of space utilization when selecting a specific warehouse automation solution.

5.1.2.2 Scalability (C2)

The second comparable factor found is scalability. Scalability in the case of warehouse automation solutions is the possibility to change the capacity, both regarding throughput and storage capacity, in an efficient way. This includes the ability to start on a small scale, easily increase capacity and ensure that the scaling process does not interrupt the operations.

The criticality of this factor was argued by [I1] since the primary reason for the workwear company's choice of warehouse automation solution was scalability. The workwear company is presently experiencing fast growth and the available warehouse operations need to be scaled accordingly. This fact highlights the criticality of scalability when selecting a warehouse automation solution. For the workwear company in specific, this has proven to be very critical, since their growth forced an expansion of their warehouse, which was efficiently done due to their automated warehouse solution being very scalable.

[I2] supports the arguments of [I1] and stated that they selected their specific automated warehouse solutions primarily due to the fact that those solutions were possible to efficiently scale according to their current needs by adding or removing capacity, something that is important for them in the 3PL context where customer demand is ever-changing. [I3] in turn supports both [I1] and [I2], by stating that scalability constitutes one of their primary considerations when selecting an automated warehouse solution.

[S1] argue that in their sales process, flexibility and scalability of automation solutions has proven to be essential factors for their customers when selecting a warehouse automation solution. [S1] further states that they commonly are selling to customers that are experiencing a growth of sales. To be able to grow, expand, and increase sales, the warehouse automation solution must be scalable, which emphasizes the importance of scalability when selecting a warehouse automation solution.

Döllinger and Larsson (2017) found in their research that scalability was important to consider when selecting between different warehouse automation solutions. According to Döllinger and Larsson (2017), it is additionally important to be able to adapt to changes in business (e.g., expansion of operations) without major disruptions or inefficiencies.

Based on the arguments of [I1], [I2], and [S1] combined with literature, it is evident that scalability is important to consider for the warehouse activity. Therefore, scalability is motivated as a critical factor when selecting a specific warehouse automation solution.

5.1.2.3 *Ergonomics (C3)*

Ergonomics has been identified as a driver for choosing to automate warehouse processes. Even if automation in general increases the ergonomics for the workers, ergonomics is something that differentiates between different solutions. This is regulated by law in many cases, in Sweden the Work Environment Authority demands that companies do regular ergonomics assessments (AFS:2012). Grosse et al. (2015) did take perception of information from the system, mental load, physical load and psychosocial aspects into consideration for their framework. Systems might differ in different aspects, for example the difference between solutions can be height of pick, how monotonous the picking is, or the working environment in general.

According to [I1], the packaging of workwear articles is very heavy and it is very demanding for the personnel to manage day-to-day operation. To improve the day-to-day operations for their workers, the workwear company that [I1] represents considered ergonomics as a critical factor when selecting a warehouse automation solution.

[I2] supported the arguments of [I1] by stating that automation can improve the working environment, i.e., ergonomics. For the company that [I2] represents, ergonomics was considered when they selected their specific solutions, highlighting ergonomics as a critical factor. [S1] also considers ergonomics and safety a key concern for their customers when selecting an automation solution.

When selecting a warehouse automation solution, [I3] stated that they considered factors such as safety of their employees, which in this case included ergonomics. [I3] therefore supported the arguments of [I1], [I2], and [S1].

Ergonomics constitutes, according to Hashemi-Petroodi et al. (2020), a soft warehouse metric which is measured qualitatively. High ergonomic level can according to Hashemi-Petroodi et al. (2020) enhance a system's performance by improving the well-being of the workers, while low ergonomic level in turn can impair the performance and safety of workers by causing e.g., accidents, absenteeism, fatigue. The arguments stated by Hashemi-Petroodi et al. (2020) highlight the criticality when selecting between different warehouse automation solutions, since the different solutions perform differently in ergonomics. Ergonomics was as well considered as a critical factor in the study by Döllinger and Larsson (2017) where in the evaluation process of automation systems they considered walking distance, ease of pick, and working environment.

Based on the arguments of [I1], [I2], [I3] and [S1] combined with literature, it is evident that ergonomics is important to consider to ensure the well-being and safety of warehouse employees. Therefore, ergonomics is motivated as a critical factor when selecting a specific warehouse automation solution.

5.1.2.4 *Environmental sustainability (C4)*

Environmental sustainability is important for all companies, regardless of industry. The environmental aspects include how resources are used considering both resources used in operation such as electricity, and resources used to produce the automation solution.

[I4] mentioned energy efficiency in regards of sustainability at the end of the interview. Energy efficiency has become increasingly important in the present energy turbulence. Therefore, [I4], argued that energy efficiency will become an increasingly critical factor when the automotive OEM are selecting between different warehouse automation solutions.

[S3] stated that they provide footprint data of their different automation solutions due to an increased customer demand of such data. Footprint data can subsequently be utilized to distinguish and compare between when selecting between different warehouse automation solutions.

Carli et al. (2020) stated that the energy consumption of material handling equipment may impact the sustainability of the warehouse activity and ultimately the supply chain as a whole. Carli et al. (2020) therefore supports the arguments of [I4] and [S3], which highlight energy consumption as a critical factor.

Shevtshenko et al. (2012) in turn researched the design of sustainable material handling equipment. The approach Shevtshenko et al. (2012) took in their research was to make material handling equipment reconfigurable, reusable, and reliable. Stated in the theoretical framework regarding different AS/RS solutions, it is evident that the solutions fulfill the Shevtshenko et al. (2012) approach to a varying degree, therefore, the environmental sustainability becomes a comparable that is possible to distinguish between the different solutions.

The arguments from [I4] and [S3] combined with the literature emphasize the importance of sustainability and ultimately motivate its criticality when selecting a specific warehouse automation solution.

5.1.2.5 Operational expenditures (C5)

Lowering the operational expenditures (OPEX) is a driver for automation. This is argued by [S1] as well as Baker and Halim (2007). For Automotive OEM 2 OPEX constitutes a key performance indicator when selecting between different automated warehouse solutions according to [I3]. This is one of the components that constitutes the business case. [S3] stated that OPEX is a key concern when choosing to automate and often the more long-term consideration.

Ultimately, when investing in an automation solution, the end goal is to make the warehouse operation more efficient and thereby lowering the OPEX. The operation efficiency can be measured in many ways, for example using picking productivity as a KPI as suggested by Kusriani et al. (2018) and also considered by [I2].

5.1.2.6 Capital expenditures (C6)

Investment budget is one of the qualifying factors identified in this study. However even if the price of the solution is within the budget, having a low cost is beneficial for the decision-making company. [S3] stated that investment size constitutes a critical factor when selecting between different warehouse automation solutions. The investment size does not only qualify or disqualify different warehouse automation solutions respectively, but it can also be prioritized differently between different companies present in different contexts. The arguments stated by [S3] highlights investment size as a comparable factor when selecting between different warehouse automation solutions.

In the interview with [S2], the trade-off between OPEX and CAPEX was discussed. Companies commonly wish to lower their OPEX, however, the lowering of OPEX oftentimes comes at the expense of increased CAPEX. [S2] therefore concluded that in order to find the best solution for the specific customer, the customer needs to calculate the total cost of ownership. [S2]'s reasoning of OPEX, CAPEX, and total cost of ownership highlights the financial tradeoffs in the selection of an automation solution.

5.1.2.7 Versatility (C7)

Versatility can be defined as the ability of a solution to be flexible and adaptable in order to effectively handle a wide range of applications, different types of customers, changing industry characteristics, and forthcoming changes.

In the context that [I2] operates within, it is important with generic solutions that can be utilized in a variety of applications, such as different types of articles with different characteristics, e.g., size, weight, shape, and material. According to [I2], a generic solution is important because they need to be able to serve a range of different types of customers, highlighting the importance of versatility.

Versatility was also highlighted in the interview with [I4]. The current systems utilized by [I4] handles pallets of three different sizes, which in turn puts a requirement of flexibility. The automotive industry is also ever-changing, especially due to recent development with emerging electrification. The characteristics of the industry put a requirement of the investments to be able to handle these changes,

i.e., versatility, which therefore becomes a critical factor to consider when e.g., selecting between different warehouse automation solutions.

[15] supported the arguments stated by [14] regarding the ever-changing characteristics of the automotive industry. The investments required for large warehouse automation solutions need to be flexible and versatile enough to withstand changes. However, it is according to [15] difficult to predict the forthcoming changes, and therefore large investments are associated with large risks and are therefore commonly avoided.

In discussions regarding their RCSRS solution, [S1] stated that flexibility (and scalability) of warehouse automation solutions are essential factors that customers consider when selecting between different warehouse automation solutions or configurations. Oftentimes, [S1] with colleagues engage in affairs with customers that are on a growth journey where both flexibility and scalability is important in order to adapt to forthcoming changes. The arguments of [S1] support the aforementioned statements and highlights flexibility, i.e., versatility, as a critical and comparable factor when selecting between different warehouse automation solutions.

5.1.2.8 Robustness (C8)

The final comparable factor that was found in the study is robustness. Depending on the context that the company is in, there is a criticality for robustness of the solution. This includes that the solution has a high uptime, a low fail rate, and can be relied on.

The 3PL that [I2] works at sells a guarantee of capacity and emphasizes the importance of being able to rely on the solution. The 3PL needs a warehouse automation solution that is robust, i.e., as little disruptions as possible, which highlights robustness as a critical factor for the 3PL when selecting between different warehouse automation solutions.

[I3], [I4], and [I5] all work at different companies within the automotive industry, of which all companies utilize takt time production systems. In the interviews, each of the interview respondents highlighted the importance of maintaining the takt time in the production and not disrupt the production of the products due to high associated costs. In regards of the aforementioned, each of [I3], [I4], and [I5] emphasized the uptime reliability, which ultimately is robustness of the warehouse automation system.

In discussion regarding the automotive industry, both [S2] and [S3], argued that the required uptime reliability induced too high risks compared to possible gains for the suppliers to engage in affairs within the automotive industry. Although each of the suppliers were able to provide a high uptime reliability, it is not enough for the automotive industry. The requirement of uptime reliability differs depending on the context of the company and its prioritizations, motivating robustness as a comparable critical factor.

Automated order picking systems can, according to Baker and Halim (2007), improve the reliability, i.e., robustness, of the warehouse activity through improved inventory control. Improved inventory control enables quality warehouse processes, and ultimately strengthens the robustness of the complete system.

Roodenberg and Vis (2018) in turn states that automated order picking systems only constitute one of several systems in the warehouse activity which of all to some extent are interdependent. Since a system is only as strong as its weakest link, it is critical to consider other systems and interfaces when selecting between different warehouse automation solutions to ensure robustness of the warehouse activity.

5.2 Warehouse automation selection framework

The proposed framework utilizes the two types of factors, qualifying and comparable and provides a model where the decision-maker will take all factors into consideration in the selection of a warehouse automation solution. The framework can be used to both identify possible solutions and then assign each solution with a score, based on what factors are important to the decision-maker. The framework is presented in Figure 5.1. The proposed method for the selection of a warehouse automation solution that aligns with the decision-making company's requirements consists of six steps described below.

WAREHOUSE AUTOMATION SELECTION FRAMEWORK								
Qualifying factors	Item characteristics		Investment budget		Size limitations		Warehouse capacity	
Comparable factors	Space utilization $p_1 \times W_1$	Scalability $p_2 \times W_2$	Ergonomics $p_3 \times W_3$	Sustainability $p_4 \times W_4$	CAPEX $p_5 \times W_5$	OPEX $p_6 \times W_6$	Versatility $p_7 \times W_7$	Robustness $p_8 \times W_8$
Total score for a solution	Total score of qualified solution $S = \sum_{i=1}^8 p_i \times W_i$							

Figure 5.1: The proposed framework. The figure visualizes all components and how to evaluate a warehouse automation solution. This includes qualifying factors, comparable factors, weights of the factors, and how to summarize the total score.

Step 1: Identify what solutions are available in the market. In chapter 2.4.3 a list of AS/RS solutions is presented and can be used as a foundation. However, due to the objectivity of the study, the framework does not suggest any specific solutions and leaves this to the decision-maker to select. A set of n solutions (t_1, \dots, t_n) are selected.

Step 2: Using the qualifying factors Q1-Q4 the decision-maker needs to set the requirements of the solution and then evaluate if the solutions identified meet the qualifying requirements. The solutions that are qualified are used in the final comparison. The solutions that are not qualified are removed from the comparison. There are now a set of m solutions (t_1, \dots, t_m) to consider where $m \leq n$. If $m = 1$ no further steps are needed, the appropriate solution is then found.

Step 3: The decision-maker will then use the BWM-method to decide the weights (W_1, \dots, W_8) of the comparable factors C1-C8. The method is described step by step in chapter 3.5.

Step 4: The remaining set of m solutions (t_1, \dots, t_m), are then assigned a performance score (p) for each comparable factor. The simple MCDM-matrix proposed by Rezaei (2015) will be filled in with performance scores (p) for each solution (t) and criteria (C).

$$C_1 \quad C_2 \quad \dots \quad C_8 \text{MCDM-matrix} = \begin{matrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{matrix} \begin{pmatrix} p_{11} & p_{21} & \dots & p_{81} \\ p_{12} & p_{22} & \dots & p_{82} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1m} & p_{2m} & \dots & p_{8m} \end{pmatrix}$$

Step 5: For every solution (t) the total score (S) is set by multiplying the performance score (p) with the factor weight (W) accordingly:

$$S_j = \sum_{i=1}^8 p_{ij} \times W_i$$

Step 6: The set of total scores (S_1, \dots, S_m) can now be compared and the solution with the highest total score can be decided as the most favorable solution.

$$\text{The selected solution} = \text{Max}(S_1, \dots, S_m)$$

6. Discussion

In this chapter, a discussion is held regarding the study. Initially, in chapter 6.1, a discussion regarding the content of the framework is conducted. Secondly, in chapter 6.2, an overview of the criticisms against the study's methodology is presented. In chapter 6.3 the framework is presented in a general application, and finally in chapter 6.4 the study's contributions to research are discussed.

6.1 Discussion of the framework

The proposed framework can be used as a decision support in the selection of a warehouse automation solution. The aim of the framework development was to provide a simple and easily understandable framework that takes a comprehensive perspective on the potential factors that will influence the decision-maker. By utilizing the best-worst method for multi-criteria decision-making, which is the proposed method for evaluating different warehouse automation solutions in the framework, the authors have provided each decision-maker with the opportunity to assign points to the warehouse automation solutions themselves. By allowing the decision-makers to assign points to the warehouse automation solutions that are to be evaluated, the authors enable each decision-maker to consider their own context, requirements, and preconditions in terms of available warehouse automation solutions. Without taking these factors into account, decision-makers may end up selecting a solution that does not meet their specific requirements. This can lead to costly mistakes and potentially negative impacts on operations. Decision-makers should take the time to thoroughly assess their needs and evaluate each solution against these needs to ensure the best possible outcome.

By proposing the best-worst method for multi-criteria decision-making, the authors enable deeper analysis of the critical factors. Deeper analysis of critical factors can be done according Rezaei (2015), which includes dividing comparable factors into subfactors. This allows the decision-makers to specify specific and individual requirements and criteria, enabling prioritization on a deeper level, which facilitates more rigorous and correct evaluation of warehouse automation solutions based on the context of each specific company. The framework is flexible as well and more or less factors can be used if the specific context requires.

The study has multiple times identified that in the context of the automotive industry, where the production system is based on takt time and just-in-time deliveries, automation is not an obvious choice. All the respondents working in the automotive industry as well as the supplier respondents stated that the automotive industry has very high demands on the robustness of the solution, and that in many cases automation is ruled out due to this factor. In this context where a stop in the production is so expensive that automation solution suppliers are not able to take on the risk, the comparable factor robustness (C8) becomes a qualifying factor where only solutions with a threshold promised uptime are a possible option.

6.2 Research methodology criticism

Regarding the qualifying and comparable critical factors, the authors of this study highlights that these critical factors were, however supported by literature, identified by interviewing a few select companies. This small sample size could have introduced biases from the respondents, potentially undermining the reliability and validity of the proposed framework. Especially since among the interview respondents representing the industry, there is a large representation of respondents working within the automotive industry, which ultimately can influence the conclusions of the study. A more robust approach would be to conduct further research with a larger and more diverse group of industry representatives to ensure the scientific rigor and generalizability of the findings.

Three supplier respondents were interviewed during the study, which of all works for companies selling warehouse automation systems. Their responses could therefore be skewed towards highlighting features and factors that are in line with the products they are selling. However, with the use of anonymization no commercial attention was given to the suppliers of warehouse automation solutions.

It was as well evident that all interview respondents across industries shared the same views and were aligned on the subject of matter. The alignment between industries supports the validity of the identified critical factors and framework which enables a wide adoption of the study's conclusions.

In the start of the study, the authors believed that the digital integration between the warehouse automation solution and the companies WMS would be a factor that would be taken more into consideration by the respondents. Surprisingly, this was not more than briefly mentioned in the data gathering. However, it was not directly asked about and could be a factor that is critical, but that it is not the professional focus area of the respondents. This highlights that a more hypothesis-driven approach could potentially be applied to achieve further insights.

The argument to use the BWM-method is to simplify and make the framework more user-friendly and having a high consistency. There are, however, many other methods to weigh the factors and if the user prefers another method, this can be used. For example, the Analytic Hierarchy Process (AHP) is another popular method that could be used to evaluate warehouse automation solutions. AHP involves breaking down a decision into a hierarchy of factors and then assigning weights to each factor based on its relative importance. While AHP may be more complex than the best-worst method, it may offer more detailed insights into the decision-making process.

6.3 Using the proposed framework in a general setting

While the critical factors identified in this study may be specific to the selection of a warehouse automation solution, the framework itself could potentially be applied to other decisions, either regarding other equipment purchases or completely other decisions. However, modifications would likely need to be made to account for differences in critical factors and decision-making criteria. A generic version of the framework is visualized in Figure 6.1.

SELECTION FRAMEWORK				
Qualifying factors	Qualifier 1	Qualifier i	Qualifier j	Qualifier n
Comparable factors	Comparable 1 $p_1 \times W_1$	Comparable i $p_i \times W_i$	Comparable j $p_j \times W_j$	Comparable n $p_n \times W_n$
Total score for a solution	Total score of qualified solution $S = \sum_{i=1}^n p_i \times W_i$			

Figure 6.1: A visualization of a generic version of the proposed selection framework, as proposed by the authors.

When utilizing the generic selection framework, there are certain prerequisites that need to be fulfilled in order for the framework to be applicable. Firstly, there have to be several (more than one) different options to select from for the framework to actually be useful. Secondly, qualifying factors need to be identified. Qualifying factors are factors highlighting contextual limitations that determine feasible solutions for the company. In the next step, comparable factors need to be identified. Comparable factors are factors where the importance of each factor will differ between companies depending on the context. In the final step a multi-criteria decision-making method, BWM is proposed since it is a simple and user-friendly method, is to be utilized to determine and evaluate the total score of each solution, with the ultimate purpose of supporting the decision-maker in their decisions.

6.4 Research contributions

While the framework is meant to be used as a practical guide for the industry, it can also contribute to research in the subject of warehouse automation. The main contributions that the framework provides are the differentiation between qualifying- and comparable factors as well as the suggestion of using BWM to

assign weights to the comparable factors and thereby creating a framework that is easy to use. Two master theses were found investigating the selection process of warehouse automation solutions, namely Döllinger and Larsson (2017) as well as Novara (2020). Döllinger and Larsson (2017) selected critical factors and evaluated the different solutions based on these, however, compared to the proposed framework in this study, the factors were not weighted and there were no qualifying factors considered. Novara (2020) did select critical factors as well and assigned weights to the factors using MCDM, however, using AHP as the weight's method. The solution presented by Novara (2020) is similar to that of this study, however, without the consideration of qualifying factors.

7. Conclusions and future research

The purpose of this research is to identify the critical factors when selecting a warehouse automation solution, and the factors will be utilized in the development of a decision-making framework. The framework aims to direct decision-makers toward the physical automation solutions that align with their requirements.

Critical factors were identified in the theoretical framework and empirical data, which was conducted with semi-structured interviews with three suppliers of warehouse automation solutions as well as five interviews with companies representing the industry. In the analysis, and ultimately in the proposed framework, the study distinguishes between qualifying critical factors and comparable critical factors. The four qualifying critical factors identified are item characteristics, investment budget, warehouse size limitations, and warehouse capacities. The eight comparable critical factors are space utilization, scalability, ergonomics, sustainability, capital expenditures, operational expenditures, versatility, and robustness.

The proposed utilization of the framework includes the best-worst method for multi-criteria decision-making, which is a simple and straightforward method for prioritizing and distinguishing between different critical factors with few comparisons. The proposed framework and method, including the identified critical factors, offers decision-makers guidance when selecting between different warehouse automation solutions, which ultimately, was the purpose of the study.

However, it is possible to strengthen the validity of the framework with future research. The proposed future research includes investigating possible subfactors of the comparable critical factors. With the proposed best-worst methods for multi-criteria decision-making, the authors have allowed for deeper and exhaustive analysis of each factor, which ultimately, can facilitate comprehensive guidance when selecting between different warehouse automation solutions.

The study's findings on critical factors for selecting warehouse automation solutions have important implications for the industry. With the increasing demand for fast and efficient fulfillment processes, warehouse automation solutions are becoming more prevalent. However, selecting the most appropriate solution can be a complex process with multiple considerations. The framework developed in this study supports decision-makers when conducting the complex process of performing multiple considerations, enabling productive selection of warehouse automation solution.

References

- AFS 2012:2. *Arbetsmiljöverkets föreskrifter och allmänna råd om belastningsergonomi*. Arbetsmiljöverket. <https://www.av.se/globalassets/filer/publikationer/foreskrifter/belastningsergonomi-foreskrifter-afs2012-2.pdf>
- Azadeh, K., De Koster, R. & Roy, D. (2019). Robotized and Automated Warehouse Systems: Review and Recent developments. *Transportation Science* 53(4), pp. 917-945.
- Baker, P. & Halim, Z. (2007). An exploration of warehouse automation implementations: cost, service and flexibility issues. *Supply Chain Management: An International Journal* 12(2), pp. 129-138. DOI 10.1108/13598540710737316.
- Blomkvist, P., & Hallin, A. (2015). *Method for Engineering Students* (UK ed.). Studentlitteratur AB.
- Brewer, A. M., Button, K. J., & Hensher, D. A. (2001). *Handbook of Logistics and Supply-Chain Management*. Elsevier.
- Buley, D., & Knott, K. (1986). Designing vertical carousels to maximize operator utilization. *Computers & Industrial Engineering*. [https://doi.org/10.1016/0360-8352\(86\)90092-6](https://doi.org/10.1016/0360-8352(86)90092-6)
- Calzavara, M., Sgarbossa, F. & Persona, A. (2019). Vertical Lift Modules for small items order picking: an economic evaluation. *International Journal of Production Economics*, 210, pp. 199-210. <https://doi.org/10.1016/j.ijpe.2019.01.012>
- Cano, J. A., Correa-Espinal, A. A., & Montoya, R. a. G. (2017). An evaluation of picking routing policies to improve warehouse efficiency. *Industrial Engineering and Management*, 229–238. <https://investigaciones-pure.udem.edu.co/es/publications/an-evaluation-of-picking-routing-policies-to-improve-warehouse-ef>
- Caputo, A. C., & Pelagagge, P. M. (2008). Capacity upgrade criteria of large-intensive material handling and storage systems: a case study. *Journal of Manufacturing Technology Management*, 19(8), 953–978. <https://doi.org/10.1108/17410380810911727>
- Carli, R., Digiesi, S., Dotoli, M., & Facchini, F. (2020). A Control Strategy for Smart Energy Charging of Warehouse Material Handling Equipment. *Procedia Manufacturing*, 42, 503–510. <https://doi.org/10.1016/j.promfg.2020.02.041>
- Cooksey, D. (1986). Comparison of conventional and automated refrigerated storage systems. *International Journal of Refrigeration-Revue Internationale Du Froid*, 9(2), pp. 99–104. [https://doi.org/10.1016/0140-7007\(86\)90041-1](https://doi.org/10.1016/0140-7007(86)90041-1)
- de Koster, R., Le-Duc, T. & Roodbergen, K.J. (2007). Design and control of warehouse order picking: A literature review. *European Journal of Operational Research* 182, pp. 481-501.
- Đukić, G., Opetuk, T., & Gajšek, B. (2020). Space, Time and Ergonomic Assessment of Order Picking Using Horizontal Carousel. *Advances in Intelligent Systems and Computing*. https://doi.org/10.1007/978-3-030-66937-9_9
- Đukić, G., Opetuk, T., & Lerher, T. (2015). A throughput model for a dual-tray Vertical Lift Module with a human order-picker. *International Journal of Production Economics*, 170, 874–881. <https://doi.org/10.1016/j.ijpe.2015.04.009>
- Döllinger, A., & Larsson, T. (2016). *Selection of Automated Order Picking Systems-Automated Storage and Retrieval Systems within Contract Logistics*. (Master's thesis, Chalmers University of Technology,

Gothenburg, Sweden). Retrieved from <https://odr.chalmers.se/items/d591b5c5-9895-4eba-93ac-9b12fec22baf>

Gruchmann, T., Mies, A., Neukirchen, T., & Gold, S. M. (2021). Tensions in sustainable warehousing: including the blue-collar perspective on automation and ergonomic workplace design. *Journal of Business Economics*, 91(2), 151–178. <https://doi.org/10.1007/s11573-020-00991-1>

Gu, J., Goetschalckx, M., & McGinnis, L. F. (2007). Research on warehouse operation: A comprehensive review. *European Journal of Operational Research*, 177(1), 1–21. <https://doi.org/10.1016/j.ejor.2006.02.025>

Gu, J., Goetschalckx, M., & McGinnis, L. F. (2010). Research on warehouse design and performance evaluation: A comprehensive review. *European Journal of Operational Research*, 203(3), 539–549. <https://doi.org/10.1016/j.ejor.2009.07.031>

Haghsheno, S., Binnering, M., Dlouhy, J. and Sterlike, S. (2016). History and Theoretical Foundations of Takt Planning and Takt Control. In: Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction, Boston, MA, USA, sect.1 pp. 53–62.

Hamberg, R., & Verriet, J. (2011). *Automation in Warehouse Development*. Springer Publishing.

Hanson, R., & Brodin, A. (2013). A comparison of kitting and continuous supply in in-plant materials supply. *International Journal of Production Research*, 51(4), 979–992. <https://doi.org/10.1080/00207543.2012.657806>

Hanson, R., & Medbo, L. (2019). Man-hour efficiency of manual kit preparation in the materials supply to mass-customised assembly. *International Journal of Production Research*, 57(11), 3735–3747. <https://doi.org/10.1080/00207543.2019.1566653>

Hanson, R., Medbo, L., & Johansson, M. (2018). Performance Characteristics of Robotic Mobile Fulfillment Systems in Order Picking Applications. *IFAC-PapersOnLine*, 51(11), 1493–1498. <https://doi.org/10.1016/j.ifacol.2018.08.290>.

Hashemi-Petroodi, S. E., Thevenin, S., Kovalev, S., & Dolgui, A. (2020). Operations management issues in design and control of hybrid human-robot collaborative manufacturing systems: a survey. *Annual Reviews in Control*, 49, 264–276. <https://doi.org/10.1016/j.arcontrol.2020.04.009>.

Hausman, W. H., Schwarz, L. B., & Graves, S. E. (1976). Optimal Storage Assignment in Automatic Warehousing Systems. *Management Science*, 22(6), 629–638. <https://doi.org/10.1287/mnsc.22.6.629>.

Higginson, J. K., & Bookbinder, J. H. (2005). *Distribution Centres in Supply Chain Operations*. Springer eBooks, 67–91. https://doi.org/10.1007/0-387-24977-x_3.

Ho, Y. C., Su, T., & Shi, Z. (2008). Order-batching methods for an order-picking warehouse with two cross aisles. *Computers & Industrial Engineering*, 55(2), 321–347. <https://doi.org/10.1016/j.cie.2007.12.018>.

İyigün, I. & Görçün, Ö. F. (2022). In *Accounting, finance, sustainability, governance & fraud*. Springer, Singapore. <https://doi.org/10.1007/978-981-16-5644-6>

Jaghbeer, Y., Hanson, R., & Johansson, M. (2020). Automated order picking systems and the links between design and performance: a systematic literature review. *International Journal of Production Research*, 58(15), 4489–4505. <https://doi.org/10.1080/00207543.2020.1788734>.

Jonsson, P., & Mattsson, S-A. (2019). *Logistik: Läran om effektiva materialflöden* (3rd edition). Studentlitteratur.

- Kusrini, E. Novendri, F. & Vembri Noor, H. (2018). Determining key performance indicators for warehouse performance measurement – a case study in construction materials warehouse. *MATEC Web Conference* 154. <https://doi.org/10.1051/mateconf/201815401058>.
- Lamballais, T., Pardalos, P. M., & De Koster, R. (2017). Estimating performance in a Robotic Mobile Fulfillment System. *European Journal of Operational Research*, 256(3), 976–990. <https://doi.org/10.1016/j.ejor.2016.06.063>.
- Lerher, T., Edl, M., & Rosi, B. (2014). Energy efficiency model for the mini-load automated storage and retrieval systems. *The International Journal of Advanced Manufacturing Technology*, 70(1–4), 97–115. <https://doi.org/10.1007/s00170-013-5253-x>
- Liang, F. (2021). Best-Worst Method: Inconsistency, Uncertainty, Consensus, and Range Sensitivity. <https://doi.org/10.4233/uuid:0fd5201c-09cd-46e1-899c-47c0d9ad1f6b>.
- Malmberg, C. J. (1996). Storage assignment policy tradeoffs. *International Journal of Production Research*, 34(2), 363–378. <https://doi.org/10.1080/00207549608904908>.
- Marchet, G., Melacini, M., & Perotti, S. (2015). Investigating order picking system adoption: a case-study-based approach. *International Journal of Logistics*, 18(1), 82–98. <https://doi.org/10.1080/13675567.2014.945400>.
- Novara, V. (2020). A New Decision-Making Tool for Automated Industrial Storage Systems Selection. [Master's thesis, Politecnico Di Torino].
- Oxford English Dictionary. (2023). “Critical.” Retrieved from: <https://www.oed.com/view/Entry/44592>.
- Park, B. C., Park, J. Y. & Foley, R. D. (2003). Carousel System Performance. *Journal of applied probability*, 40, pp. 602-612.
- Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, 53, 49–57. <https://doi.org/10.1016/j.omega.2014.11.009>
- Roodenberg, K. J. & Vis, I. F.A. (2008). A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research* 194(2009), pp. 343-362
- Rushton, A., Croucher, P., & Baker, P. (2022). *The Handbook of Logistics and Distribution Management: Understanding the Supply Chain*. Kogan Page.
- Shevtshenko, E., Bashkite, V., Maleki, M., & Wang, Y. (2012). SUSTAINABLE DESIGN OF MATERIAL HANDLING EQUIPMENT: A WIN-WIN APPROACH FOR MANUFACTURERS AND CUSTOMERS. *Mechanika*, 18(5). <https://doi.org/10.5755/j01.mech.18.5.2703>
- Takakuwa, S. (1996). Efficient module-based modeling for a large-scale AS/RS-AGV system. *Proceedings of the 1996 Winter Simulation Conference*.
- Tan, K., Ahmed, M. D., & Sundaram, D. (2009). Sustainable warehouse management. In *Proceedings of the International Workshop on Enterprises & Organizational Modeling and Simulation*. <https://doi.org/10.1145/1750405.1750415>
- Tutam, M. (2021). Warehousing 4.0 in Logistics 4.0. *Accounting, Finance, Sustainability, Governance & Fraud*, 95–118. https://doi.org/10.1007/978-981-16-5644-6_7

Van Gils, T. Ramaekers, K., Caris, A. & de Koster, R. (2018). Design efficient order picking systems by combining planning problems: State-of-the-art classification and review. *European Journal of Operational Research* 267, pp. 1-15.

Wholey, J. S., Hatry, H. P., & Newcomer, K. E. (2010). *Handbook of Practical Program Evaluation*. John Wiley & Sons.

Yong, H. N. A. (2009). Warehouse Management System and Business Performance: Case Study of a Regional Distribution Centre. International Conference on Computing and Informatics (ICOCI 2009).

Yu, M., & De Koster, R. (2009). The impact of order batching and picking area zoning on order picking system performance. *European Journal of Operational Research*, 198(2), 480–490. <https://doi.org/10.1016/j.ejor.2008.09.011>

Zou, B., De Koster, R., & Xu, X. (2018). Operating Policies in Robotic Compact Storage and Retrieval Systems. *Transportation Science*, 52(4), 788-811. <https://doi.org/10.1287/trsc.2017.0786>

Zrnica, D. S., Čuprić, N., & Radenković, B. (1992). A study of material flow systems (input/output) in high-bay warehouses. *International Journal of Production Research*, 30(9), pp, 2137–2149. <https://doi.org/10.1080/00207549208948141c>

Appendix A: Industry interview framework

	Questions
Introduktion	<p>Presentation av författarna</p> <p>Presentation av arbetets syfte</p> <p>Vi ber respondenten presentera sig och dess roll</p> <p>Praktisk information</p>
State	
As-Is	<p>Berätta om [Företag], hur ser automatiseringen av lager ut hos er?</p> <p>Vad har ni valt att automatisera?</p> <p>Berätta om lagret, vilken roll i försörjningskedjan har det?</p> <p>Varför har ni valt att automatisera? Varför just det lagret? Den typen av lager?</p> <p>Varför valde in den lösningen?</p> <p>Fanns det andra alternativ som ni övervägde? Varför valde ni bort dem?</p> <p>Vilka produkter lämpar sig bäst att automatisera för er?</p> <p>Vilka faktorer var viktiga när ni valde just den lösningen?</p> <p>Vad har den automatiserade lösningen resultat i? Hur har den förbättrat försämrat era processer? Vilka begränsningar har den automatiserade lösningen?</p> <p>Hur kombinerar ni automatiserat och manuellt lager? Vad är fortfarande manuellt och varför?</p> <p>Om det är så att ni inte har automatiserat, varför?</p> <p>Vad är showstopper för automatisering?</p> <p>Har ni testat automation och gått ifrån det? Varför?</p> <p>Om ni övervägt att automatisera men inte gjort det, vilka lösningar kollade ni på då?</p> <p>Vad var anledningen till att ni beslutade att inte gå vidare?</p>
To-Be	<p>Har ni planer på att automatisera något lager?</p> <p>Vilka lösningar kollar ni på?</p> <p>Varför just de lösningarna?</p> <p>Vad är för- respektive nackdelar med de lösningarna?</p> <p>Vilka faktorer är viktiga när ni väljer lösningar?</p> <p>Vad har ni för inställning/strategi gällande automatisering?</p> <p>Vilka faktorer driver er mot/från automatisering?</p> <p>Hur ser ni på automatiseringens roll i framtiden?</p>
Avslut	<p>Finns det något vi missat i dagens diskussion som du önskar att lägga till?</p> <p>Vet du någon som kan hjälpa oss få mer information?</p> <p>Har ni möjlighet att svara på eventuell enkät framgent? Cirka 20 minuter?</p>

Appendix B: Automation supplier interview framework

	Frågor
Introduktion	Presentation av författarna Presentation av arbetets syfte Vi ber respondenten presentera sig och dess roll Vi ber om tillstånd att spela in intervjun med ljud Praktisk information
Arbetsätt	Vi har sett att ni erbjuder Autostore som lösning. Är det någon lösning som ni erbjuder som vi missat? Hur går det till när era kunder väljer system? Hur stöttar ni i det valet? Använder ni er av någon form av ramverk för att undersöka kundernas kravställning? Hade det varit intressant för er att ha ett sådant? Vilka faktorer är viktiga när kunder väljer system? Skiljer det sig mellan industrier? Vilken information är viktig att få från kunder? Vilka industrier jobbar ni mest mot? Vilka typer av lager jobbar ni mest mot? Demand-driven, supply-driven?
Avslut	Finns det något vi missat i dagens diskussion som du önskar att lägga till? Har du/ni möjlighet att svara på eventuella enkäter framgent? Cirka 20 minuter?

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY