CRANFIELD UNIVERSITY

Alp YILDIRIM

MOBILE ROBOT AUTOMATION IN WAREHOUSES

SCHOOL OF MANAGEMENT
PhD in Leadership and Management

Doctor of Philosophy
Academic Year: 2019 - 2022

Supervisor: Dr Hendrik Reefke
Associate Supervisor: Prof Emel Aktas
Dec 2022

CRANFIELD UNIVERSITY

SCHOOL OF MANAGEMENT
PhD in Leadership and Management

Doctor of Philosophy

Academic Year 2019 - 2022

Alp YILDIRIM

MOBILE ROBOT AUTOMATION IN WAREHOUSES

Supervisor: Dr Hendrik Reefke
Associate Supervisor: Prof Emel Aktas
Dec 2022

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Mobile robot systems are an automation solution in warehouses that make order fulfilment agile, flexible, and scalable to cope with customer orders' increasing volumes and complexities. Compared with manual operations, they combine higher productivity and throughput with lower operating costs. As the practical use of mobile robot systems increases, decision-makers are confronted with a plethora of decisions, but research is lagging in providing the needed academic insights and managerial guidance on the adoption and deployment of this novel technology. This PhD thesis aims to explain the mobile robot system implementation journey by conducting a mixed methods approach through three independent but interconnected papers. Paper 1 is based on a systematic literature review involving 107 papers from the literature. Paper 2 is a continuation of the systematic literature review to identify and evaluate available mobile robot systems in the market. It also offers mobile robot system selection approaches using the insights of five supply chain experts. Paper 3 is a multiple-case study involving four logistics functions from different countries.

This thesis lists the potential motivations to adopt mobile robot systems. It offers multiple approaches to selecting an appropriate mobile robot system. It also provides a comprehensive adoption framework that elaborates on innovation diffusion theory and explains the entire mobile robot system adoption journey. Devising the phases of the mobile robot system adoption journey and categorising thirteen managerial decisions and nineteen contextual factors, this study offers guidance to supply chain managers and decision-makers.

Keywords:

supply chain management, case study, innovation adoption, automated guided vehicles, autonomous mobile robots, full-consistency method (FUCOM), innovation diffusion theory, technology-organisation-environment (TOE) framework

ACKNOWLEDGEMENTS

I was able to complete this thesis thanks to a lot of people. My dear super supervisors; Dr Hendrik Reefke and Prof Emel Aktas, greatest thanks to you for your patient guidance and endless support. You were not only the experts for me but also two of my closest friends. I am very very lucky to have you two on this challenging journey.

I would also like to thank some of the valuable people I met in the School of Management. Thank you, my case study teacher; Dr Heather Skipworth, for being such a supportive, helpful, and kind panel chair. Dr Soroosh Saghiri and Dr Abhijeet Ghadge, thank you for your valuable and constructive feedback. I cannot count all the names but thank you Prof Michael Bourlakis, Dr Hamid Moradlou, Debbie Bramwell, Lynne Wall, and Mary Betts-Gray for your help and support. Thank you Dr Carl-Christian Kühl for our valuable discussions and for being one of my closest friends during my time in the UK. Finally, thank you Cohort 19! I am hoping to stay in touch with all of you.

Collecting data during Covid-19 was not easy. Therefore, I am grateful to the practitioners involved in my study. I hope I was able to help you too in some ways.

Thank you Dr Berkcan Uyan. I would not be writing these lines if you had not sent me the application link for this PhD. You opened up your place, took me wherever I needed, and your family became my family in the UK in these three years.

I have whined to many of my friends about this thesis. I cannot count all of them, but here is my top five that suffered the most (alphabetical): Çağlar Saka, Halil Ertuğrul, Semih Danış, Toğrul Tağızade, Yiğit Gürbüz. I am grateful to each and every friend I have as all of them encouraged me in different ways.

Finally, my special thanks go to my dear large family who is always there for me. My wife Zeynep, I love you for many reasons and could not have wished for a better partner. My dearest dog and cat, Sortie and Mümtaz, I will not get bored petting you. My parents, Birol and Sibel, thank you for raising me. I am who I am because of you. İlter; my brother, blood of my blood. Also, I cannot thank you more my in-laws; Şuayip, Korel, Emine, and Can.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
APMS	Advances in Production Management Systems
AS/RS	Automated Storage and Retrieval System
CEO	Chief Executive Officer
Co-bot	Collaborative Robot
e-SCM	Electronic Supply Chain Management
EURO	European Operational Research Societies
FUCOM	Full Consistency Method
G2P	Goods-to-Picker
IDT	Innovation Diffusion Theory
KPI	Key Performance Indicator
LRN	Logistics Research Network
MCDM	Multi-Criteria Decision-Making
MRS	Mobile Robot System
P2G	Picker-to-Goods
R2G	Robots-to-Goods
SCM	Supply Chain Management
SKU	Stock Keeping Unit
SLR	Systematic Literature Review
TAD	Technology Access Decision
TAM	Technology Acceptance Model
TOE	Technology-Organisation-Environment
UK	United Kingdom
UTAUT	Unified Theory of Acceptance and Use of Technology

1 Introduction

Fulfilling customers’ orders swiftly and efficiently whilst managing the increasing complexity and variability of these orders is an ongoing challenge in warehouses. Especially with the effect of the e-commerce era, warehouse operations in many retail sectors such as consumer electronics, clothing and footwear, grocery, or pharmaceuticals got more complicated for a number of alterations in demand characteristics as follows.

- **Order structures:** Customers prefer ordering fewer order lines to benefit from the competitive supply chain environment (free deliveries). In Germany, Amazon warehouses have an average of 1.6 products per order (Boysen et al., 2017).
- **Product variety:** On top of having few order lines in a single order; led by the introduction of digital stores, product assortments have increased to attract more customers (Boysen et al., 2019).
- **Lead times:** Customers expect to receive their orders the next day or even on the same day which also ignited a lot of studies on distribution centre locations and/or delivery optimisations (e.g., Rai et al., 2019; Voccia et al., 2017; Yaman et al., 2012).
- **Demand variations:** The demand is volatile. It can decrease with supply chain disruptions such as chip shortages (J.P. Morgan Research, 2022), or increase by up to fivefold in revenue on special retail days such as Black Friday (Adobe Analytics, 2019).

To address this increased complexity of demand, warehousing people started investigating their bottlenecks to optimise their operations. Bartholdi and Hackman (2019) define warehousing processes based on the direction of physical flows: inbound and outbound. Inbound operations consist mainly of receiving, put-away, and storage, whereas outbound processes include picking, packing, and shipping. Frazelle (2016) includes sortation as a main outbound activity of warehouses, whereas Rushton et al. (2014) consider replenishment as well (Figure 1-1). Among these operations; order picking, which is the process of removing items from storage to shipping to meet a specific demand, is generally the main operation that influences the design of a warehouse (Frazelle, 2016). The order picking phase may account for 50-55% of the total operating costs of manually operated warehouses (Bartholdi and Hackman, 2019; De Koster et al., 2007; Rushton et al., 2014). This high percentage is primarily due to the amount of time lost by pickers walking within the warehouse, looking for the necessary products to pick (Boysen et al., 2019). This horizontal and manual travelling activity takes around 55% of the picker's total time (Frazelle, 2016).

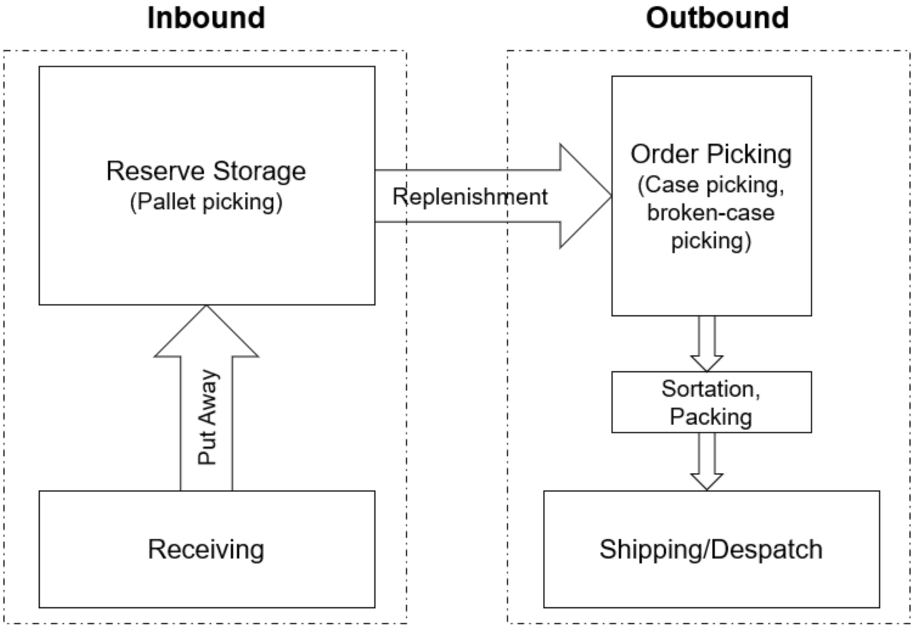


Figure 1-1 Warehouse operations

The complex nature of demands and operational bottlenecks mentioned above, caused warehouses to receive increasing attention from both academia and practice over the past few decades. Ultimately, warehouses have changed substantially with many new storage and handling systems. Companies have been re-engineering their warehouse operations towards automated and optimised fulfilment systems. As a horizontal automation solution, mobile robot automation systems were developed from 1950 onwards to eliminate the unproductive travelling time of human workers. Cambridge Dictionary (n.d.) defines a robot as: 'a machine controlled by a computer that is used to perform jobs automatically'. Similarly, an unpersonned mobile robot is a mobile version of a robot. The first unpersonned mobile robot automation is the well-known automated guided vehicles (AGVs). Since 2006, autonomous mobile robots (AMRs) have become an alternative to AGVs, offering more flexible and scalable solutions (Wurman et al., 2008). These robots have onboard intelligence helping them decide whether to slow down or stop and where to go next (Kattepur et al., 2018). They can map the environment, plan their paths, dynamically respond to their surroundings, and bypass an obstacle without being remotely controlled (Horňáková et al., 2019). These functions make AMRs more flexible and suitable than AGVs for chaotic and complicated warehouse settings such as e-commerce.

1.1 Research Motivation

Amazon, one of the most successful e-commerce companies, automated fulfilling e-commerce orders in their warehouses with AMRs by acquiring Kiva Systems in 2012. Alibaba, Ocado, and JD.com are among the first companies that followed the warehouse automation move. With this shift in order picking operations, Amazon has cut its operational warehouse costs by 20% and saved $22 million per annum in picking costs for each of its fulfilment centres (Bogue, 2016). They achieved this saving through AMRs that bring shelves full of various items to the pickers while pickers stay in the packing station to prepare orders from items brought to them (Wurman et al., 2008).

Owing to the automation successes of early adopters, mobile robot adoption in warehouses had a spectacular boost. Grey Orange, Geek+, IAM Robotics, 6 River Systems, Magazino, and many other start-up companies are developing autonomous mobile robots for warehouses. Industry forecasts estimate that more than 50,000 warehouses, up from 4,000 warehouses in 2018, will be using over 4 million mobile robots globally by 2025 (ABI Research, 2019).

Although mobile robot systems seem quite promising, it is a very recent topic that drew attention from 2005 onwards. On top of that, 80% of the warehouses are fully manual even without basic automation, such as conveyors (Benady, 2016). These two points have led me to conduct an initial literature review on the subject.

The initial literature review showed that the mobile robots, mobile robot systems, and managerial decision areas in the warehouse context are fragmented. There were reviews (Le-Ahn et al., 2006; Vis, 2006) mentioning AGVs but most of them were technology-oriented and had fragmented managerial focus. Further, as some of these reviews are outdated for such a fast-moving subject, it would be beneficial to conduct a systematic literature review before an empirical work to cover the current literature and organise all the managerial decisions under one roof.

During the literature review, it became evident that, apart from a few studies (e.g., Azadeh et al., 2019; Boysen et al., 2019; Wior et al., 2018), none of the reviews attempted (the reviews mentioned here include some mobile robot systems in a larger automation focus) on categorising and evaluating available mobile robot systems which would have a crucial practical output. Such highly productive systems require a rationale, alongside a set of evaluation criteria, for system selection to justify the capital investment associated with automation (Azadeh et al., 2019). Therefore, it is evident that an empirical study is necessary to offer potential system selection approaches.

More importantly, all of these reviews, that the researcher came across, were calling researchers to action for further empirical studies that would aid the adoption of MRS from different angles. This is also because we still are in the ‘early adopters’ stage for MRS innovation (Rogers, 2003), and we should be laying out the experience of early adopters for late comers; helping them to create a feasible, efficient, and comprehensive implementation strategy.

There are lots of studies concentrating on innovation adoption in supply chain management (SCM). However, the main focus is on information systems (IS) technologies such as blockchain, big data analytics, and cloud computing. Mobile robots have received very little attention and thus empirical research (Hofmann et al., 2019). Moreover, there is a lack of a tailored MRS adoption framework that would aid decision-makers in the integration and implementation of warehouse mobile robot systems. Previous studies that have been conducted, fails to integrate managerial decisions, and mainly took a mathematical optimisation perspective of a particular MRS. Providing a fragmented list of managerial decisions, the reviews on mobile robots are not focused on the process of innovation diffusion (Table 1-1). One of the studies concentrates on the adoption journey (process) but approaches to the journey in the healthcare context (Benzidia et al., 2019). Shamout et al. (2022) concentrate on MRS adoption but only focus on the factors affecting the decision to adopt such technologies rather than the implementation journey as a whole. Also, this work mentions contextual factors and is among a few, leaving the factors and their effect on MRS implementation only partially explained.

Overall, an adoption framework offered in mobile robot industry need to support the decisions, factors, and steps across the MRS adoption journey in warehouses as highlighted in Table 1-1. However, current state-of-the-art is fragmented and falls short towards creating such frameworks. To help creating an efficient and beneficial implementation environment, this thesis addresses these gaps in the literature and includes the necessary aspects of the MRS adoption journey through a paper-based structure. The following section explains the overall research aim and objectives that are targeted to fulfil the aim.

Table 1-1 Overview of MRS in warehousing literature

Focus on…	*MRS in Warehousing*	*Managerial Decisions*	*MRS Adoption Decision*	*MRS Adoption Process*	*Factors Affecting MRS Adoption*
Fazlollahtabar and Saidi-Mehrabad, 2015; Lamballais et al., 2017; Merschformann et al., 2019; Roy et al., 2019; Vivaldini et al., 2015	✓				
Bechtsis et al., 2017; Fragapane et al., 2021; Jaghbeer et al., 2020; Le-Anh and De Koster, 2006; Vis, 2006	✓	✓			
Benzidia et al., 2019				✓	
Shamout et al., 2022	✓		✓		✓

1.2 Research Aim and Objectives

This PhD thesis aims to shed light on the entire MRS adoption journey in warehouses. It includes the motivation of warehouse managers to adopt such systems and also examines the implementation journey of these automation solutions (Figure 1-2). This study uses a mixed method approach, as it employs both qualitative and quantitative methods to collect and analyse data (Tashakkori and Creswell, 2007). There are three research objectives:

1) To systematically review and categorise the managerial decisions that warehouse managers need to consider from the extant literature.
2) To identify, categorise, and evaluate MRS from the extant literature and investigate potential system selection approaches.
3) To empirically investigate the MRS adoption journey and elaborate on the literature about the managerial decisions and factors affecting the MRS adoption journey.

Table 1-2 provides a summary of these objectives, relating them to their respective chapters, research methods, and key findings. The table also highlights the outline of this thesis.

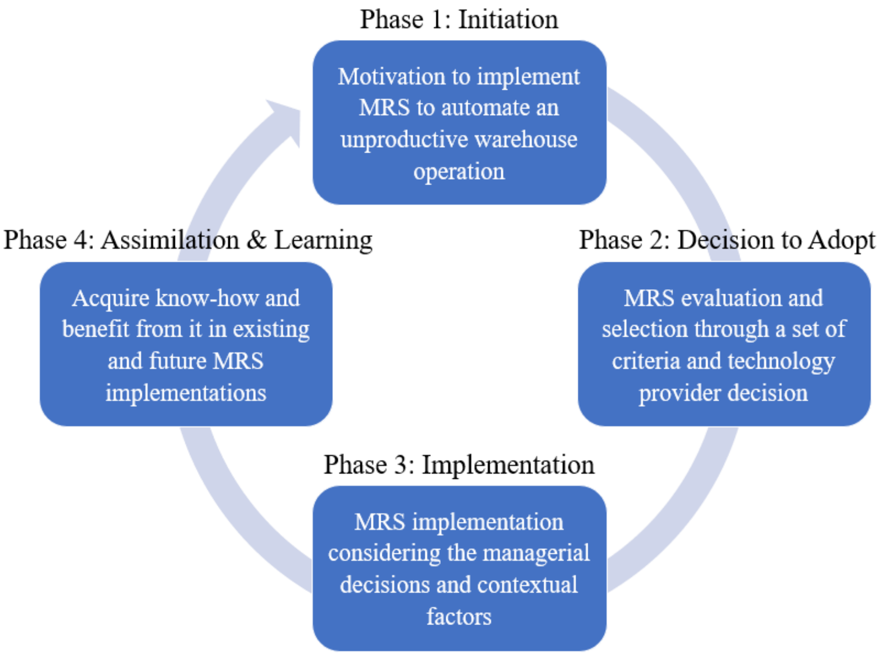


Figure 1-2 A brief MRS adoption journey

Table 1-2 Thesis structure, objectives, research methods, and key findings

Chapter	*Title*	*Relevant Objective*	*Research Methods*	*Description or Key Findings*
Chapter 1	*Introduction*		-	***Description:*** *Introduces the context of the study and provides the research motivation, research design, philosophical paradigm, and outputs of the study.*
Chapter 2 (Paper 1)	*Systematic Review of Mobile Robots in Warehouses: Decision Framework and Research Agenda*	*1*	*Systematic literature review (SLR)*	***Key Findings:*** *Synthesises the managerial decisions from 107 scholarly papers and categorises these decisions into three levels to offer a conceptual framework for the case study. It also devises a structured research agenda for further research.*
Chapter 3 (Paper 2)	*Mobile Robots in Warehouses: Evaluation Criteria for System Selection*	*2*	*Systematic literature review & Survey with five supply chain experts*	***Key Findings:*** *Categorises and evaluates MRS through a set of criteria. It also applies equal weight and full consistency method (FUCOM) approaches to the set of criteria informed by supply chain experts to select a suitable MRS.*
Chapter 4 (Paper 3)	*Mobile Robot System Implementation in Warehouses: an Adoption Framework*	*3*	*A multiple-case study involving four companies and eight warehouses*	***Key Findings:*** *Elaborates on innovation diffusion theory to explain the MRS adoption journey. It also illustrates the interaction of managerial decisions and contextual factors and how they affect MRS implementation to finally offer an integrated adoption framework.*
Chapter 5	*Conclusion*		-	***Description:*** *Highlights the overall theoretical and practical contribution of the thesis. Also mentions the limitations of the study and proposes future research directions.*

1.3 Research Design and Structure

This study benefit from two distinct research method stances simultaneously by combining qualitative and quantitative methods for data collection and analysis procedures, resulting in the mixed method approach. This approach aims to produce a more complete and comprehensive understanding of the phenomenon being studied by including both extreme approaches (Plano Clark and Ivankova, 2016). This way, it also reflects the aim to help practitioners in their decision-making processes.

Figure 1-3 sets out the overview of the research design implemented in this thesis. Chapter 2 lays the conceptual foundation of further studies by conducting a systematic literature review. Even though Chapter 3 and Chapter 4 seem merely interconnected, they do align in the path of MRS adoption through the italic questions written in Figure 1-3. Further, both of them uses the outputs of Chapter 2 to make their contributions.

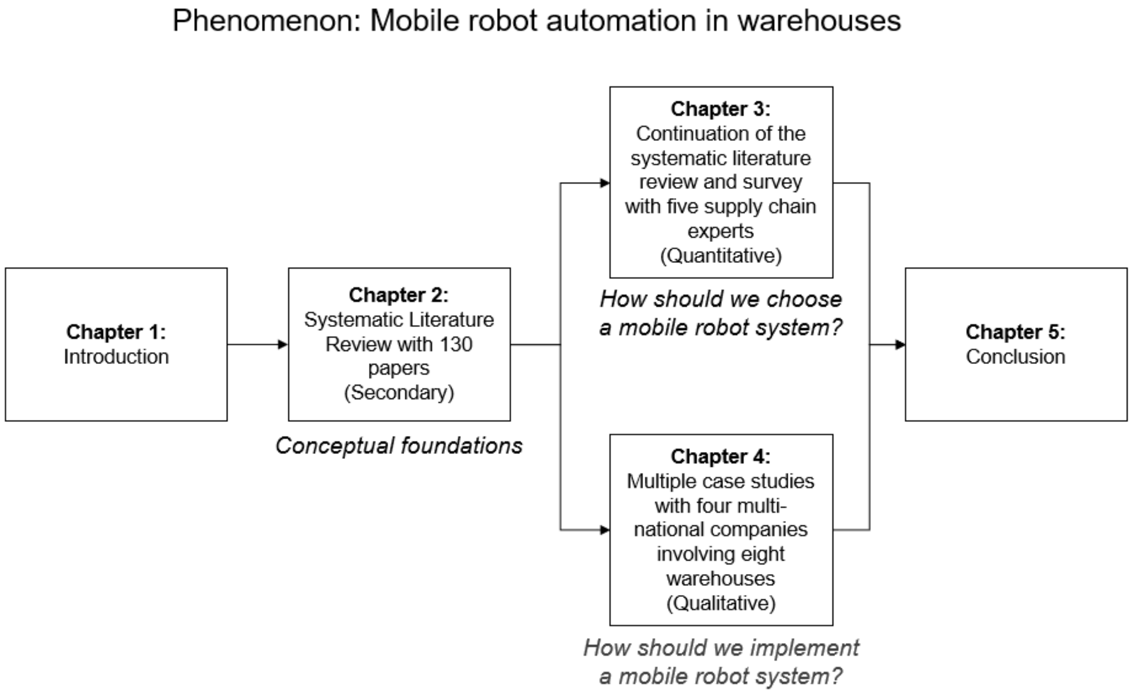


Figure 1-3 Overview of the research design

1.3.1 Paper 1: The systematic literature review

Conceptual foundations

The main aim of conducting an SLR is not only to obtain an overview of the literature on mobile robots in warehouses but also to be able to replicate the study again whenever necessary. SLRs are characterised by being replicable, rigorous, and transparent (Mallett et al., 2012). Therefore, it would be ideal to devise managerial decisions in this structured manner which is also the first objective of this thesis.

Paper 1 gathered 107 papers either from scholarly journals or conferences and addressed the first lack of knowledge mentioned in Section 1.1 by providing an integrative and conceptual managerial decision framework. The framework has thirteen decisions stemming from the literature to support implementation decisions of MRS in warehouses which are then categorised as strategic, tactical, and operational. Strategic level decisions involve comprehensive, long-term (+1-year time horizon) business decisions such as the warehouse layout and the type of MRS. These decisions are generally taken before the installation of the mobile robot systems because they are rather hard to alter during the implementation. Based on strategic decisions, tactical decisions need to be made. These decisions are comparably easier to adjust during the implementation such as storage assignment plan and quantity of robots. Still, these decisions should not, and generally cannot, be changed in the short term. Operational level decisions could be altered even within the same day, and their effect on warehouse operations could be observed within the same day or week. Thus, they can easily be adjusted experientially to optimise operational performance.

The managerial decision framework formed from these decisions aims to help decision-makers to implement an MRS step-by-step in their warehouses. Yet, it is a conceptual framework that potentially requires elaboration, and therefore, acts as a foundation for Paper 3. In this way, Paper 1 contributes to third objective.

Paper 1 also proposes a research agenda relevant to MRS adoption in warehouses. It concludes that further study is necessary with the participation of experts and practitioners to explain the MRS adoption process elaborating on the conceptual framework with more focus areas and/or decision questions.

1.3.2 Paper 2: MRS selection strategies – quantitative piece

How should we choose a mobile robot system?

Paper 2 begins with a continuation of the SLR undertaken in Paper 1 to identify and categorise MRS from the extant literature. It takes the ten MRS identified in Paper 1 and categorises them under four navigation types: linear route, guided, freeway, and hybrid. Therefore, it creates a pool of available MRS for decision-makers.

Before implementing a particular MRS, the motivation towards such solutions and expectations should carefully be identified and discussed. This paper defines a ranking system involving five criteria (mobile robot cost, flexibility of the infrastructure, flexibility in material handling, scalability, and time to implement) to support the selection of potential MRS. It, then, assesses each MRS by rating its characteristics according to the ranking system. From that point, it offers two multi-criteria decision-making (MCDM) approaches for system selection: 1) the equal weight approach, and 2) the full consistency method (FUCOM) (Pamučar et al., 2018).

The ‘Equal Weight’ approach pays equal importance to each criterion and uses a decision tree. To be able to use a decision tree, we require a specific order of decisions to eliminate underperforming MRS. Therefore, this paper creates a realistic scenario to choose an MRS fitting to that scenario. Its results are subject to change following the scenario of the company that is willing to adopt such solutions. For this paper, this approach is selected mainly due to having a benchmark for FUCOM.

While the ‘Equal Weight’ approach is simple to use, the importance of each criterion may not be equal and may depend on the context in which the automation will take place. Therefore, through a survey, supply chain experts were asked to rate the importance of each criterion for a generic warehouse, respectively. Then, FUCOM is applied to select the best MRS for that particular importance distribution.

There are two reasons this paper offers the novel FUCOM as a selection approach. Firstly, FUCOM can provide better results in terms of result consistency than the other subjective methods such as the ‘Best Worst Method’ and the ‘Analytic Hierarchy Process’ with the ability to validate the results (Durmić, 2019; Pamučar et al., 2018). Secondly, it has proved its validity in supply chain research (Durmić, 2019; Erceg and Mularifović, 2019; Fazlollahtabar et al., 2019; Sharma et al., 2021; Zavadskas et al., 2018).

As a result, these two approaches can be used by the supply chain managers either directly or to create a benchmark result to aid their MRS selection decision. In addition to showing a way for decision-makers to choose an MRS, this paper discusses additional criteria stemming from the insights of supply chain experts that might become useful for different scenarios.

1.3.3 Paper 3: MRS adoption journey – qualitative piece

How should we implement a mobile robot system?

Paper 3 takes a more comprehensive approach to finally shed light on the entire MRS adoption journey. It uses the conceptual managerial decision framework of Paper 1 and emphasises the decision to adopt and implementation phases of MRS adoption while also covering the focus of Paper 2 which is the potential motivations/criteria of MRS adoption.

Theory selection was quite significant for Paper 3 to initially develop the conceptual foundation of the study although it is not directly addressed in the previous papers. It uses innovation diffusion theory (IDT) (Rogers, 2003) as the theoretical lens and tries to elaborate it in the context of MRS adoption with abductive reasoning.

This paper conducts a multiple-case study involving four companies (each located in a different country – United Kingdom, Norway, Denmark, and Turkey) and eight warehouses to observe and collect data about their MRS adoption journey. It forms an adoption framework through three interconnected elements: adoption phases, decision focus areas, and contextual factors.

Adoption phases were initially taken from the IDT and fitted into the MRS context. In addition to IDT, the ‘decision to adopt’ phase is elaborated as it also includes the technology access decision which is how a company accesses the solution (buy, make, or ally). Further, a new phase is included named ‘assimilation and learning’ which is a critical phase for the current and future implementations.

Decision focus areas are the decisions that are gathered in Paper 1. Of course, the list of decisions is further developed, and new sub-decisions are also included in this study. The perspective of Tornatzky and Fleischer (1990) is adopted for contextual factors and all the factors were categorised into technological, organisational, and environmental (TOE framework) factors.

By combining these three interconnected elements, Paper 3 fulfils the third research objective. It also contributes to the first research objective by elaborating on the conceptual managerial decision framework devised in Paper 1.

1.4 Research Philosophy

This thesis is built on the pragmatism philosophy. Pragmatism does not focus on methods but on the research problem and uses every method and approach available to attack the problem (Rossman and Wilson, 1985; Kaushik and Walsh, 2019). Creswell (2017) sets out two significant characteristics about pragmatism that would relate to the aim of this thesis: 1) individual researchers have the freedom to choose the methods and techniques that best serve their needs and purposes, and 2) pragmatist researchers do not see the world as an absolute unity and similarly they seek different approaches for collecting and analysing data rather than signing up to only one way (e.g., quantitative or qualitative).

As this thesis aims explain the entire MRS adoption journey, it tries to benefit from every approach available whether it is qualitative or quantitative. This approach of the thesis also favours the mixed-method approach undertaken. While using pragmatism as the philosophical stance, this study seeks balance among the key extreme characteristics of qualitative and quantitative research. According to Morgan (2007), there are three main dualities in the qualitative and quantitative approach that can somehow be balanced by the pragmatic approach. Table 1-3 mentions these dualities and addresses how the pragmatic approach balances these distinctions to benefit from both extreme (qualitative and quantitative) approaches.

Table 1-3 A Pragmatic alternative to the key issues in social science research methodology. Source: Morgan, 2007

	Qualitative Approach	**Quantitative Approach**	**Pragmatic Approach**
Connection of theory and data	Induction	Deduction	Abduction
Relationship to the research process	Subjectivity	Objectivity	Intersubjectivity
Inference from data	Context	Generality	Transferability

1.4.1 Connection of theory and data

In social science, the connection between theory and data is rarely in one direction (Morgan, 2007). Further to this thought, this paper considers the dominance of deductive, and therefore, quantitative approach in logistics and supply chain management (Kovács and Spens, 2005). Although the survey in Paper 2 takes deductive reasoning to evaluate MRS, this study takes abductive reasoning with an inductive Paper 3 to connect the theory and data. It tests and modifies the logic of the innovation diffusion theory in order to reconcile it with contextual idiosyncrasies (cases) (Ketokivi and Choi, 2014). Going in between induction & deduction and data & theory is the essence of abduction in the pragmatic approach (Morgan, 2007).

1.4.2 Relationship to the research process

The dichotomy between entire subjectivity and objectivity is also a matter of consideration in the pragmatic approach. Rather than trying to be completely objective or subjective, this study goes back and forth between these two concepts to capture the duality and achieve intersubjectivity (Maarouf, 2019). Intersubjectivity is the degree of communication and shared meaning (both to the audience and participants) the study carries with itself (Morgan, 2007).

This work includes objectivity, such as applying the pre-defined methodologies (case study, survey) or ranking of evaluation criteria in Paper 2, but it also includes subjectivity, such as comments of interviewees in Paper 3 and its inductive analysis by the researcher. This duality is particularly helpful to explain the MRS adoption phenomenon in warehouses. It helps this work to achieve an understanding with both the participants of the study and the academics who are curious about the outputs of this study (Morgan, 2007).

1.4.3 Inference from data

The qualitative approach is generally context-bound, whereas the quantitative approach aims to generalise the findings it develops (Morgan, 2007). The pragmatic approach avoids travelling to these two extremes and tries also to investigate the factors that might make the study transferable to other settings.

For instance, Paper 3 aims: (i) to validate the analysis through within-method triangulation in the context of the study for each case (Jick, 1979), (ii) to obtain analytically generalisable outcomes from the multiple cases in hand, and (iii) to discuss the outcomes to make it transferrable to similar studies or other innovation adoption contexts (see 4.5.2). Similar to this logic, Paper 2 is aiming to transfer multi-criteria decision-making methods to the mobile robot context to offer an MRS selection logic through a set of evaluation criteria for mobile robots. It does not stop there and mentions different warehousing-related criteria to create a transferable output and method for similar automation studies.

1.5 Research Outputs

This thesis by papers is formed of three independent but interconnected papers. The first paper, which is a systematic literature review, serves as the conceptual foundation for the MRS adoption framework with a managerial decision framework and establishes a research agenda for the thesis. The second paper identifies available MRS in the literature and offers an evaluation framework for managers to select the best system through a novel multi-criteria decision-making method. Finally, the third paper uses the outcome of the first two papers to offer a mobile robot system adoption framework that covers the entire implementation journey. It sets out the phases of the MRS adoption journey, adding the consideration of assimilation and learning to MRS adoption, with managerial decision focus areas and relevant contextual factors.

In all publishing opportunities, the researcher was the lead author as he was the researcher conducting the study. The researcher’s supervisors supported him to refine the research processes as well as the manuscripts. As each paper is independent of the others with different research objectives, the initial intention was to publish these papers in separate instances (Table 1-4). However, the researcher faced many opportunities to disseminate his work (as a book or through conferences) and sometimes combined these papers on these occasions.

Palgrave Series: Studies in Logistics and Supply Chain Management

Paper 1 and Paper 2 were combined to publish a monograph book (Yildirim et al., 2023) with minor extensions (written by the researcher’s supervisors as a separate chapter in the book) who are also co-authors of the book.

Advances in Production Management Systems (APMS) Conference 2021

Paper 1 and Paper 3 were combined to submit a proposal to APMS 2021, Marco Garetti Doctoral Workshop. The proposal was received well by the jury and awarded as the Best Research Proposal in the workshop.

Logistics Research Network (LRN) Conference 2021

Paper 2 was submitted to LRN 2021 initially as a conference paper. It was acknowledged as one of the best papers and received an invitation to a Special Issue (SI) of the International Journal of Logistics: Research & Applications.

European Operational Research Societies (EURO) 2022 ESPOO Conference

Paper 3 was submitted to EURO 2022 ESPOO to receive feedback over a presentation. The feedback helped a lot in terms of methodology and new contribution perspectives.

Table 1-4 Papers and targeted journals

Paper	Title	Type	Targeted Journal
1	Systematic Review of Mobile Robots in Warehouses: Decision Framework and Research Agenda	Conceptual	International Journal of Computer Integrated Manufacturing
2	Mobile Robots in Warehouses: Evaluation Criteria for System Selection	Empirical	Supply Chain Analytics
3	Mobile Robot System Implementation in Warehouses: an Adoption Framework	Empirical	International Journal of Operations & Production Management

Finally, as the topic is quite practical, the researcher was also involved outside the academia and published short articles relevant to his study in ‘SHD Logistics’ magazine and ‘AGV Network’ website to increase his presence (Burman, 2017; Yildirim, n.d.).

1.6 References to Chapter 1

ABI Research. (2019). 50,000 Warehouses to Use Robots by 2025 as Barriers to Entry Fall and AI Innovation Accelerates. ABI Research. https://www.abiresearch.com/press/50000-warehouses-use-robots-2025-barriers-entry-fall-and-ai-innovation-accelerates/ (accessed 21 February 2021)

Adobe Analytics. (2019). Adobe Holiday Shopping Trends. Adobe Analytics. https://www.adobe.com/content/dam/www/us/en/experience-cloud/digital-insights/pdfs/adobe_analytics-holiday-predictions-2019.pdf?promoid=NV3KR4X2&mv=other (accessed 21 February 2021)

Azadeh, K., De Koster, R., and Roy, D. (2019). Robotized and Automated Warehouse Systems: Review and Recent Developments. Transportation Science, 53(4), 917–945. https://doi.org/10.1287/trsc.2018.0873

Bartholdi, J., and Hackman, S. T. (2017). Warehouse & Distribution Science. 337.

Bechtsis, D., Tsolakis, N., Vlachos, D., and Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Benady, D. (2016). Will a robot take my job? DHL. https://www.dhl.com/global-en/home/about-us/delivered-magazine/articles/2016/issue-3-2016/will-a-robot-take-my-job.html

Benzidia, S., Ageron, B., Bentahar, O., and Husson, J. (2019). Investigating automation and AGV in healthcare logistics: A case study based approach. International Journal of Logistics Research and Applications, 22(3), 273–293. https://doi.org/10.1080/13675567.2018.1518414

Bogue, R. (2016). Growth in e-commerce boosts innovation in the warehouse robot market. Industrial Robot, 43(6), 583–587. https://doi.org/10.1108/IR-07-2016-0194

Boysen, N., Briskorn, D., and Emde, S. (2017). Parts-to-picker based order processing in a rack-moving mobile robots environment. European Journal of Operational Research, 262(2), 550–562. https://doi.org/10.1016/j.ejor.2017.03.053

Boysen, N., de Koster, R., and Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. European Journal of Operational Research, 277(2), 396–411. https://doi.org/10.1016/j.ejor.2018.08.023

Burman, J. (2022). Futureproofing with automation. SHD Logistics. https://www.shdlogistics.com/robotics-automation/futureproofing-automation

Cambridge Dictionary. (n.d.). Cambridge Dictionary. Cambridge Dictionary. Retrieved February 21, 2021, from https://dictionary.cambridge.org/dictionary/english/robot

Creswell, J. W., and Creswell, J. D. (2017). Research design: Qualitative, quantitative, and mixed methods approaches. Sage publications.

De Koster, R. B. M., Le-Duc, T., and Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. In European Journal of Operational Research (Vol. 182, Issue 2). https://doi.org/10.1016/j.ejor.2006.07.009

Durmić, E. (2019). The Evaluation of the Criteria for Sustainable Supplier Selection by Using the FUCOM Method. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901085d

Erceg, Ž., and Mularifović, F. (2019). Integrated MCDM model for processes optimization in the supply chain management in the wood company. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901015e

Fazlollahtabar, H., and Saidi-Mehrabad, M. (2015). Methodologies to Optimize Automated Guided Vehicle Scheduling and Routing Problems: A Review Study.

Journal of Intelligent & Robotic Systems, 77(3–4), 525–545. https://doi.org/10.1007/s10846-013-0003-8

Fazlollahtabar, H., Smailbašić, A., and Stević, Ž. (2019). FUCOM method in group decision-making: Selection of forklift in a warehouse. Decision Making: Applications in Management and Engineering, 2(1), 49–65. https://doi.org/10.31181/dmame1901065f

Fragapane, G., de Koster, R., Sgarbossa, F., and Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. European Journal of Operational Research, 294(2), 405–426. https://doi.org/10.1016/j.ejor.2021.01.019

Frazelle, Edward H. 2016. World-Class Warehousing and Material Handling. 2nd ed. New York: McGraw-Hill Education. https://www.accessengineeringlibrary.com/content/book/9780071842822

Hofmann, E., Sternberg, H., Chen, H., Pflaum, A., and Prockl, G. (2019). Supply chain management and Industry 4.0: conducting research in the digital age. International Journal of Physical Distribution & Logistics Management.

Horňáková, N., Jurík, L., Hrablik Chovanová, H., Cagáňová, D., and Babčanová, D. (2019). AHP method application in selection of appropriate material handling equipment in selected industrial enterprise. Wireless Networks. https://doi.org/10.1007/s11276-019-02050-2

J.P. Morgan Research. (2022). Supply Chain Issues and Autos: When Will the Chip Shortage End? https://www.jpmorgan.com/insights/research/supply-chain-chip-shortage (accessed 27 December 2022)

Jaghbeer, Y., Hanson, R., and Johansson, M. I. (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

Jick, T. D. (1979). Mixing Qualitative and Quantitative Methods: Triangulation in Action. Administrative Science Quarterly, 24(4), 602. https://doi.org/10.2307/2392366

Kattepur, A., Rath, H. K., Simha, A., and Mukherjee, A. (2018). Distributed optimization in multi-agent robotics for industry 4.0 warehouses. Proceedings of the ACM Symposium on Applied Computing, 808–815. https://doi.org/10.1145/3167132.3167221

Kaushik, V., & Walsh, C. A. (2019). Pragmatism as a Research Paradigm and Its Implications for Social Work Research. Social Sciences, 8(9), 255. https://doi.org/10.3390/socsci8090255

Ketokivi, M., and Choi, T. (2014). Renaissance of case research as a scientific method. Journal of Operations Management, 32(5), 232–240. https://doi.org/10.1016/j.jom.2014.03.004

Kovács, G. and Spens, K.M. (2005) Abductive Reasoning in Logistics Research. International Journal of Physical Distribution & Logistics Management, 35, 132-144. http://dx.doi.org/10.1108/09600030510590318

Lamballais, T., Roy, D., and De Koster, M. B. M. (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

Le-Anh, T., and De Koster, M. B. M. (2006). A review of design and control of automated guided vehicle systems. European Journal of Operational Research, 171(1), 1–23. https://doi.org/10.1016/j.ejor.2005.01.036

Maarouf, H. (2019). Pragmatism as a supportive paradigm for the mixed research approach: Conceptualizing the ontological, epistemological, and axiological stances of pragmatism. International Business Research, 12(9), 1-12. https://doi.org/10.5539/ibr.v12n9p1

Mallett, R., Hagen-Zanker, J., Slater, R., and Duvendack, M. (2012). The benefits and challenges of using systematic reviews in international development research. Journal of Development Effectiveness, 4(3), 445–455. https://doi.org/10.1080/19439342.2012.711342

Merschformann, M., Lamballais, T., de Koster, M. B. M., and Suhl, L. (2019). Decision rules for robotic mobile fulfillment systems. Operations Research Perspectives, 6, 100128. https://doi.org/10.1016/j.orp.2019.100128

Morgan, D. L. (2007). Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods. Journal of Mixed Methods Research, 1(1), 48–76. https://doi.org/10.1177/2345678906292462

Pamučar, D., Stević, Ž., and Sremac, S. (2018). A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). Symmetry, 10(9), 393. https://doi.org/10.3390/sym10090393

Plano Clark, V., and Ivankova, N. (2016). Mixed methods research: A guide to the field. SAGE Publications, Inc., https://dx.doi.org/10.4135/9781483398341

Rai, H., Verlinde, S. and Macharis, C. (2019), "The “next day, free delivery” myth unravelled: Possibilities for sustainable last mile transport in an omnichannel environment", International Journal of Retail & Distribution Management, Vol. 47 No. 1, pp. 39-54. https://doi.org/10.1108/IJRDM-06-2018-0104

Rogers, E. M. (2003). Diffusion of Innovations (5th ed). Free Press.

Rossman, G. B., & Wilson, B. L. (1985). Numbers and words: Combining quantitative and qualitative methods in a single large-scale evaluation study. Evaluation Review, 9(5), 627–643. https://doi.org/10.1177/0193841X8500900505

Roy, D., Nigam, S., de Koster, R., Adan, I., and Resing, J. (2019). Robot-storage zone assignment strategies in mobile fulfillment systems. Transportation Research Part E: Logistics and Transportation Review, 122, 119–142. https://doi.org/10.1016/j.tre.2018.11.005

Rushton, A., Croucher, P., and Baker, P. (2014). The handbook of logistics & distribution management (5th edition). Kogan Page.

Shamout, M., Ben-Abdallah, R., Alshurideh, M., Alzoubi, H., Kurdi, B. A., and Hamadneh, S. (2022). A conceptual model for the adoption of autonomous robots in supply chain and logistics industry. Uncertain Supply Chain Management, 10(2), 577–592. https://doi.org/10.5267/j.uscm.2021.11.006

Sharma, M., Luthra, S., Joshi, S., and Kumar, A. (2021). Accelerating retail supply chain performance against pandemic disruption: Adopting resilient strategies to mitigate the long-term effects. Journal of Enterprise Information Management, 34(6), 1844–1873. https://doi.org/10.1108/JEIM-07-2020-0286

Tashakkori, A., and Creswell, J. W. (2007). Editorial: Exploring the Nature of Research Questions in Mixed Methods Research. Journal of Mixed Methods Research, 1(3), 207–211. https://doi.org/10.1177/1558689807302814

Tornatzky, L. G., and Fleischer, M. (1990). The Processes of Technological Innovation. Lexington, Mass. : Lexington Books.

Vis, I. F. A. (2006). Survey of research in the design and control of automated guided vehicle systems. European Journal of Operational Research, 170(3), 677–709. https://doi.org/10.1016/j.ejor.2004.09.020

Vivaldini, K. C. T., Rocha, L. F., Becker, M., and Moreira, A. P. (2015). Comprehensive Review of the Dispatching, Scheduling and Routing of AGVs. In A. P. Moreira, A. Matos, and G. Veiga (Eds.), CONTROLO’2014 – Proceedings of the 11th Portuguese Conference on Automatic Control (Vol. 321, pp. 505–514). Springer International Publishing. https://doi.org/10.1007/978-3-319-10380-8_48

Voccia, S. A., Campbell, A. M., and Thomas, B. W. (2019). The same-day delivery problem for online purchases. Transportation Science, 53(1), 167-184.

Wior, I., Jerenz, S., and Fay, A. (2018). Automated transportation systems subject to interruptions in production and intralogistics - a survey and evaluation. International Journal of Logistics Systems and Management, 30(4), 421. https://doi.org/10.1504/IJLSM.2018.093581

Wurman, P. R., DAndrea, R., and Mountz, M. (2008). Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses.

Yaman, H., Karasan, O. E., and Kara, B. Y. (2012). Release time scheduling and hub location for next-day delivery. Operations research, 60(4), 906-917.

Yildirim, A. (n.d.). What are Autonomous Mobile Picking Robots? It's time to replace hands. AGV Network. Retrieved December 28, 2022, from https://www.agvnetwork.com/what-are-autonomous-mobile-picking-robots

Yildirim, A., Reefke, H., and Aktas, E. (2023). Mobile Robot Automation in Warehouses: A Framework for Decision Making and Integration. Springer International Publishing. https://books.google.com.tr/books?id=4ak6zwEACAAJ

Zavadskas, E. K., Nunić, Z., Stjepanović, Ž., and Prentkovskis, O. (2018). Novel Rough Range of Value Method (R-ROV) for selecting automatically guided vehicles (AGVs). Studies in Informatics and Control, 27(4), 385–394. https://doi.org/10.24846/v27i4y201802

2 Systematic Review of Mobile Robots in Warehouses: Decision Framework and Research Agenda

Abstract

Mobile robot systems are an automation solution in warehouses that make order fulfilment agile, flexible, and scalable to cope with the increasing volumes and complexities of customer orders. As the practical use of mobile robot systems is increasing, decision-makers are confronted with a plethora of decisions. Currently, the lack of a structured decision framework tailored for mobile robot system applications in warehouses increases the probability of problems when choosing automation systems.

A systematic literature review of mobile robot systems in warehouses is conducted including 107 peer-reviewed papers from 2000 onwards. This review illustrates the characteristics of ten mobile robot systems used in warehouse operations through a set of evaluation criteria. Inductive theory building leads to a theoretical framework for strategic, tactical, and operational decisions connected to system selection and implementation. Further, it provides a research agenda identifying and structuring future research avenues.

Keywords Mobile robot automation, Warehousing, Managerial decision framework, Automated guided vehicles, Autonomous mobile robots, Systematic literature review

2.1 Introduction

Fulfilling customers' orders swiftly and efficiently whilst managing the increasing complexity and variability is an ongoing challenge in warehouses. The growing tendency of customers to buy online leads to thousands of small daily orders, making the warehouse environment complex and complicating operations such as receiving, picking, sorting, and packing.

Picking may account for 50-55% of the total operating costs of manually operated warehouses (Rushton et al., 2014). This high percentage is primarily due to the travelling activity that takes around 55% of the picker's total time spent (Bartholdi and Hackman, 2019). Mobile robot automation systems were developed from the 1950s onwards to eliminate the unproductive travelling time of human workers. An early version of mobile robots is automated guided vehicles (AGVs). Since 2006, autonomous mobile robots (AMRs) have become an alternative to AGVs, offering more flexible and scalable solutions (Wurman et al., 2008). These robots have onboard intelligence helping them decide whether to slow down or stop and where to go next (Kattepur et al., 2018). They can map the environment, plan their paths, dynamically respond to their surroundings, and bypass an obstacle without being remotely controlled (Horňáková et al., 2019). These functions make AMRs more flexible and suitable than AGVs for chaotic and complicated warehouse settings such as e-commerce.

Owing to the automation successes of early adopters such as Amazon, Alibaba, and Ocado, mobile robot adoption in warehouses had a spectacular boost. Grey Orange, Geek+, IAM Robotics, 6 River Systems, Magazino, and many other start-up companies are developing autonomous mobile robots for warehouses. Industry forecasts estimate that more than 50,000 warehouses, up from 4,000 warehouses in 2018, will be using over 4 million mobile robots globally by 2025 (ABI Research, 2019).

Based on these developments and forecasts, applicable mobile robot systems should be identified. Moreover, such highly productive systems require a rationale, alongside a set of evaluation criteria, for system selection to justify the capital investment associated with automation (Azadeh et al., 2019). Finally, the selected system needs a feasible, efficient, and comprehensive application strategy that covers the decisions involved in the implementation and operation of mobile robot systems.

The literature on mobile robots, mobile robot systems, and managerial decision areas in the warehouse context is fragmented (Table 2-1). Since other reviews only partially identify applicable mobile robot systems and fail to deliver a holistic managerial decision framework for their warehouse implementations, reviewing these aspects is well justified. In addressing the aforementioned gaps, this review builds and offers a contextualised theory by integrating the literature on mobile robots in warehouses (Durach et al., 2021). The review questions are as follows:

RQ1. How are mobile robot systems applied in warehouse operations?

RQ2. How can managerial decisions be structured when adopting mobile robot systems in warehouses

Table 2-1 Literature on mobile robots

Review Paper	**Review Focus**	**Review Outcome**	**Analysed Mobile Robot Managerial Decisions**												
			Criteria for System Evaluation	Identifying KPIs	Type and Coordination of Robots	Facility Layout	Human-Robot Interaction	Storage Assignment	Order Management	Quantity of Robots	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Conflict Management
Vis, 2006	Planning and control of AGV systems	Focus areas to plan and control large AGV systems				✓				✓		✓	✓	✓	✓
Le-Ahn et al., 2006	Planning and control of AGV systems	A framework for the design and control of AGV systems		✓	✓	✓				✓		✓	✓		✓
Vivaldini et al., 2015	AGV and AMR systems path planning and task allocation algorithms	Algorithm and approach review for path planning and task allocation of mobile robots											✓	✓	✓
Bechtsis et al., 2017	Role AGVs and AMRs in smart distribution and manufacturing systems	A framework covering key decisions with a sustainability perspective		✓	✓		✓						✓		
Azadeh et al., 2018	Modelling, designing, and control of automated order picking	System analysis, design optimisation, and operations planning and		✓				✓					✓		

	systems in warehouses	control for robotic systems													
Wior et al., 2018	Automated transportation system types and influences of their interruptions	Advantages and disadvantages of transportation systems in various domains	✓	✓							✓				✓
Boysen et al., 2019	Automated order picking systems in warehouses with an e-commerce focus	Analysis of automated order picking systems that suits B2C e-commerce	✓					✓	✓						
Fragapane et al., 2021	Planning and control of AMRs	Technological developments and decision areas for the planning and control of AMRs			✓	✓			✓	✓			✓	✓	✓
This paper	Planning and control of automated and autonomous systems in warehouses that include mobile robots	A managerial decision framework tailored for mobile robot implementation in warehouses	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

2.2 Methodology

The rationale behind the SLR is to have a clear view of the decisions to be made and the complications faced while applying mobile robot systems to warehouses. Compared to a traditional literature review, an SLR is robust, scientific, and transparent and summarises existing information in a thorough and unbiased manner (Tranfield et al., 2003).

The research protocol followed in this review was adapted from Tranfield et al. (2003) and started with a scoping study that informed the research questions in two primary and broad contexts: ‘Warehouse’ and ‘Mobile Robots’. Keyword groups were formed (S1 for warehouse and S2 for mobile robots), and keyword strings were gathered and combined with the ‘AND’ operator (Figure 2-1) to search Scopus, Web of Science, ABI Inform, and EBSCO. This study intended to capture as many mobile robot solutions and decision topics as possible by being flexible with only two search strings and hence refrained from narrowing the search results further through the use of additional primary context. Only articles from 2000 and conference papers from 2015 to 2020 were considered relevant owing to the recency of the technology (Table A-1). Only peer-reviewed papers in English on warehouses and mobile robots were considered.

Quality criteria (Table A-2) were adopted from Pittaway et al. (2004) to select and evaluate publications, including theory robustness, contribution to knowledge, methodology and arguments, and implications for practice. Papers were rated on a scale of zero to three in each of the four criteria, and papers scoring 8 out of 12 qualified for review, which resulted in a total of 107 papers.

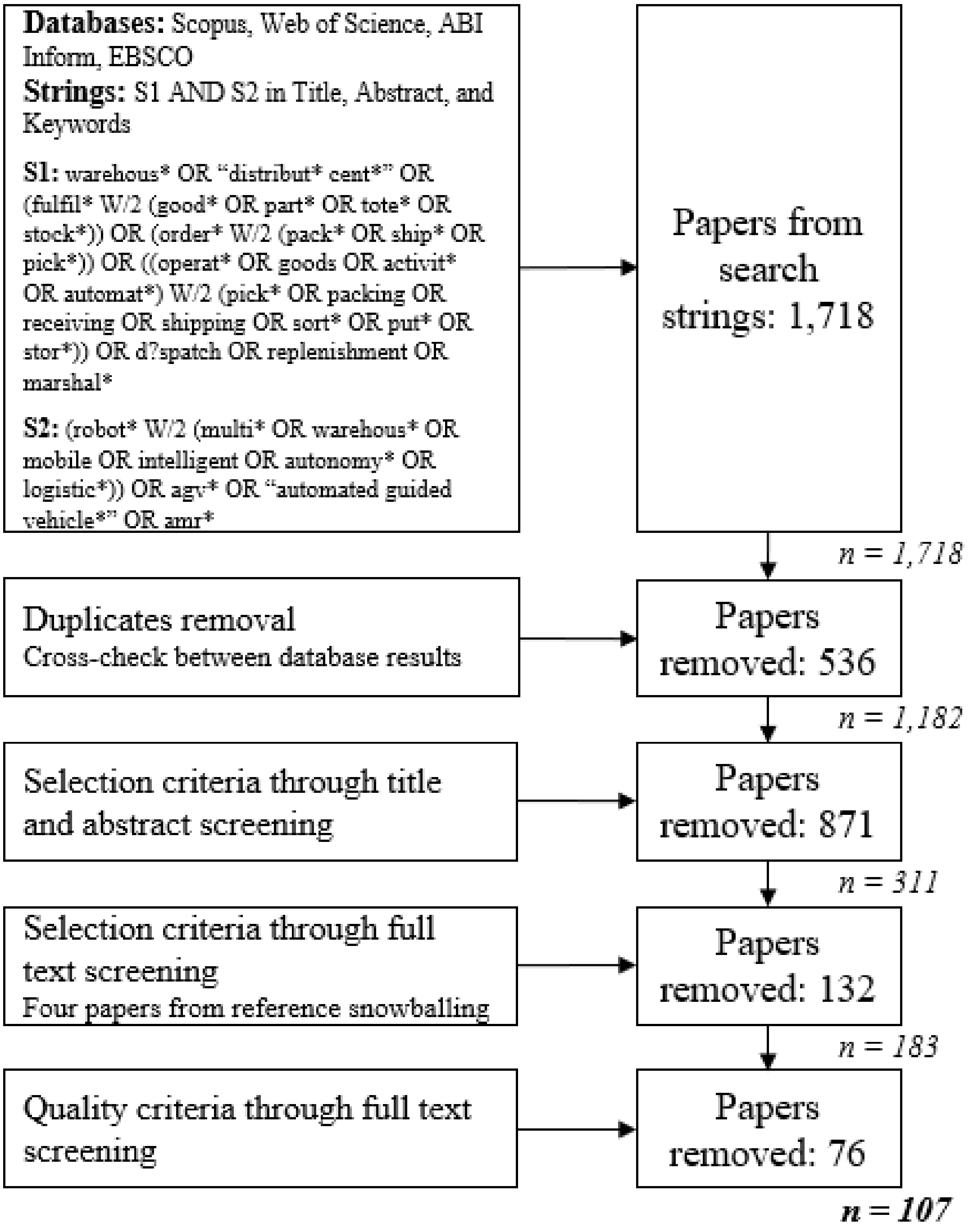
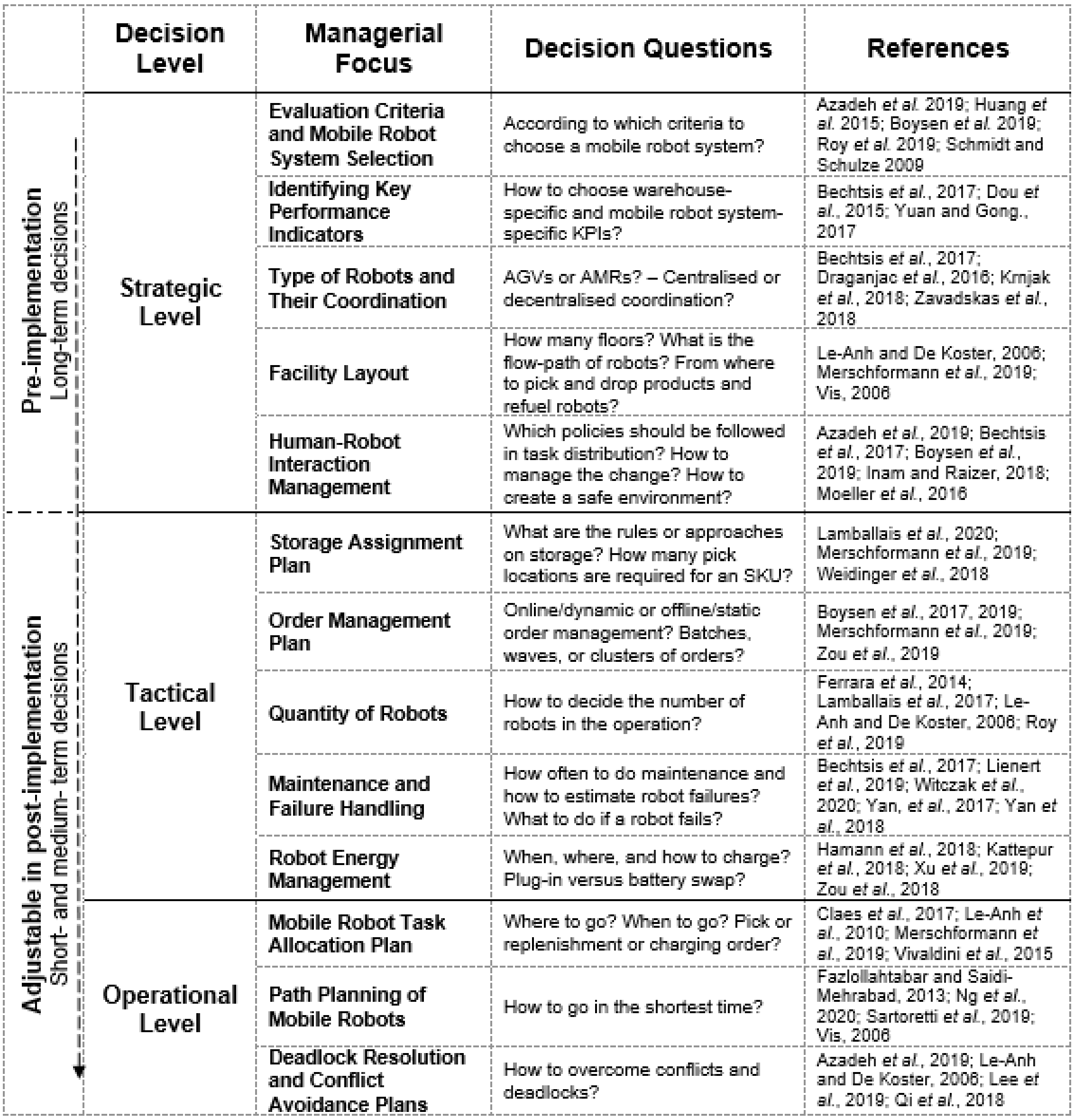


Figure 2-1 The systematic literature review process

2.3 Managerial Decision Framework

Implementing mobile robot systems in warehouses is a complex decision problem with multiple dimensions, affecting the current and future capabilities of the warehouse. Thus, along with identifying the correct system, many decisions need to be made at strategic, tactical, and operational levels, in order of precedence (Bechtsis et al., 2017; Fragapane et al., 2021; Le-Anh and De Koster, 2006). Each decision level is divided into managerial focus areas, as shown in Figure 2-2. A detailed analysis of all the papers involved exists in Table A-3.



	Decision Level	Managerial Focus	Decision Questions	References
Pre-implementation Long-term decisions	Strategic Level	Evaluation Criteria and Mobile Robot System Selection	According to which criteria to choose a mobile robot system?	Azadeh *et al.* 2019; Huang *et al.* 2015; Boysen *et al.* 2019; Roy *et al.* 2019; Schmidt and Schulze 2009
		Identifying Key Performance Indicators	How to choose warehouse-specific and mobile robot system-specific KPIs?	Bechtsis *et al.*, 2017; Dou *et al.*, 2015; Yuan and Gong., 2017
		Type of Robots and Their Coordination	AGVs or AMRs? – Centralised or decentralised coordination?	Bechtsis *et al.*, 2017; Draganjac *et al.*, 2016; Krnjak *et al.*, 2018; Zavadskas *et al.*, 2018
		Facility Layout	How many floors? What is the flow-path of robots? From where to pick and drop products and refuel robots?	Le-Anh and De Koster, 2006; Merschformann *et al.*, 2019; Vis, 2006
		Human-Robot Interaction Management	Which policies should be followed in task distribution? How to manage the change? How to create a safe environment?	Azadeh *et al.*, 2019; Bechtsis *et al.*, 2017; Boysen *et al.*, 2019; Inam and Raizer, 2018; Moeller *et al.*, 2016
Adjustable in post-implementation Short- and medium- term decisions	Tactical Level	Storage Assignment Plan	What are the rules or approaches on storage? How many pick locations are required for an SKU?	Lamballais *et al.*, 2020; Merschformann *et al.*, 2019; Weidinger *et al.*, 2018
		Order Management Plan	Online/dynamic or offline/static order management? Batches, waves, or clusters of orders?	Boysen *et al.*, 2017, 2019; Merschformann *et al.*, 2019; Zou *et al.*, 2019
		Quantity of Robots	How to decide the number of robots in the operation?	Ferrara *et al.*, 2014; Lamballais *et al.*, 2017; Le-Anh and De Koster, 2006; Roy *et al.*, 2019
		Maintenance and Failure Handling	How often to do maintenance and how to estimate robot failures? What to do if a robot fails?	Bechtsis *et al.*, 2017; Lienert *et al.*, 2019; Witczak *et al.*, 2020; Yan, *et al.*, 2017; Yan *et al.*, 2018
		Robot Energy Management	When, where, and how to charge? Plug-in versus battery swap?	Hamann *et al.*, 2018; Kattepur *et al.*, 2018; Xu *et al.*, 2019; Zou *et al.*, 2018
	Operational Level	Mobile Robot Task Allocation Plan	Where to go? When to go? Pick or replenishment or charging order?	Claes *et al.*, 2017; Le-Anh *et al.*, 2010; Merschformann *et al.*, 2019; Vivaldini *et al.*, 2015
		Path Planning of Mobile Robots	How to go in the shortest time?	Fazlollahtabar and Saidi-Mehrabad, 2013; Ng *et al.*, 2020; Sartoretti *et al.*, 2019; Vis, 2006
		Deadlock Resolution and Conflict Avoidance Plans	How to overcome conflicts and deadlocks?	Azadeh *et al.*, 2019; Le-Anh and De Koster, 2006; Lee *et al.*, 2019; Qi *et al.*, 2018

Figure 2-2 Overview of managerial decision framework

2.3.1 Strategic Level

Strategic level decisions involve comprehensive, long-term business decisions such as warehouse layout plans and the type of mobile robot systems. These decisions are taken before the installation stage of mobile robot systems and are rather hard to alter during the implementation. The effects of these decisions occur in the long run, which might be years.

2.3.1.1 Evaluation Criteria and Mobile Robot System Selection

Analysing and choosing mobile robot systems should be the first step towards mobile robot automation. This paper classifies mobile robot systems according to their type of navigation Wior et al. (2018) into four categories: Linear route, guided, freeway mobile robots, and hybrid systems. To evaluate these systems, Schmidt and Schulze (2009) highlight four criteria: cost, service-level, flexibility, and scalability. Apart from the service-level criterion, the other three criteria are also mentioned in many other studies (Huang et al., 2015; Roy et al., 2019; Zou et al., 2018).

Firstly, to prevent the cost criterion from becoming too broad, this review only considers mobile robot costs through the presence of onboard intelligence and gripping arms. Moreover, flexibility is considered as ‘Flexibility of the Infrastructure’ and ‘Flexibility in Material Handling’. If the warehouse layout and environment change frequently during operations, infrastructural flexibility becomes crucial. On the other hand, if the company is in a sector that has different-sized products, a system with high material handling flexibility is recommended. Scalability is the ability of mobile robot systems to cope with demand fluctuations and is a necessity particularly if a company has a growth expectation. According to DHL, 80% of the warehouses are manually operated with no automation (Benady, 2016). Once they want to change their operational model, they will need to consider the required implementation time of the mobile robot systems. For this reason, ‘Time to Implement’ is another evaluation criterion (see Llopis-Albert et al., 2019) that offers managers an indication of system implementation times which is especially valuable in agile sectors such as e-commerce. Mobile robot systems are reviewed under these criteria in Table 2-2.

In case of information deficiency in the reviewed literature, the researcher benefited from the grey literature.

Lastly, operation or warehouse-specific strengths and weaknesses help determine the correct system. For example, barcode-guided mobile robot systems require a large and dedicated operation area, laser-guided mobile robot systems hardly operate with small and medium-sized products, and mobile picking robots cannot operate in a palletised-products-only environment.

2.3.1.2 Identifying Key Performance Indicators

Key Performance Indicators (KPIs) help decision-makers assess the performance of the warehouse through tangible measures (Rushton et al., 2014). This review divides KPIs into warehouse-specific and mobile robot system-specific in order to evaluate the performance of warehouse and automation systems separately.

Warehouse-specific KPIs are financial (costs, return on investment, capital), customer-related (on-time delivery, quality), process-related (productivity, inventory levels, order picking error, utilisation), and worker-related (labour turnover, training, safety) (Bartholdi and Hackman, 2019; Llopis-Albert et al., 2019; Rushton et al., 2014).

Mobile robot system-specific KPIs refer to the performance of the chosen system and should be identified to develop the system and keep track of the potential improvement areas. In the chosen mobile robot system context, a decision-maker should determine the KPIs from the list provided in Table 2-3 to monitor the performance and effectiveness of the system at the macro level.

Table 2-2 Mobile robot systems

System Name	Brief System Definition	Material Handling Context	Robot Type & Cost	Flexibility of Infrastructure	Flexibility in Material Handling	Scalability	Time to Implement	References
Rail Using Robots	Robots follow a linear route made of rails	Person-to-Goods	AGVs	Fixed infrastructure - hard to adjust	Pallets and small items (with tote bins add-on)	Scales within a few weeks: extra robots and low-level construction	Mid-level construction: railways	Füßler et al., 2019; Wior et al., 2018; “SSI Schaefer”, n.d.
Wire Using Robots	Robots follow a linear route with wires underneath	Person-to-Goods	AGVs	Fixed infrastructure - hard to adjust	Pallets and small items (with tote bins add-on)	Scales within a few weeks: extra robots and low-level construction	Mid-level construction: wires	Wior et al., 2018; Vis, 2006; “SSI Schaefer”, n.d.
Barcode Guided Robots	Robots travel on grid-based and barcoded floor layouts	Goods-to-Person	Mostly AMRs	Flexible with barcode and shelf relocations but requires a dedicated area	Shelves or bins	Scales within a few days: extra robots and minor installations	Low-level construction: barcode and shelf installation	Wurman et al., 2008; Boysen et al., 2019; “Geek+”, n.d.
Laser Guided Robots	Big vehicles travel with laser beams and mirrors in strategic locations for mapping and free navigation	Robot-to-Goods	Mostly AGVs with forks	Flexible with mirror setups or removals but requires a dedicated area	Pallets	Scales within a few days: extra robots and minor installations	Low-level construction: mirror installation	Hornakova et al., 2019; Raineri et al., 2019; Ferrara et al., 2014

Autonomous Forklifts and Pallet Trucks	Autonomous big vehicles with free navigation capability	Robot-to-Goods	AMRs with forks	High flexibility - no fixed infrastructure	Pallets	Scales within a few days: extra robots	No installation or construction	Draganjac et al., 2016; Polten and Emde, 2020; “Geek+”, n.d.
Human Collaborated Robots (Cobots)	Autonomous robots with bins attached navigating either with or to a human picker to carry materials	Person-to-Goods	AMRs	High flexibility - no fixed infrastructure	Small items, boxes, or bins	Scales within a few days: extra robots and human workforce	No installation or construction	Zou et al., 2019; Boysen et al., 2019; Azadeh et al., 2019; “Locus”, n.d.
Mobile Picking Robots	Autonomous robots with bins, free navigation, and gripping function to pick from shelves	Robot-to-Goods	AMRs with gripping function	High flexibility - no fixed infrastructure	Small items, boxes, or bins with shape and weight restrictions	Scales within a few days: extra robots	No installation or construction	Bogue 2016; Huang et al., 2015; Kimura et al. 2015; “Magazino”, n.d.
AS/RS, Conveyors, and Linear Route Robots	Required material handling unit is retrieved by the AS/RS, taken by mobile robots, and put on a conveyor for transportation	Robot-to-Goods	AGVs	Fixed and bulky infrastructure - hard to adjust	Pallets	Scales within several weeks: high-level construction	High-level construction	Azadeh et al., 2019; Wurman et al., 2008
Picker & Transport Robots	Picker robots (mobile picking robots) and transport robots with bins travel together	Robot-to-Goods	AMRs with gripping function	High flexibility - no fixed infrastructure	Small items, boxes, or bins with shape and weight restrictions	Scales within a few days: extra robots	No installation or construction	Bogue 2016; Azadeh et al., 2019

Laser Guided Robots & Pallet Shuttles	Pallet shuttles move pallets from the face to the interior for laser guided robots to pick them	Robot-to-Goods	AMRs with forks	Pallet shuttles stand on fixed infrastructure - hard to adjust	Pallets	Scales within several weeks: high-level construction	High-level construction	Ferrara et al., 2014

Table 2-3 Mobile robot system KPIs

KPIs	Explanation	Considered By
System throughput	Orders or order lines picked per hour	Yuan and Gong, 2017; Tai et al., 2018; Lamballais et al., 2017, 2020
Robot travel distance	Single robot travel distance on the average in a time interval or cumulative distances	Dou et al., 2015; Weidinger et al., 2018; Merschformann et al., 2019
Robot utilisation / idleness	Robot allocation or idleness percentages	Azadeh et al., 2019; Dou et al., 2015; Qi et al., 2018; Merschformann et al., 2019
Robot travel time	Cumulative time of robot travelling	Dou et al., 2015; Qi et al., 2018; Le-Anh and De Koster, 2006
Avg. task completion time / deadline miss	The average time required to fulfil a task	Xue and Dong, 2018; Singhal et al., 2018; Qi et al., 2018; Dou et al., 2015
Task delay/response time	The time it takes to find a robot for a task	Azadeh et al., 2019; Le-Anh and De Koster, 2006; Wior et al., 2018
Computation / negotiation time	The time it takes to calculate/negotiate a solution for a specific task group	Weidinger et al., 2018; Tai et al., 2019; Sarkar et al., 2019
# of deadlocks / conflicts / routing failures	Deadlocks, conflicts, and routing failures encountered in a time interval	Dou et al., 2015; Fan et al., 2018; Wior et al., 2018; Zou et al., 2017
Workstation utilisation / idleness	For instance, the utilisation of picking workstations	Bauters et al., 2016; Merschformann et al., 2019; Tai et al., 2019; Yuan and Gong, 2017
Task density	In a zone or other specific area	Qi et al., 2018;
Robot-Human ratio	The number of human workers required to operate with a certain number of robots or vice versa	Yuan and Gong, 2017
Number of active robots	The number of robots required in the field	Fan et al., 2018

2.3.1.3 Type of Mobile Robots and Their Coordination

If the chosen system requires extensive onboard intelligence, such as the ability of dynamic path planning according to the environment and the obstacles, AMRs should be preferred. Otherwise, AGVs would be a satisfactory and cheaper solution. Horňáková et al. (2019) and Zavadskas et al. (2018) define several criteria and use multi-criteria decision-making methods to choose the best alternative.

After choosing the type of mobile robots, their coordination method should be determined. The literature focuses on three coordination methods: centralised, mixed, and decentralised. In centralised coordination, a single decision-making software gathers all the information and manages the robots accordingly. It theoretically guarantees an optimal solution (Tai et al., 2018), as it solves the system as a whole but requires extensive computational power (Fan et al., 2018). In distributed coordination, robots communicate with other robots and make their own decisions as decision-makers. Even though distributed coordination is more scalable and flexible than centralised coordination (Claes et al., 2017), the solution can be sub-optimal (Fan et al., 2018) or even non-existent due to deadlocks (Draganjac et al., 2016). Mixed coordination aims to benefit from the advantages of both approaches. They are faster than centralised coordination and have a higher potential to find a solution closer to the optimal when compared to distributed coordination (Singhal et al., 2018). Note that only AMRs could have distributed or mixed coordination thanks to their onboard intelligence.

Many operational decisions depend on the method of coordination. For instance, in mixed coordination, robots could plan their path while a central mechanism assigns tasks to them (Dou et al., 2015). However, in the presence of a solely centralised architecture, it might not be economical to use AMRs as their autonomy would not make a difference.

2.3.1.4 Facility Layout

Integration of many mobile robot systems requires a major change in the layout when deployed in manually operated warehouses. In addition to the general flow of the warehouse, decisions need to be made about the following subjects.

Number of floors. Modern warehouses are 8.5 to 11 meters high (Bartholdi and Hackman, 2019). However, many mobile robot systems, especially the ones for picking small products off shelving, do not utilise that height. Thus, single-floored warehouses now have the potential to double their storage area and throughput by installing a second floor (Lienert et al., 2019). This could be achieved through a mezzanine floor where mobile robots are operable (Wurman et al., 2008).

Number, size, and location of pick-up and delivery points. Most research on warehouse layout subjects related to mobile robot automation focuses on the aisle, cross-aisle, shelf, picking workstation and replenishment workstation quantities and sizes, and where to locate them. However, the literature is mainly concentrated on barcode-guided mobile robots, influenced by research focused on Kiva (Lamballais et al., 2020; Weidinger et al., 2018).

Queueing network models investigating the movement of tasks, such as from a shelf to a picking workstation, help design various layouts (Wang et al., 2020). The other option is to model the warehouse layout with variables and constraints and apply algorithms or heuristics to optimise the throughput (Zou et al., 2019).

Flow-path layout of mobile robots. The robots could travel on unidirectional (simple but inefficient) or bidirectional (complex but efficient) paths together with the idea of having multiple lanes on one route (Le-Anh and De Koster, 2006; Vis, 2006). Freeway robots do not require an infrastructure for routing, and alterations are much easier.

Idle vehicle and robot charging locations. When mobile robots are not assigned a task, they become idle and require a parking area (Vis, 2006). A parking area should minimise the reaction time of mobile robots to new assignments and avoid potential congestion (Le-Anh and De Koster, 2006). The same idea applies to robot charging locations. Hamann et al. (2018) and Zou et al. (2018) include them in the operational area to guarantee a close charging location. However, in many papers, idle vehicle parking and charging locations are overlooked or omitted, which makes empirical works unrealistic.

2.3.1.5 Human-Robot Interaction

Human-robot interaction and the role of human workers receive little attention with almost no research on the subject (Boysen et al., 2019). However, many automation systems involve human-robot interaction. Therefore, issues related to human-robot interaction should be considered before applying the chosen mobile robot system. Where possible, a change management team should be formed before introducing an automation system (Moeller et al., 2016).

Human Tasks. Currently, humans grasp items more efficiently. Since humans perform maintenance of robots, picking, broken-case replenishment, and packing tasks, human-robot interaction remains unavoidable. The distribution of tasks should be done according to the capabilities of both sides to maximise joint performance and minimise errors (Azadeh et al., 2019; Bechtsis et al., 2017).

Personnel Management. With the introduction of an automation solution, human workers feel a risk of job loss since some of the tasks are starting to be performed by robots (Bechtsis et al., 2017; Moeller et al., 2016). For this reason, human workers should be trained and incentivised to increase efficiency and throughput (Boysen et al., 2017, 2019). Moeller et al. (2016) illustrate an automation system implementation through a real-life case, propose ways of communicating with the workforce and outline a successful change management approach.

Human Safety. On one hand, the introduction of mobile robots may improve human safety due to more unmanned operations. However, especially when freely moving robots are involved, human safety can also be endangered (Raineri et al., 2019). A risk assessment study is required to identify unsafe scenarios in the simulation stage of a mobile robot system implementation (Inam and Raizer, 2018). Further, mobile robot multi-sensory systems could be used to increase awareness and decrease potential accidents (Bechtsis et al., 2017). Velocity planners (Raineri et al., 2019) and reinforcement learning applications (Sartoretti et al., 2019) are used to devise efficient trajectories while ensuring human safety. Petković et al. (2019) apply a Bayesian theory of mind approach for robots to estimate humans’ intentions and avoid entering areas which humans will occupy. Lastly, human vision could be enhanced through augmented reality showing workers the planned path of mobile robots and allowing them to draw virtual walls to prevent mobile robots from entering those safe areas (Papcun et al., 2019).

2.3.2 Tactical Level

Based on strategic decisions, tactical decisions need to be made next which have a medium-term effect on warehouse operations. These decisions are comparably easier to adjust during the implementation and ongoing operation compared to strategic level decisions. Still, they should not and generally cannot be changed in the short term.

2.3.2.1 Storage Assignment Plan

Decisions regarding quantity and type of products in pick locations are aligned with facility layout decisions at the strategic level. Once storage locations are decided, products should be distributed in a way that maximises product availability and accessibility. Product distribution depends on the quantities, shapes, and sizes of stock keeping units (SKUs) (Lamballais et al., 2020). Traditionally, these decisions remained unchanged for several months in most warehouses, but they can now be altered at short notice as some robots (barcode-guided mobile robots) are able to carry and change shelf positions whilst others (i.e., autonomous forklifts, mobile picking robots) can change product locations overnight without human assistance (Füßler et al., 2019).

ABC (class-based) storage divides products based on their turnover rate (De Koster, 2018). According to Weidinger et al. (2018), it performs best in the presence of mobile robots among five different storage policies, i.e., random storage, closest open location storage, dedicated storage, full-turnover storage, and ABC storage. However, better results could be achieved with hybrid approaches such as first dividing the warehouse into zones according to the ABC storage and then applying the closest open location storage within these zones (Ly, 2019).

Simulated annealing, a probabilistic optimisation algorithm could be used to assign one pick location to one SKU (Merschformann et al., 2019). However, having only one pick location for one SKU may impede efficient access, and it is common to distribute the same SKUs to more than one shelf (mixed-shelves storage) (Roy et al., 2019). Placing SKUs on different shelves increases availability and accessibility, which would deliver the same throughput with fewer mobile robots (Boysen et al., 2017; Lamballais et al., 2020).

Increasing product availability and accessibility improves warehouse efficiency. Related studies on storage assignment with robots are limited, and further research is needed to evaluate different storage policies for the various mobile robot systems.

2.3.2.2 Order Management Plan

The order management plan governs how to process incoming customer orders. This paper divides order management for mobile robots into static (offline) and dynamic (online) strategies.

Static order management. Customer orders are collected by the system and then divided into batches or waves with a cut-off point (Boysen et al., 2019). For batches, the cut-off point could be a certain quantity of orders, while for waves, it could be a time of the day (Rushton et al., 2014).

As order batching is computationally complex and time-consuming, heuristics might be used to obtain feasible but sub-optimal solutions (Li et al., 2017). Boysen et al. (2017) apply simulated annealing to batch orders and assert that sequencing orders present better solutions than sequencing shelves. Few papers use waves of orders as a static order management strategy (Sarkar et al., 2018; Xue and Dong, 2018). However, they do not analyse or compare the performance of wave picking to batching strategies, indicating a potential gap for future research.

Dynamic order management. Customer orders placed through the warehouse management system are directly added at the end of a picklist or get prioritised if they are urgent (Boysen et al., 2019). This way, urgent orders could quickly be dealt with, making the order fulfilment system agile and responsive. Even though many papers such as Lamballais et al. (2017) and Tai et al. (2018) use dynamic order management, none of them presents a performance comparison with static order management strategies.

Storage assignment and order management strategies should be jointly and dynamically determined to increase the throughput (He et al., 2018). Distributing the workload fairly among mobile robots or workstations would ensure all partial orders are finished nearly at the same time, which would decrease the sortation and packing challenges or robot conflicts and deadlocks (Boysen et al., 2019).

2.3.2.3 Quantity of Robots

The variable cost of mobile robot systems is based on the number of robots (Wang et al., 2020). For this reason, fleet sizing is a decision that should be made carefully as underestimating the fleet size would delay fulfilling orders and overestimating it would increase traffic, leading to conflicts and deadlocks.

There are two types of robot fleet behaviours. A ‘dedicated’ robot fleet can divide and dedicate themselves to workstations or human workers, whilst a ‘pooled’ robot fleet can act homogeneously to maximise the throughput (Yuan and Gong, 2017). Deciding on fleet behaviour helps the decision-maker to evaluate the fleet size more systematically. Roy et al. (2019) and Yuan and Gong (2017) studied pooled and dedicated mobile robots. Roy et al. (2019) suggest that using pooled robots instead of dedicated robots reduces the throughput time for order picking by up to one-third. Considering robot congestion and operable area, Yuan and Gong (2017) provide the optimal ratio for human pickers and robots for both alternatives.

Some of the papers minimised or optimised their fleet sizes while keeping the throughput the same using various models and algorithms (Ferrara et al., 2014; Liu, Ji, et al., 2019; Sarkar et al., 2018). Boysen et al. (2017) relate the optimum number of robots to SKU diversity and calculate the fleet size accordingly. For big vehicles such as autonomous forklifts, Polten and Emde (2020) advise decision-makers to have fewer mobile robots than the number of aisles to avoid congestion. Finally, as fleet size could be affected by task allocation strategies and traffic congestion, simulations could test different fleet sizes before or during real-life implementation (Le-Anh and De Koster, 2006).

Empirical papers that mention fleet sizing concentrate on proving their algorithms on various fleet sizes and most of them do not go beyond fleet comparisons on throughput performances. However, fleet size should also be optimised as an outcome of the algorithm as it is the biggest portion of the variable cost of mobile robot systems.

2.3.2.4 Maintenance and Failure Handling

Unmanned mobile robots can work continuously yet have lower maintenance costs compared to manned vehicles (Bechtsis et al., 2017). Maintenance costs could be lowered further if tasks are distributed evenly (Weidinger et al. 2018). Still, maintenance of mobile robots should be planned, including backup strategies for their downtime.

Mobile robots fail the most at ‘travelling to storage area’ and ‘travelling to workstation’ tasks (Yan, Zhang, et al., 2017). Corrective maintenance appears as a more expensive choice than preventive maintenance, but it provides long-term high efficiency (Yan et al., 2018).

To include robot failure in simulations, Witczak et al. (2020) apply a predictive fault-tolerant control algorithm and guarantee that all tasks would be completed irrespective of the faults of the robots. Another way to ensure task completion without system interruptions is a migration strategy that governs the transfer of tasks to another robot in case of a failure (Draganjac et al., 2016; Kattepur et al., 2018).

When a robot fails, four strategies may be followed: 1) ignore the broken robot, 2) pause the whole system, 3) restart the system and replan tasks, 4) reroute tasks from the broken robot to other robots (Lienert et al., 2019). Rerouting (Liu, Zhou, et al., 2019) only the robots affected by the malfunctioning robot’s tasks can maximise the throughput the most as it does not stop the whole system.

2.3.2.5 Robot Energy Management

Although one of the main advantages of mobile robots is the ability to work continuously through battery charging, energy management is one of the least attended subjects at tactical and operational levels. Besides, efficient energy management would affect the fleet size of mobile robots as well as the throughput of the warehouse by increasing robot availability (Vis, 2006).

Three energy management strategies are compared through queueing network. Taking into account that not all robot types can be inductively charged, it stands out as the best alternative in terms of throughput maximisation compared to plug-in charging and battery swapping (Zou et al. 2018). Even though battery swapping outperforms plug-in charging, it is a more expensive strategy.

Robots can create a charging task request based on their battery levels (Kattepur et al. 2018), or their battery levels could be calculated in time windows or task sequences to create a charging task for them (Xu et al., 2019). Amazon charges its Kiva robots for five minutes every 55 minutes (Hamann et al., 2018). Many studies charge mobile robots based on their energy levels using thresholds such as 20%, 40%, or 50% (Lee et al., 2019; Yoshitake et al., 2019; Zhang et al., 2018). An alternative approach is to create charging tasks according to the power consumed by active time and speed (Liu, Ji, et al., 2019).

The technology behind the energy capacity of robots is always developing to either power a stronger robot or increase the active time of a robot. An efficient charging type should be case-specific, and a charging threshold should be set to avoid energy-based failures during the operation.

2.3.3 Operational Level

Operational level decisions could be altered in the short term, and their effect on warehouse operations could be observed within the same month, week or day. Thus, warehouse managers can experiment with day-to-day decisions to optimise operational performance.

2.3.3.1 Mobile Robot Task Allocation

Allocation of tasks to a mobile robot could differ according to the chosen mobile robot system. For instance, for barcode-guided mobile robot systems, a picking task could be the transportation of a shelf, while it could mean picking a box from a shelf for mobile picking robots. In either application, robots should divide these tasks into subtasks such as navigating to the correct location, performing the lifting or the picking operation, and then carrying the material to where it is supposed to go (Wurman et al., 2008). As a solution approach, few papers apply the queueing theory to sort tasks and observe their performance outputs (Lamballais et al., 2017; Wang et al., 2020). Task allocation can be static/fixed or dynamic/online (Vivaldini et al., 2015).

Static/Fixed Task Allocation. Tasks are grouped with a cut-off point, a globally optimal plan is generated, and tasks are distributed to mobile robots (Singhal et al., 2018). However, the solution could be disrupted through unforeseen events such as breakdowns of robots, cancellation of tasks, or alterations in navigation times due to conflicts or deadlocks (Le-Anh and De Koster, 2006; Vivaldini et al., 2015). Furthermore, a globally optimised solution might not be scalable to hundreds of robots as it requires high computation time (Claes et al., 2017).

Dynamic/Online Task Allocation. With the help of this strategy, the system becomes more robust and scalable by prioritising tasks (Vivaldini et al., 2015). Task allocation requests are triggered through system status changes such as the completion of a task or the arrival of a new task, and the allocation is re-planned each time there is a trigger (Claes et al., 2017; Vivaldini et al., 2015). As these systems distribute the responsibility to intelligent robots with imperfect information and could only compute sub-optimal solutions (Claes et al., 2017), studies focus on having the best performance on optimality/computation efficiency ratio. Dynamic task allocation approaches need to be adapted and verified when hundreds of robots operate in the same warehouse, increasing the occurrences of unforeseen events.

2.3.3.2 Path Planning of Mobile Robots

Path planning determines the route mobile robots follow from the initial position to the desired position to start or finish a task in the shortest time. Generating the shortest path with numerous static and dynamic obstacles, including other mobile robots, make path planning a significant concern.

The performance of path planning algorithms can be assessed through four criteria: completeness (the ability to find the complete path), optimality (finding the path with the lowest time), time complexity (computational time to find the path), and space complexity (total computer memory absorbed to obtain the path) (Ng et al., 2020). Path planning algorithms are classified as coupled, decoupled, and dynamically coupled (Sartoretti et al., 2019).

Coupled algorithms such as Dijkstra’s and A* consider the system as a whole and theoretically guarantee optimality and completeness, but they suffer from time and space complexities (Draganjac et al., 2016). Further, coupled algorithms do not possess the ability to replan the paths in time as the environment changes (Ng et al., 2020).

Decoupled algorithms break path planning into instantaneous route planning and robot motion coordination forward through time to avoid collisions/conflicts. They are faster than coupled algorithms, but they suffer from completeness and optimality (Draganjac et al., 2016).

Dynamically coupled algorithms, a mixture of coupled and decoupled algorithms, plan routes and coordinate movement in the robot’s local area to decrease time complexity while still possessing the ability to find optimal or near-optimal solutions (Sartoretti et al., 2019). Dynamically coupled algorithms could be further studied and combined with task allocation and conflict avoidance strategies to obtain resilient and sustainable systems.

2.3.3.3 Deadlock Resolution and Conflict Avoidance Plans

Simply calculating a feasible route is not sufficient for multi-robot systems to operate. The operational structure should avoid or resolve any conflicts and deadlocks that may occur between mobile robots. This subject is often considered with path planning as ‘Multi-agent pathfinding’ (Sartoretti et al., 2019).

Robots have a variety of actions to overcome conflicts. After a negotiation or using a prioritisation strategy, a robot may wait, reroute, or step aside (Lee et al., 2019). Routes of robots may also be converted to time windows, and the same actions can be taken according to detected overlaps (Tai et al., 2018).

Deadlocks can cause more time loss than conflicts if they cannot be immediately identified. Vis (2006) defines deadlocks as the inability of multiple robots to move further because each robot aims to occupy the location currently occupied by another robot in the same group. Many papers follow cycles to identify deadlocks and pause mobile robots, change a robot’s task time to infinity, turn robots off for several seconds, or show neighbour robots as obstacles to force the robots to reroute (Qi et al., 2018; Sabattini et al., 2017).

Most of the research is focused on reactive approaches to conflict and deadlock avoidance. Instead, companies like Alibaba are adopting proactive approaches to finding an alternative route before a conflict occurs in order to maintain the flow of robots (Lee et al., 2019).

2.4 Discussion and Research Agenda

2.4.1 Mobile robot systems and selection criteria

This review mentions a variety of criteria to evaluate and choose mobile robot systems. The criteria outlined are derived from the literature to support decision-makers in warehouses. The research directions below could further support this logic and eliminate information deficiencies about mobile robot systems.

- A list of criteria to select the correct mobile robot system (i.e., cost, flexibility in infrastructure, flexibility in material handling, scalability, time-to-implement) could be developed and refined through practical applications with empirical evidence to aid decision-makers to choose the best solution.

- Even though picking is the most time-consuming and costliest activity in the warehouse, other operations such as sortation, put-away, and loading/unloading should also be evaluated when considering mobile robot system implementation.
- The performance (e.g., throughput, labour productivity) of mobile robot systems other than barcode-guided mobile robots have not been systematically evaluated due to a lack of simulations and real-life applications. Theory and practice should work together to analyse the performance of these other types under different scenarios.

2.4.2 Managerial decision framework

The hierarchical decision framework (Figure 2-2) is targeted at the design, planning and management of warehouses adopting mobile robot technologies in the digitalisation era. It synthesises decision areas identified through the systematic literature review and organises these across managerial decisions. It considers various choices put forward by the reviewed papers to capture a wide array of decision areas and criteria. Research areas stemming from the framework are as follows.

- To test and improve this conceptual framework’s structure and robustness with more focus areas and decision questions, further investigations could be carried out with the participation of experts and practitioners familiar with mobile robot implementation.
- The framework should be implemented with various mobile robot systems to illuminate the differences within the focus areas in distinct systems.

The following sub-sections provide research directions aimed at enhancing the applicability and generalisability of the managerial decision framework.

2.4.2.1 Strategic level focus areas

This review limits the strategic level to pre-implementation decisions, which would require considerable time and investment to implement selected technologies. For instance, Bechtsis et al. (2017) consider the number of robots (fleet sizing) as a strategic decision, whereas Wang et al. (2020) and Le-Anh and De Koster

(2006) suggest that it is tactical. Although the initial number of robots is decided before implementing a solution, the total number may be altered at the medium-term or tactical level. Keeping in mind this logic, the following pre-implementation research areas are identified.

- More than half of the studies do not mention how robots would be coordinated in the warehouse, yet future empirical research must explicitly consider it.
- Most papers assume a fixed layout which does not adequately reflect the flexible use of mobile robots and decreases the generalisability of the results. Thus, researchers should incorporate alternative layouts into the implementation of mobile robot automation.
- Human-robot interaction is not mentioned adequately and studying a mobile robot-only warehouse lacks practicality. Subjects such as ‘change management’ and ‘human safety’ require researchers’ attention to support system implementations and raise managers’ awareness of and sensibility to issues in human-robot interaction.

2.4.2.2 Tactical level focus areas

Tactical level decisions have impacts across time horizons and decision levels. For example, storage assignment is considered at the strategic and operational levels in separate studies (Füßler et al., 2019). Further, the order management plan is a common subject, but none of the papers reviewed allocates it to a particular level. It is considered tactical since it does not need to be decided before the system is implemented, and its effect on the system would be observed in the medium term. In support of managerial decisions at the tactical level, the following research avenues are put forward.

- Storage assignment decision is one of the least attended subjects, possibly because it is perceived as an inventory management decision rather than a mobile robot-related decision. However, how SKUs should be distributed in a warehouse can decrease the number of robots required and increase warehouse throughput.

- Fleet sizing is a significant barrier to implementing mobile robot systems. Yet, many papers leave fleet size optimisation unattended as their main aim is to prove the feasibility of algorithms. Optimum fleet size considerations should be included in empirical scenarios and simulations.
- Maintenance strategies should be evaluated and compared considering cost trade-offs, frequency, time requirements, and prevention effectiveness. Predictive maintenance for robot fleets is a promising research direction that could be coupled with actions in case of robot failures to maintain the continuity of operations.
- Robot energy management is understudied despite its impact on warehouse throughput, traffic congestion, fleet size, and space requirements for charging stations. Empirical studies need to optimise energy management strategies under trade-offs.

2.4.2.3 Operational level focus areas

Even though task allocation is mentioned as a tactical decision by Le-Anh and De Koster (2006), most authors consider it operational because it can be altered daily.

- Dynamic task allocation approaches need to be adapted to mobile robot systems as they hold the potential to improve managing chaotic warehouse environments.
- In path planning, instead of focusing on algorithms such as Dijkstra’s and A* that provide optimal solutions, computationally scalable sub-optimal approaches should be studied for large warehouses.
- Studies should concentrate on proactive conflict and deadlock management instead of reactive approaches (Lee et al., 2019). Proactive approaches are scarce in the literature, although they eliminate the time loss of two robots coming across each other.
- Many warehouses require large fleets of mobile robots in practice, but academic studies often simplify the scale of problems. Thus, suggested algorithms tend to be developed for unrealistic scenarios and should be tested for larger-scale applications. Additionally, traffic management

should be studied as the required sophistication and flexibility of a solution may increase at scale.

2.4.3 Research Agenda Summary

Figure 2-3 presents the research agenda of key topics for warehouse mobile robot systems. Each topic highlights an information deficiency or a necessity for elaboration on a decision-level-related subject. These subjects are a synthesis of the researcher's observations and the research suggestions gathered from the reviewed papers.

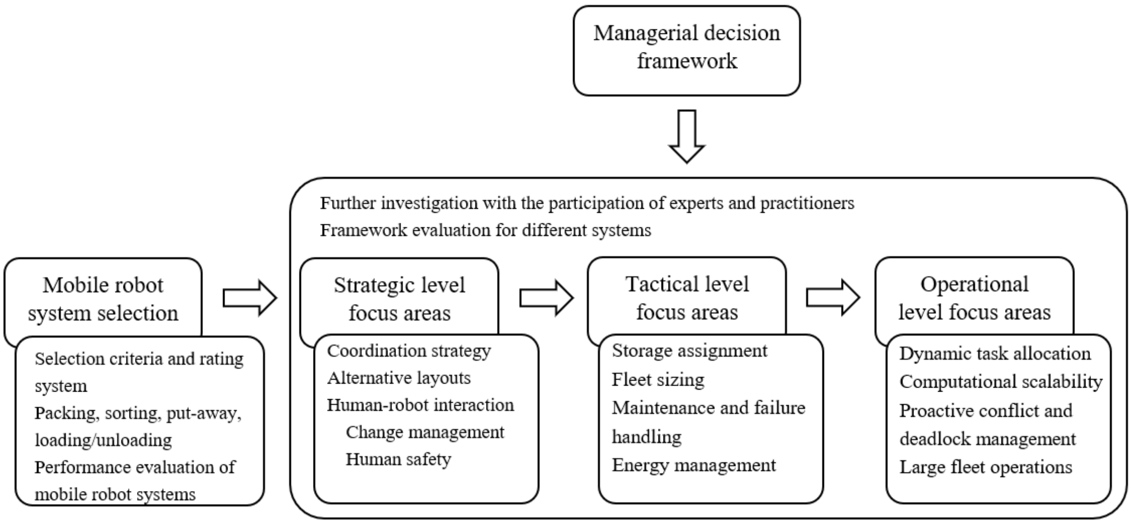


Figure 2-3 Key topics for the research agenda

2.5 Conclusion

This paper identified ten mobile robot systems in warehouses through a systematic literature review of 107 papers from four databases. A conceptual managerial decision framework was developed with thirteen strategic, tactical, and operational focus areas for the selection, implementation, and operations of mobile robot systems in warehouses. The framework will aid decision-makers to implement a suitable mobile robot solution, whilst the research avenues will help academics illuminate unattended areas, forming a balanced and complete guide to practice. Academia needs similar studies to explain the mobile robot system adoption process.

As with any study, there are limitations to this analysis. Firstly, the research reviewed is based on applicable academic databases only, focussing on studies from 2000 onwards. Thus, its outcomes might not completely reflect available mobile robot systems and all potential managerial focus areas of mobile robot applications in warehouses. Secondly, the managerial decision framework is conceptual, and its building blocks are exclusively derived from the identified papers. Hence, opportunities will be explored to test and develop the framework, incorporating implementation practices in future studies.

2.6 References to Chapter 2

Abbas, A.S., Mohamed, T.A. and Hazem, M. (2018), "Optimization of Warehouse Material Handling Parameters to Enhance the Efficiency of Automated Sorting and Storage Systems", Vol. 11 No. 1, p. 2018.

ABI Research. (2019), "50,000 Warehouses to Use Robots by 2025 as Barriers to Entry Fall and AI Innovation Accelerates", ABI Research, available at: https://www.abiresearch.com/press/50000-warehouses-use-robots-2025-barriers-entry-fall-and-ai-innovation-accelerates/ (accessed 21 February 2021).

Azadeh, K., De Koster, R.B.M. and Roy, D. (2019), Robotized and Automated Warehouse Systems: Review and Recent Developments, Transportation Science, Vol. 53, available at:https://doi.org/10.1287/trsc.2018.0873.

Bartholdi, J.J. and Hackman, S.T. (2019), Warehouse & Distribution Science, Available on Line at:/Http://Www. Tli. Gatech. Edu/

Bauters, K., De Cock, K., Hollevoet, J., Dobbelaere, G. and Van Landeghem, H. (2016), "A simulation model to compare autonomous vehicle based warehouses with traditional AS/RS systems", European Simulation and Modelling Conference 2016, ESM 2016, pp. 451–460.

Bechtsis, D., Tsolakis, N., Vlachos, D. and Iakovou, E. (2017), "Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles", Journal of Cleaner Production, Elsevier Ltd, Vol. 142, pp. 3970–3984.

Benady, D. (2016), "Will a robot take my job?", DHL, available at: https://www.dhl.com/global-en/home/about-us/delivered-magazine/articles/2016/issue-3-2016/will-a-robot-take-my-job.html (accessed 21 February 2021).

Bogue, R. (2016), "Growth in e-commerce boosts innovation in the warehouse robot market", Industrial Robot, Emerald Group Publishing Ltd., Vol. 43 No. 6, pp. 583–587.

Boysen, N., Briskorn, D. and Emde, S. (2017), “Parts-to-picker based order processing in a rack-moving mobile robots environment”, European Journal of Operational Research, Elsevier B.V., Vol. 262 No. 2, pp. 550–562.

Boysen, N., De Koster, R.B.M. and Weidinger, F. (2019), “Warehousing in the e-commerce era: A survey”, European Journal of Operational Research, Elsevier B.V., 1 September.

Chen, H., Wang, Q., Yu, M., Cao, J. and Sun, J. (2018), “Path Planning for Multi-robot Systems in Intelligent Warehouse”, Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Vol. 11226 LNCS, Springer Verlag, pp. 148–159.

Claes, D., Oliehoek, F., Baier, H. and Tuyls, K. (2017), Decentralised Online Planning for Multi-Robot Warehouse Commissioning.

Confessore, G., Fabiano, M. and Liotta, G. (2013), “A network flow based heuristic approach for optimising AGV movements”, Journal of Intelligent Manufacturing, Vol. 24 No. 2, pp. 405–419.

D’Emidio, M. and Khan, I. (2019), “Collision-free allocation of temporally constrained tasks in multi-robot systems”, Robotics and Autonomous Systems, Elsevier B.V., Vol. 119, pp. 151–172.

De Koster, R. B. M. (2018). Automated and robotic warehouses: developments and research opportunities. Logistics and Transport, 2(38De Koster, R. B. M. (2018). Automated and robotic warehouses: developments and research opportunities. Logistics and Transport, 2(38), 33–40. https://doi.org/10.26411/83-1734-2015-2-38-4–18), 33–40. https://doi.org/10.26411/83-1734-2015-2-38-4-18

De Koster, R. B. M., Le-Anh, T., and Van Der Meer, J. R. (2004). Testing and classifying vehicle dispatching rules in three real-world settings. Journal of Operations Management, 22(4 SPEC. ISS.), 369–386. https://doi.org/10.1016/j.jom.2004.05.006

Digani, V., Hsieh, M. A., Sabattini, L., and Secchi, C. (2019). Coordination of multiple AGVs: a quadratic optimization method. Autonomous Robots, 43(3), 539–555. https://doi.org/10.1007/s10514-018-9730-9

Digani, V., Sabattini, L. and Secchi, C. (2016), “A probabilistic Eulerian traffic model for the coordination of multiple AGVs in automatic warehouses”, IEEE Robotics and Automation Letters, Institute of Electrical and Electronics Engineers Inc., Vol. 1 No. 1, pp. 26–32.

Digani, V., Sabattini, L., Secchi, C. and Fantuzzi, C. (2015), “Ensemble Coordination Approach in Multi-AGV Systems Applied to Industrial Warehouses”, IEEE Transactions on Automation Science and Engineering, Institute of Electrical and Electronics Engineers Inc., Vol. 12 No. 3, pp. 922–934.

Dou, J., Chen, C. and Yang, P. (2015), “Genetic Scheduling and Reinforcement Learning in Multirobot Systems for Intelligent Warehouses”, Mathematical Problems in Engineering, Hindawi Publishing Corporation, Vol. 2015, available at:https://doi.org/10.1155/2015/597956.

Draganjac, I., Miklic, D., Kovacic, Z., Vasiljevic, G. and Bogdan, S. (2016), “Decentralized Control of Multi-AGV Systems in Autonomous Warehousing Applications”, IEEE Transactions on Automation Science and Engineering, Institute of Electrical and Electronics Engineers Inc., Vol. 13 No. 4, pp. 1433–1447.

Durach, C.F., Kembro, J.H. and Wieland, A. (2021), “How to advance theory through literature reviews in logistics and supply chain management”, International Journal of Physical Distribution and Logistics Management, available at:https://doi.org/10.1108/IJPDLM-11-2020-0381.

Enright, J. J., and Wurman, P. R. (2011). Optimization and coordinated autonomy in mobile fulfillment systems. AAAI Workshop - Technical Report, WS-11-09, 33–38.

Fan, Z., Gu, C., Yin, X., Liu, C. and Huang, H. (2018), “Time window based path planning of multi-AGVs in logistics center”, Proceedings - 2017 10th International

Symposium on Computational Intelligence and Design, ISCID 2017, Vol. 2, Institute of Electrical and Electronics Engineers Inc., pp. 161–166.

Farinelli, A., Boscolo, N., Zanotto, E. and Pagello, E. (2017), “Advanced approaches for multi-robot coordination in logistic scenarios”, Robotics and Autonomous Systems, Elsevier B.V., Vol. 90, pp. 34–44.

Fazlollahtabar, H. and Saidi-Mehrabad, M. (2015), “Methodologies to Optimize Automated Guided Vehicle Scheduling and Routing Problems: A Review Study”, Journal of Intelligent and Robotic Systems: Theory and Applications, Kluwer Academic Publishers, Vol. 77 No. 3–4, pp. 525–545.

Feng, L., Qi, M., Hua, S. and Zhou, Q. (2019), Picking Station Location in Traditional and Flying-V Aisle Warehouses for Robotic Mobile Fulfillment System, IEEE International Conference on Industrial Engineering and Engineering Management, Vol. 2019-Decem, available at:https://doi.org/10.1109/IEEM.2018.8607301.

Ferrara, A., Gebennini, E. and Grassi, A. (2014), “Fleet sizing of laser guided vehicles and pallet shuttles in automated warehouses”, International Journal of Production Economics, Elsevier B.V., Vol. 157 No. 1, pp. 7–14.

Fragapane, G., de Koster, R., Sgarbossa, F. and Strandhagen, J.O. (2021), “Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda”, European Journal of Operational Research, Elsevier B.V., Vol. 294 No. 2, pp. 405–426.

Füßler, D., Boysen, N. and Stephan, K. (2019), “Trolley line picking: storage assignment and order sequencing to increase picking performance”, OR Spectrum, Springer, Vol. 41 No. 4, pp. 1087–1121.

Geek+. (n.d.). “Forklift”, Geek+, available at: https://www.geekplus.com/robot/f-robot (accessed 21 February 2021).

Ghassemi, P. and Chowdhury, S. (2018), “Decentralized task allocation in multi-robot systems via bipartite graph matching augmented with fuzzy clustering”, ASME, 20 July.

Haiming, L., Weidong, L., Mei, Z. and An, C. (2019), Algorithm of Path Planning Based on Time Window for Multiple Mobile Robots in Warehousing System, Chinese Control Conference, CCC, Vol. 2019-July, available at:https://doi.org/10.23919/ChiCC.2019.8866325.

Hamann, H., Markarian, C., Auf Der Heide, F.M. and Wahby, M. (2018), "Pick, Pack, & Survive: Charging Robots in a Modern Warehouse based on Online Connected Dominating Sets", Leibniz International Proceedings in Informatics, LIPIcs, Vol. 100, Schloss Dagstuhl- Leibniz-Zentrum fur Informatik GmbH, Dagstuhl Publishing, pp. 221–2213.

Hanson, R., Medbo, L. and Johansson, M.I. (2018), "Performance Characteristics of Robotic Mobile Fulfilment Systems in Order Picking Applications", IFAC-PapersOnLine, Elsevier B.V., Vol. 51 No. 11, pp. 1493–1498.

He, Z., Aggarwal, V. and Nof, S.Y. (2018), "Differentiated service policy in smart warehouse automation", International Journal of Production Research, Taylor and Francis Ltd., Vol. 56 No. 22, pp. 6956–6970.

Horňáková, N., Jurík, L., Hrablik Chovanová, H., Cagáňová, D. and Babčanová, D. (2019), "AHP method application in selection of appropriate material handling equipment in selected industrial enterprise", Wireless Networks, Springer New York LLC, available at:https://doi.org/10.1007/s11276-019-02050-2.

Huang, G.Q., Chen, M.Z.Q. and Pan, J. (2015), "Robotics in ecommerce logistics", HKIE Transactions Hong Kong Institution of Engineers, Hong Kong Institution of Engineers, Vol. 22 No. 2, pp. 68–77.

Inam, R. and Raizer, K. (2018), Risk Assessment for Human-Robot Collaboration in an Automated Warehouse Scenario.

Kattepur, A., Rath, H.K., Simha, A. and Mukherjee, A. (2018), "Distributed optimization in multi-agent robotics for industry 4.0 warehouses", Proceedings of the ACM Symposium on Applied Computing, Association for Computing Machinery, pp. 808–815.

Kimura, N., Ito, K., Fuji, T., Fujimoto, K., Esaki, K., Beniyama, F. and Moriya, T. (2015), “Mobile dual-arm robot for automated order picking system in warehouse containing various kinds of products”, 2015 IEEE/SICE International Symposium on System Integration (SII), IEEE, pp. 332–338.

Krnjak, A., Draganjac, I., Bogdan, S., Petrovic, T., Miklic, D. and Kovacic, Z. (2015), Decentralized Control of Free Ranging AGVs in Warehouse Environments, Proceedings - IEEE International Conference on Robotics and Automation, Vol. 2015-June, available at:https://doi.org/10.1109/ICRA.2015.7139465.

Lamballais, T., Roy, D. and De Koster, R.B.M. (2017), “Estimating performance in a Robotic Mobile Fulfillment System”, European Journal of Operational Research, Elsevier B.V., Vol. 256 No. 3, pp. 976–990.

Lamballais, T., Roy, D. and De Koster, R.B.M. (2020), “Inventory allocation in robotic mobile fulfillment systems”, IISE Transactions, Taylor and Francis Ltd., Vol. 52 No. 1, pp. 1–17.

Lau, H.Y.K., Wong, V.W.K. and Lee, I.S.K. (2007), “Immunity-based autonomous guided vehicles control”, Applied Soft Computing Journal, Vol. 7 No. 1, pp. 41–57.

Le-Anh, T. and De Koster, R.B.M. (2006), “A review of design and control of automated guided vehicle systems”, European Journal of Operational Research, Elsevier, Vol. 171 No. 1, pp. 1–23.

Le-Anh, T., De Koster, R. B. M., and Yu, Y. (2010). Performance evaluation of dynamic scheduling approaches in vehicle-based internal transport systems. International Journal of Production Research, 48(24), 7219–7242. https://doi.org/10.1080/00207540903443279

Lee, C., Lin, B., Ng, K.K.H., Lv, Y. and Tai, W.C. (2019), “Smart robotic mobile fulfillment system with dynamic conflict-free strategies considering cyber-physical integration”, Advanced Engineering Informatics, Elsevier Ltd, Vol. 42, available at:https://doi.org/10.1016/j.aei.2019.100998.

Lee, H.Y. and Murray, C.C. (2019), “Robotics in order picking: evaluating warehouse layouts for pick, place, and transport vehicle routing systems”, International Journal of Production Research, Taylor and Francis Ltd., Vol. 57 No. 18, pp. 5821–5841.

Li, X., Zhang, C., Yang, W. and Qi, M. (2019), “Multi-AGVs conflict-free routing and dynamic dispatching strategies for automated warehouses”, Lecture Notes in Electrical Engineering, Vol. 513, Springer Verlag, pp. 277–286.

Li, Z., Barenji, A.V., Jiang, J., Zhong, R.Y. and Xu, G. (2020), “A mechanism for scheduling multi robot intelligent warehouse system face with dynamic demand”, Journal of Intelligent Manufacturing, Springer, Vol. 31 No. 2, pp. 469–480.

Li, Z.P., Zhang, J.L., Zhang, H.J. and Hua, G.W. (2017), “Optimal selection of movable shelves under cargo-to-person picking mode”, International Journal of Simulation Modelling, Vienna University of Technology, Vol. 16 No. 1, pp. 145–156.

Lienert, T., Stigler, L. and Fottner, J. (2019), “Failure-Handling Strategies For Mobile Robots In Automated Warehouses”, ECMS 2019 Proceedings Edited by Mauro Iacono, Francesco Palmieri, Marco Gribaudo, Massimo Ficco, ECMS, pp. 199–205.

Liu, S. (2018), “Research on scheduling policy of automated warehouse system”, ACM International Conference Proceeding Series, pp. 1–5.

Liu, Y., Chen, M. and Huang, H. (2019), Multi-Agent Pathfinding Based on Improved Cooperative A∗ in Kiva System, 2019 5th International Conference on Control, Automation and Robotics, ICCAR 2019, available at:https://doi.org/10.1109/ICCAR.2019.8813319.

Liu, Y., Ji, S., Su, Z. and Guo, D. (2019), “Multi-objective AGV scheduling in an automatic sorting system of an unmanned (intelligent) warehouse by using two adaptive genetic algorithms and a multi-adaptive genetic algorithm”, PLoS ONE, Public Library of Science, Vol. 14 No. 12, available at:https://doi.org/10.1371/journal.pone.0226161.

Liu, Z., Zhou, S., Wang, H., Shen, Y., Li, H. and Liu, Y.H. (2019), A Hierarchical Framework for Coordinating Large-Scale Robot Networks, Proceedings - IEEE International Conference on Robotics and Automation, Vol. 2019-May, available at:https://doi.org/10.1109/ICRA.2019.8793719.

Llopis-Albert, C., Rubio, F. and Valero, F. (2019), “Fuzzy-set qualitative comparative analysis applied to the design of a network flow of automated guided vehicles for improving business productivity”, Journal of Business Research, Elsevier Inc., Vol. 101, pp. 737–742.

Locus Robotics. (n.d.). “Locus”, Locus Robotics, available at: https://locusrobotics.com/why-locus/deployment/ (accessed 21 February 2021).

Ly, G.B. (2019), “Storage Assignment Policy and Route Planning of AGVS in Warehouse Optimization”, Proceedings of 2019 International Conference on System Science and Engineering, ICSSE 2019.

Ma, H. and Koenig, S. (2016), “Optimal Target Assignment and Path Finding for Teams of Agents”, Proceedings of the 15th International Conference on Autonomous Agents and Multiagent Systems.

Ma, H., Kumar, T.K.S., Li, J. and Koenig, S. (2017), “Lifelong multi-Agent path finding for online pickup and delivery tasks”, Proceedings of the International Joint Conference on Autonomous Agents and Multiagent Systems, AAMAS, Vol. 2, pp. 837–845.

Ma, Y., Wang, H., Xie, Y. and Guo, M. (2014), “Path planning for multiple mobile robots under double-warehouse”, Information Sciences, Elsevier Inc., Vol. 278, pp. 357–379.

Magazino. (n.d.). “Toru”, Magazino, available at: https://www.magazino.eu/products/toru/?lang=en (accessed 21 February 2021).

Merschformann, M., Lamballais, T., De Koster, R.B.M. and Suhl, L. (2019), “Decision rules for robotic mobile fulfillment systems”, Operations Research Perspectives, Elsevier Ltd, Vol. 6, available at:https://doi.org/10.1016/j.orp.2019.100128.

Moeller, K., Gabel, J. and Bertagnolli, F. (2016), “FISCHER FIXING SYSTEMS: MOVING FORWARD WITH THE WORKFORCE - CHANGE COMMUNICATION AT THE GLOBAL DISTRIBUTION CENTER”, Journal of Information Technology Education: Discussion Cases, Vol. 5 No. September 2017, p. 01.

Ng, M.K., Chong, Y.W., Ko, K. man, Park, Y.H. and Leau, Y.B. (2020), “Adaptive path finding algorithm in dynamic environment for warehouse robot”, Neural Computing and Applications, Springer, available at:https://doi.org/10.1007/s00521-020-04764-3.

Pagani, P., Colling, D. and Furmans, K. (2017), “Neural Network-Based Genetic Job Assignment for Automated Guided Vehicles”, Logistics Journal, Wissenschaftliche Gesellschaft fur Technische Logistik, Vol. 2017, available at:https://doi.org/10.2195/lj_Proc_pagani_en_201710_01.

Panda, M.R., Das, P.K., Dutta, S. and Pradhan, S.K. (2018), “Optimal path planning for mobile robots using oppositional invasive weed optimization”, Computational Intelligence, Blackwell Publishing Inc., Vol. 34 No. 4, pp. 1072–1100.

Papcun, P., Cabadaj, J., Kajati, E., Romero, D., Landryova, L., Vascak, J. and Zolotova, I. (2019), “Augmented Reality for Humans-Robots Interaction in Dynamic Slotting ‘Chaotic Storage’ Smart Warehouses”, IFIP Advances in Information and Communication Technology, Vol. 566, Springer New York LLC, pp. 633–641.

Petković, T., Puljiz, D., Marković, I. and Hein, B. (2019), “Human intention estimation based on hidden Markov model motion validation for safe flexible robotized warehouses”, Robotics and Computer-Integrated Manufacturing, Elsevier Ltd, Vol. 57, pp. 182–196.

Pittaway, L., Robertson, M., Munir, K., Denyer, D. and Neely, A. (2004), “Networking and innovation: A systematic review of the evidence”, International Journal of Management Reviews, Vol. 5–6 No. 3–4, pp. 137–168.

Polten, L. and Emde, S. (2020), “Scheduling automated guided vehicles in very narrow aisle warehouses”, Omega (United Kingdom), Elsevier Ltd, available at:https://doi.org/10.1016/j.omega.2020.102204.

Qi, M., Li, X., Yan, X. and Zhang, C. (2018), “On the evaluation of AGVS-based warehouse operation performance”, Simulation Modelling Practice and Theory, Elsevier B.V., Vol. 87, pp. 379–394.

Raineri, M., Perri, S. and Guarino Lo Bianco, C. (2019), “Safety and efficiency management in LGV operated warehouses”, Robotics and Computer-Integrated Manufacturing, Elsevier Ltd, Vol. 57, pp. 73–85.

Roy, D., Nigam, S., De Koster, R.B.M., Adan, I. and Resing, J. (2019), “Robot-storage zone assignment strategies in mobile fulfillment systems”, Transportation Research Part E: Logistics and Transportation Review, Elsevier Ltd, Vol. 122, pp. 119–142.

Rushton, A., Croucher, P. and Baker, P. (2014), Handbook of Logistics and Distribution Management.

Sabattini, L., Digani, V., Secchi, C. and Fantuzzi, C. (2017), Optimized Simultaneous Conflict-Free Task Assignment and Path Planning for Multi-AGV Systems, IEEE International Conference on Intelligent Robots and Systems, Vol. 2017-Septe, available at:https://doi.org/10.1109/IROS.2017.8202278.

Santos, J., Costa, P., Rocha, L., Vivaldini, K., Moreira, A.P. and Veiga, G. (2016), “Validation of a time based routing algorithm using a realistic automatic warehouse scenario”, Advances in Intelligent Systems and Computing, Vol. 418, Springer Verlag, pp. 81–92.

Sarkar, C., and Agarwal, M. (2019). Cannot avoid penalty? Let’s minimize. In Proceedings - IEEE International Conference on Robotics and Automation (Vols. 2019-May). https://doi.org/10.1109/ICRA.2019.8794338

Sarkar, C., Paul, H.S. and Pal, A. (2018), A Scalable Multi-Robot Task Allocation Algorithm, Proceedings - IEEE International Conference on Robotics and Automation, available at:https://doi.org/10.1109/ICRA.2018.8460886.

Sartoretti, G., Kerr, J., Shi, Y., Wagner, G., Satish Kumar, T.K., Koenig, S. and Choset, H. (2019), PRIMAL: Pathfinding via Reinforcement and Imitation Multi-Agent Learning, IEEE Robotics and Automation Letters, Vol. 4, available at:https://doi.org/10.1109/LRA.2019.2903261.

Schmidt, T. and Schulze, F. (2009), “Future approaches to meet complexity requirements in material handling systems”, FME Transactions, Vol. 37 No. 4, pp. 159–166.

Semwal, T., Jha, S.S. and Nair, S.B. (2018), “On Ordering Multi-Robot Task Executions within a Cyber Physical System”, ACM Transactions on Autonomous and Adaptive Systems, Vol. 12 No. 4, pp. 1–27.

Singhal, A., Singh, H.V., Penumatsa, A., Bhatt, N., Ambwani, P., Kumar, S. and Sinha, R. (2018), “An actor based architecture for multi-robot system with application to warehouse”, IoPARTS 2018 - Proceedings of the 2018 International Workshop on Internet of People, Assistive Robots and ThingS, Association for Computing Machinery, Inc, pp. 13–18.

Smolic-Rocak, N., Bogdan, S., Kovacic, Z. and Petrovic, T. (2010), “Time windows based dynamic routing in multi-AGV systems”, IEEE Transactions on Automation Science and Engineering, Vol. 7 No. 1, pp. 151–155.

SSI Schaefer. (n.d.). “Weasel”, SSI Schaefer, available at: https://www.ssi-schaefer.com/resource/blob/56444/83497a9083769c1946bcc30f9f706473/brochure-weasel-en-dam-download-en-2054--data.pdf.

Stern, R. (2019), “Multi-agent path finding – an overview”, Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Vol. 11866 LNAI, Springer, pp. 96–115.

Tai, R., Wang, J. and Chen, W. (2019), “A prioritized planning algorithm of trajectory coordination based on time windows for multiple AGVs with delay disturbance”, Assembly Automation, Emerald Group Publishing Ltd., Vol. 39 No. 5, pp. 753–768.

Tai, R., Wang, J., Tian, W., Chen, W., Wang, H. and Zhou, Y. (2018), “A Time-Efficient Approach to Solve Conflicts and Deadlocks for Scheduling AGVs in Warehousing Applications”, 2018 IEEE International Conference on Real-Time Computing and Robotics (RCAR), IEEE, pp. 166–171.

Thanos, E., Wauters, T. and Vanden Berghe, G. (2019), “Dispatch and conflict-free routing of capacitated vehicles with storage stack allocation”, Journal of the Operational Research Society, Taylor and Francis Ltd., available at:https://doi.org/10.1080/01605682.2019.1595191.

Tranfield, D., Denyer, D. and Smart, P. (2003), “Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review* Introduction: the need for an evidence- informed approach”, British Journal of Management, Vol. 14, pp. 207–222.

Tsang, K.F.E., Ni, Y., Wong, C.F.R. and Shi, L. (2018), “A Novel Warehouse Multi-Robot Automation System with Semi-Complete and Computationally Efficient Path Planning and Adaptive Genetic Task Allocation Algorithms”.

Vis, I.F.A. (2006), “Survey of research in the design and control of automated guided vehicle systems”, European Journal of Operational Research, Elsevier, Vol. 170 No. 3, pp. 677–709.

Vivaldini, K., Rocha, L.F., Becker, M. and Moreira, A.P. (2015), “Comprehensive review of the dispatching, scheduling and routing of AGVs”, Lecture Notes in Electrical Engineering, Vol. 321 LNEE, Springer Verlag, pp. 505–514.

Vivaldini, K., Rocha, L.F., Martarelli, N.J., Becker, M. and Moreira, A.P. (2016), “Integrated tasks assignment and routing for the estimation of the optimal number of AGVS”, International Journal of Advanced Manufacturing Technology, Springer-Verlag London Ltd, Vol. 82 No. 1–4, pp. 719–736.

Wang, H., Chen, W. and Wang, J. (2019), “Heterogeneous multi-agent routing strategy for robot-and-picker-to-good order fulfillment system”, Advances in Intelligent Systems and Computing, Vol. 867, Springer Verlag, pp. 237–249.

Wang, K., Yang, Y. and Li, R. (2019), “Travel time models for the rack-moving mobile robot system”, International Journal of Production Research, Taylor and Francis Ltd., available at:https://doi.org/10.1080/00207543.2019.1652778.

Wang, W., Wu, Y., Zheng, J. and Chi, C. (2020), “A comprehensive framework for the design of modular robotic mobile fulfillment systems”, IEEE Access, Institute of Electrical and Electronics Engineers Inc., Vol. 8, pp. 13259–13269.

Wei, C. and Ni, F. (2018), “Tabu temporal difference learning for robot path planning in uncertain environments”, Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Vol. 10965 LNAI, Springer Verlag, pp. 123–134.

Weidinger, F., Boysen, N. and Briskorn, D. (2018), “Storage assignment with rack-moving mobile robots in KIVA warehouses”, Transportation Science, INFORMS Inst.for Operations Res.and the Management Sciences, Vol. 52 No. 6, pp. 1479–1495.

Wior, I., Jerenz, S. and Fay, A. (2018), “Automated transportation systems subject to interruptions in production and intralogistics - a survey and evaluation”, International Journal of Logistics Systems and Management, Vol. 30 No. 4, p. 421.

Witczak, M., Majdzik, P., Stetter, R. and Lipiec, B. (2020), “A fault-tolerant control strategy for multiple automated guided vehicles”, Journal of Manufacturing Systems, Elsevier B.V., Vol. 55, pp. 56–68.

Wurman, P.R., DAndrea, R. and Mountz, M. (2008), Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses.

Xu, J., Wang, J. and Chen, W. (2019), An Efficient Recharging Task Planning Method for Multi-Robot Autonomous Recharging Problem, IEEE International Conference on Robotics and Biomimetics, ROBIO 2019, available at:https://doi.org/10.1109/ROBIO49542.2019.8961439.

Xue, F. and Dong, T. (2018), Research on the Logistics Robot Task Allocation Method Based on Improved Ant Colony Algorithm, Int. J. Wireless and Mobile Computing, Vol. 14.

Yan, R., Jackson, L.M. and Dunnett, S.J. (2017), "Automated guided vehicle mission reliability modelling using a combined fault tree and Petri net approach", International Journal of Advanced Manufacturing Technology, Springer London, Vol. 92 No. 5–8, pp. 1825–1837.

Yan, R.D., Dunnett, S.J. and Jackson, L.M. (2018), Optimising the Maintenance Strategy for a Multi-AGV System Using Genetic Algorithms, Safety and Reliability – Safe Societies in a Changing World, CRC Press, available at:https://doi.org/10.1201/9781351174664.

Yoshitake, H., Kamoshida, R. and Nagashima, Y. (2019), "New Automated Guided Vehicle System Using Real-Time Holonic Scheduling for Warehouse Picking", IEEE Robotics and Automation Letters, Institute of Electrical and Electronics Engineers Inc., Vol. 4 No. 2, pp. 1045–1052.

Yuan, R., Wang, H. and Li, J. (2019), The Pod Assignment Model and Algorithm in Robotic Mobile Fulfillment Systems, Proceedings - IEEE International Conference on Service Operations and Logistics, and Informatics 2019, SOLI 2019, available at:https://doi.org/10.1109/SOLI48380.2019.8955103.

Yuan, Z. and Gong, Y.Y. (2017), "Bot-in-time delivery for robotic mobile fulfillment systems", IEEE Transactions on Engineering Management, Institute of Electrical and Electronics Engineers Inc., Vol. 64 No. 1, pp. 83–93.

Zavadskas, E.K., Nunić, Z., Stjepanović, Ž. and Prentkovskis, O. (2018), "Novel Rough Range of Value Method (R-ROV) for selecting automatically guided vehicles (AGVs)", Studies in Informatics and Control, National Institute for R and D in Informatics, Vol. 27 No. 4, pp. 385–394.

Zhang, Z., Guo, Q., Chen, J. and Yuan, P. (2018), "Collision-Free Route Planning for Multiple AGVs in an Automated Warehouse Based on Collision Classification", IEEE Access, Institute of Electrical and Electronics Engineers Inc., Vol. 6, pp. 26022–26035.

Zou, B., Gong, Y. (Yale), Xu, X. and Yuan, Z. (2017), “Assignment rules in robotic mobile fulfilment systems for online retailers”, International Journal of Production Research, Taylor and Francis Ltd., Vol. 55 No. 20, pp. 6175–6192.

Zou, B., Xu, X., Gong, Y. (Yale) and De Koster, R.B.M. (2018), “Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system”, European Journal of Operational Research, Elsevier B.V., Vol. 267 No. 2, pp. 733–753.

Zou, Y., Zhang, D. and Qi, M. (2019), “Order picking system optimization based on picker-robot collaboration”, ACM International Conference Proceeding Series, Association for Computing Machinery, pp. 1–6.

3 Mobile Robots in Warehouses: Evaluation Criteria for System Selection

Abstract

Mobile robot systems are warehouse automation solutions that make order fulfilment scalable, agile, and flexible to cope with the increasing complexity of customer orders. A wide array of potential options exists in the market today. This study proposes a multiple-criteria decision framework based on a systematic literature review of 107 peer-reviewed papers to reduce the probability of a mismatch between the warehouse mobile robot system and the operational requirements. It also uses five supply chain experts' opinions on pre-defined criteria to address mobile robot system selection.

This paper illustrates the characteristics of ten mobile robot systems used in warehouse operations. Further, it defines a rating system consisting of evaluation criteria to support the selection of potential automation systems. Finally, it demonstrates how the 'Equal Weight' approach and the Full Consistency Method (FUCOM) can assist in the selection of the most appropriate mobile robot system. Managerial implications discuss how flexibility, scalability, cost, and adaptability could be incorporated into the strategic decision of mobile robot system selection.

3.1 Introduction

Warehouses face the challenge of meeting customers’ orders swiftly and efficiently whilst managing the increasing complexity and variability in order fulfilment. Driven by e-commerce, customer orders in retail sectors such as consumer electronics, groceries, clothing, pharmaceuticals, and footwear have become complex with large assortments of small products. Tens of thousands of daily orders for thousands of different products make the warehouse environment chaotic and complicate operations, especially the picking.

An order fulfilment system should be capable of handling fluctuating customer demand. On retail days such as Cyber Monday, the daily revenue of even a small-sized retailer could increase by up to threefold (ABI Research, 2019), which puts extreme pressure on all warehouse operations. Further, many customers expect their orders to be fulfilled on the same day or the next day, making scalability and flexibility vital for warehouse operations.

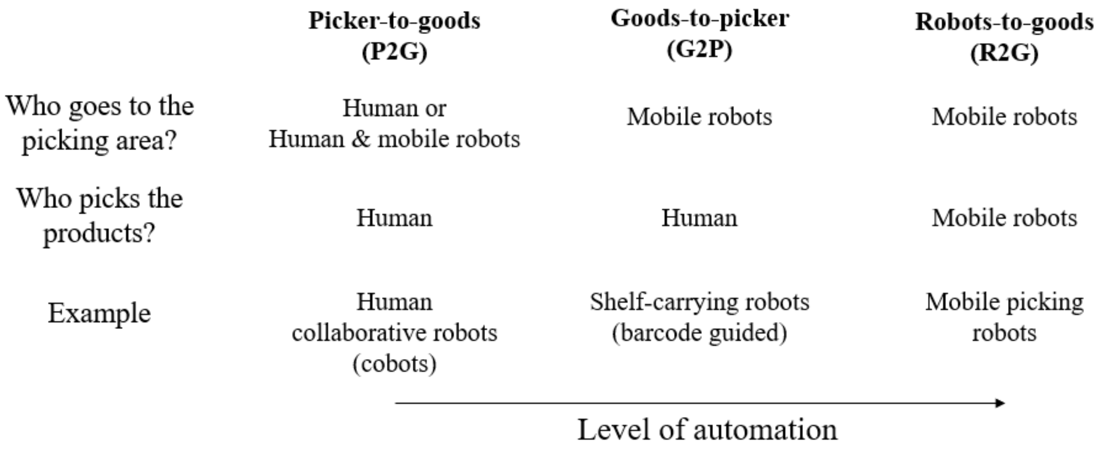
Order picking, which is the process of removing items from storage to shipping to meet a specific demand, is generally the most expensive operation, which may account for 50-55% of the total operating costs in manually operated warehouses (Bartholdi and Hackman, 2019). This high percentage is primarily due to the amount of time lost by pickers travelling, accounting for around 55% of the picker’s total time spent (Boysen et al., 2019).

By acquiring Kiva Systems, Amazon automated fulfilling e-commerce orders with autonomous mobile robots (AMRs) in their warehouses. Alibaba, Ocado, and JD.com are among the first companies that followed the warehouse automation move. With this technology adoption in order picking operations, Amazon has cut its operational warehouse costs by 20% and saved $22 million per annum in picking costs for each of its fulfilment centres (Bogue, 2016). They achieved this saving through AMRs in a goods-to-picker (G2P) setting (Wurman et al., 2008).

Automated Guided Vehicles (AGVs) were the only type of mobile robots without human drivers in warehouses until the early 2000s. These robots move materials by moving pallets, shelves, totes, boxes, or the material itself. They have little or no onboard intelligence and rely on orders coming from a centralised mechanism. They follow fixed and pre-programmed routes and stop when their sensors face an obstacle (Horňáková et al., 2019; Kattepur et al., 2018).

In the 2000s, AMRs were introduced to warehouses. These robots have high onboard intelligence, which helps them make decisions on their own (Kattepur et al., 2018). They can map the environment, plan their paths, dynamically respond to their surroundings, and bypass an obstacle by themselves, i.e., without being remotely controlled (Horňáková et al., 2019; Kattepur et al., 2018). These characteristics make AMRs more flexible and suitable for chaotic and complex warehouse environments such as those operated by e-commerce retailers.

G2P is an order picking method where goods are brought to the human picker by an automated system. Pickers stay stationary to do the picking and other related tasks while retrieved products are restored to their positions automatically (Azadeh et al., 2019). The second type of order picking method is the picker-to-goods (P2G) method, where human pickers travel to the goods generally with a material handling unit (De Koster, 2018). Human collaborative robot (co-bot) solutions are examples of this method. Recently there is a third type of order picking method named the robots-to-goods (R2G) method. In this more automated method, mobile picking robots travel to the shelves alone and do the picking on their own (Huang et al., 2015) (Figure 3-1).



	Picker-to-goods (P2G)	**Goods-to-picker (G2P)**	**Robots-to-goods (R2G)**
Who goes to the picking area?	Human or Human & mobile robots	Mobile robots	Mobile robots
Who picks the products?	Human	Human	Mobile robots
Example	Human collaborative robots (cobots)	Shelf-carrying robots (barcode guided)	Mobile picking robots

Figure 3-1 Order picking methods

A number of studies focus on warehouse design and order picking systems in an agile context (e.g., Azadeh et al., 2019; Baker, 2006; Boysen et al., 2019; Jaghbeer et al., 2020; Marchet et al., 2015; Wior et al., 2018). However, mobile robot automation and their evaluation and selection process through a set of evaluation criteria topics not covered or briefly mentioned. The research questions of this study are as follows.

RQ1. Which mobile robot systems are utilised in warehouses to support picking operations?

RQ2. Which decision criteria can facilitate mobile robot system evaluation and selection?

RQ3. How can warehouse decision-makers evaluate mobile robot systems before adoption?

This paper contributes to knowledge by developing a typology of mobile robots and associated systems that are adopted in picking operations. Further, this study evaluates mobile robot system alternatives through multiple-criteria decision-making approaches. It first aims to select the mobile robot system in a realistic scenario through an ‘Equal Weight’ approach for each criterion with a step-by-step decision tree. The ‘Equal Weight’ approach is used as a starting point to show when the decision changes depending on the criterion and how much each mobile robot system fulfils it. However, the weights of criteria influence the outcome of the decision-making process, and the importance of a criterion may depend on the context in which the warehouse automation will take place. Hence, the ‘Full Consistency Method’ (FUCOM) (Pamučar et al., 2018) is executed to show how the decisions vary depending on criteria weights inferred from expert opinions. FUCOM has already become quite popular and proved its validity in supply chain research (Durmić, 2019; Erceg and Mularifović, 2019; Sharma et al., 2021), for example, in forklift (Fazlollahtabar et al., 2019) and AGV (Zavadskas et al., 2018) selection. After implementing FUCOM, this study discusses additional criteria using the insights of five supply chain experts. In different scenarios, these additional criteria could be included with the primary evaluation and selection criteria defined in this study in the future to make more specific assessments.

The paper is organised as follows. Section 2 describes the methodology, which combines a systematic literature review with the multiple criteria decision-making approach demonstrated to select a mobile robot system. Section 3 presents the findings of the systematic literature review and an assessment of the mobile robot systems under five main criteria identified from the literature. Section 4 demonstrates the application of the equal-weight and the full consistency method with criteria importance data collected from supply chain experts. Section 5 discusses the results and areas to consider in the future. Finally, Section 6 concludes the paper.

3.2 Methodology

3.2.1 Identification of evaluation criteria through a systematic literature review

This paper builds on key insights from a large systematic literature review, including 107 peer-reviewed articles from 2000 to 2020. The rationale behind the systematic literature review (SLR) is to have a clear and comprehensive view of mobile robot systems being adopted in warehouses and the decisions that need to be made to integrate them with the operation. The research protocol followed in this review was adapted from Tranfield et al. (2003) and started with a scoping study that informed the research questions in two primary contexts: ‘Warehouse’ and ‘Mobile Robots’. Keyword groups were formed (S1 for warehouse and S2 for mobile robots), and keyword strings were gathered and combined with the ‘AND’ operator to search Scopus, Web of Science, ABI Inform, and EBSCO. Only articles from 2000 and conference papers from 2015 to 2020 were considered relevant owing to the recency of the technology. Only peer-reviewed papers in English on warehouses and mobile robots were considered (Figure 2-1).

Quality criteria were adopted from Pittaway et al. (2004) to select and evaluate publications, including theory robustness, contribution to knowledge, methodology and arguments, and implications for practice. Papers were rated on a scale of zero to three in each of the four criteria, and articles scoring 8 out of 12 qualified for review, resulting in 107 papers.

3.2.2 The 'Equal Weight' Approach

Using the insights of the SLR, a list of evaluation criteria was derived to aid decision-makers in choosing the most suitable mobile robot system. Giving equal weight to each criterion, a realistic but hypothetical scenario is created to demonstrate the execution of mobile robot system selection through multiple evaluation criteria. The scenario is further elaborated by a step-by-step decision tree to choose the appropriate mobile robot system for that specific scenario.

3.2.3 The Full Consistency Method (FUCOM)

While the 'Equal Weight' approach is simple to use and can be compared with other multi-criteria decision-making (MCDM) methods as a benchmark to the case where managers accommodate different weights to criteria. FUCOM is selected to demonstrate the decision approach, a recent MCDM method introduced by Pamučar et al., (2018). It can provide better results in terms of result consistency than the other subjective methods such as the 'Best Worst Method' and the 'Analytic Hierarchy Process' with the ability to validate the results by defining the deviation from maximum consistency (Durmić, 2019; Pamučar et al., 2018). It also requires a smaller number of pairwise criteria comparisons that are even fewer than the number of criteria (number of comparisons = number of criteria - 1) (Đorđević et al., 2019).

As FUCOM uses expert evaluations, before FUCOM steps, the researcher approached five supply chain experts to act as decision-makers in this study. Data are collected through a questionnaire with informed consent (5.5B.1). Experts are identified from the researcher's and his supervisors' networks as they have 30+ years of expertise in the warehouse, supply chain management, and decision-making among themselves. All supply chain experts have been working at a large-sized company (headcount 250+) for more than ten years (Table 3-1).

Table 3-1 Information about experts

Experts	Years of Experience	Role	Company Sector	Company Headcount
Expert 1	17	Strategic Relationship Manager (Supply Chain)	Aviation	680
Expert 2	20	Head of Logistics Engineering	Automotive	4,160
Expert 3	27	Logistics Transformation Project Manager	Food Products and Beverages	270,000
Expert 4	10	Senior Lecturer in Logistics and Supply Chain	University	3,000
Expert 5	20	Head of Accelerated Digitalisation	Logistics Provider	500,000

In the FUCOM method, a predefined set of evaluation criteria *C = {C1, C2, …, Cn}* are initially ranked by decision-makers individually. The ranking is performed according to the significance of the criteria, i.e., starting from the criterion, which is expected to have the highest significance to the criterion of the least significance. Thus, the criteria ranked according to the expected values of the weight coefficients are obtained:

$$C_{j(1)} > C_{j(2)} > \cdots > C_{j(k)}$$

(3-1) Ranking of criteria according to their weight

where 'k' represents the rank of the criterion. If two of the criteria are judged to have the same significance, the sign '>' is replaced with the sign of equality in Expression (3-1).

In the second step, a comparison of the ranking criteria is carried out and the comparative priority ($\phi_{k/(k+1)}$, k = 1, 2, …, n, where k represents the rank of the criteria) of the evaluation criteria is determined. The comparative priority ($\phi_{k/(k+1)}$) represents the significance or the priority that the criterion $C_{j(k)}$of $C_{j(k)}$ rank over the criterion of $C_{j(k+1)}$ rank. For instance, if the criterion of C_(j(k)) rank has the same significance as the criterion of $C_{j(k+1)}$ rank, then the comparative priority is $\phi_{k/(k+1)}$ = 1. The comparison scale is [1,9], where ‘1’ means equal importance and ‘9’ means nine times more important compared to the next most important criterion (Pamučar et al., 2018).

$$\phi = (\phi_{\frac{1}{2}}, \phi_{\frac{2}{3}}, \dots, \phi_{\frac{k}{k+1}})$$ **(3-2) Comparative priority vector**

In the third step, the final values of the weight coefficients of the evaluation criteria $(w_1, w_2, \dots, w_n)^T$ are calculated. The final values of the weight coefficients should satisfy the following two conditions:

(a) the ratio of the weight coefficients is equal to the comparative priority among the observed criteria ($\varphi_{k/(k+1)}$) defined in Step 2, i.e., the following condition is met:

$$\frac{w_k}{w_{k+1}} = \phi_{k/(k+1)}$$ **(3-3) Equation of ratio of the weight coefficients to comparative priority**

(b) In addition to the previous condition, the final values of the weight coefficients should satisfy the condition of mathematical transitivity, i.e., $\phi_{k/(k+1)} \otimes \phi_{(k+1)/(k+2)} = \phi_{k/(k+2)}$.

Since $\phi_{k/(k+1)} = \frac{w_k}{w_{k+1}}$ and $\phi_{(k+1)/(k+2)} = \frac{w_{k+1}}{w_{k+2}}$, $\frac{w_k}{w_{k+1}} \otimes \frac{w_{k+1}}{w_{k+2}} = \frac{w_k}{w_{k+2}}$ is obtained. Hence, another condition that the final values of the weight coefficients of the evaluation criteria need to meet is obtained:

$$\frac{w_k}{w_{k+2}} = \phi_{k/(k+1)} \otimes \phi_{(k+1)/(k+2)}$$ **(3-4) Equation of mathematical transitivity condition**

Based on the defined settings, the model for determining the final values of the weight coefficients of the evaluation criteria can be defined.

$$\min \chi$$ **(3-5) Final model**

s.t.

$$\left|\frac{w_{j(k)}}{w_{j(k+1)}} - \phi_{k/(k+1)}\right| \leq \chi, \forall_j$$

$$\left|\frac{w_{j(k)}}{w_{j(k+2)}} - \phi_{k/(k+1)} \otimes \phi_{(k+1)/(k+2)}\right| \leq \chi, \forall_j$$

$$\sum_{j=1}^{n} w_j = 1, \forall_j$$

$$w_j \geq 0, \forall_j$$

By solving the model (3-5), the final weights of the evaluation criteria (w_1, w_2, …, w_n)^T and the degree of deviation from full consistency, 'χ' are generated where the closer this value is to zero, the more reliable and consistent the result gets. The last step would be using the resulting criteria weights to select the suitable mobile robot system.

3.3 Analysis of Mobile Robot Systems

Systems involving these mobile robots can be categorised into three according to their types of navigation: rail-using, guided, and freeway (Wior et al., 2018). This paper adopts that categorisation strategy and introduces a fourth category: linear route robots, guided robots, freeway robots, and hybrid systems. Linear route robots cover rail using robots and add wire using robots. Since these systems might be used together with Automated Storage and Retrieval Systems (AS/RS) or other systems, hybrid systems are included as the fourth category.

Cost, service level, flexibility, and scalability are the four main criteria to evaluate mobile robot systems (Schmidt and Schulze, 2009). Except for the service level criterion, the other three criteria are mentioned in many other studies (Azadeh et al., 2019; Bauters et al., 2016; Hanson et al., 2018; Huang et al., 2015; Roy et al., 2019; Zou et al., 2018). In these studies, flexibility is explained in two contexts: 'Flexibility of the Infrastructure' and 'Flexibility in Material Handling'. Further, to estimate the cost criterion, this paper considers cost as the fixed 'Mobile Robot

Cost'. Costs associated with the decisions on fleet size, i.e., how many robots to deploy in a warehouse, are not included in the current demonstration.

Many warehouses are still manually operated. Once these warehouses recognise the need to transform their operational model into an automated system, they should consider the mobile robot systems' required installation and implementation time. Hence, 'Time to Implement' is considered as a decision criterion in this paper to give the managers an idea of the time these systems require to implement. These criteria are rated by the researcher on a 3-point scale where the higher the score, the better the performance in the given criterion. Explanations of these criteria in terms of ratings are presented in Table 3-2. Considering these factors, an overview of mobile robot systems is made, and their use cases in picking operations are explained in the following sub-sections. To supplement the information available in the reviewed academic literature, the researcher also utilised additional selected sources. After the analysis, a synthesis table displays the ratings of mobile robot systems from each criterion.

Table 3-2 Mobile robot system evaluation criteria and ratings

Rating	Mobile Robot Cost	Flexibility of the Infrastructure	Flexibility in Material Handling	Scalability	Time to Implement
3	Has neither the onboard intelligence nor the gripping function	Infrastructure is not fixed; it is easy to adapt to process/layout changes	Capable of handling bulky products (palletised) or small products (bins/boxes)	Responds to dynamic demand changes within days with extra robots only	Needs weeks for the setup (software installation and training)
2	Has either onboard intelligence or gripping function	Infrastructure is not completely fixed; a new setup is necessary to adapt	Capable of handling a variety of products, but might require adjustments	Besides extra robots, needs low-level construction or human workforce	Needs a few months for the setup (railways, barcodes, laser systems)
1	Has both the gripping function and the onboard intelligence	Infrastructure is fixed; it is hard to adapt to process/layout changes	Can only handle either bulky products or small products	Besides extra robots, it has high-level construction requirements	Needs several months for the setup (high level of construction)

3.3.1 Linear Route Robots

Mobile robots that follow a linear route, made of rails or wires, have been used in logistics to transport products within the warehouse since the 1950s (Wurman et al., 2008). The main difference between them is the structure they travel on (rail or wire). Recent P2G examples also adaptable to chaotic warehouse contexts are the trolley line picking system (Füßler et al., 2019) and the AGV Weasel system (AGV Weasel, n.d.). These systems can also be utilised in put-away (S. Liu, 2018) and sortation (Abbas et al., 2018) operations. As both types of linear route robots have similar outcomes in decision criteria evaluation, the researcher deems one evaluation for both systems sufficient.

Mobile Robot Cost. Linear route robots can only move linearly in the environment and cannot bypass obstacles. Thus, instead of AMRs, AGVs are preferred for such systems that do not require extensive onboard intelligence (Wior et al., 2018) (Rating: 3).

Flexibility of the Infrastructure. They are not adaptable to process or layout changes since they stand on a fixed infrastructure (railways or wires) (Rating: 1).

Flexibility in Material Handling. They are flexible from the material handling perspective as they can transport heavy products on pallets and small products in bins (Rating: 3).

Scalability. They are not easily scalable because, along with mobile robots, these systems require new routes and a low-medium level of floor construction which may last for several weeks to increase the existing system capacity (Rating: 2).

Time to Implement. SSI Schaefer mentions the implementation time of the system as five weeks since warehouse floors require construction (AGV Weasel, n.d.) (Rating: 2).

3.3.2 Guided Robots

Guided robots are more recent systems and, due to their ability to move non-linearly, they have more flexibility in terms of navigation when compared to linear route robots. There are two types of guided robots used in picking operations: barcode-guided robots and laser-guided robots.

3.3.2.1 Barcode Guided Robots

Barcode-guided robots became popular with Amazon's acquisition of Kiva Systems, which increased Amazon's worker productivity up to threefold (Enright and Wurman, 2011). Mobile robots travel on grid-based and restricted layouts in a G2P method. They are generally used in order picking operations (Wurman et al., 2008; Yoshitake et al., 2019), but they are also included in solutions to other warehouse operations such as sortation (Fan et al., 2018; Y. Liu et al., 2019).

Mobile Robot Cost. Due to their ability to sense and bypass dynamic obstacles during their navigation, AMRs are preferred over AGVs. Overall, with the requirement of specialised shelves and barcode floor construction and AMRs, these systems are costlier than linear route robots in terms of mobile robot costs (Rating: 2).

Flexibility of the Infrastructure. They require a dedicated area that might necessitate additional time to adapt to the potential process/layout changes (Wurman et al., 2008) (Rating: 2).

Flexibility in Material Handling. They can carry shelves that have tote bins to pickers or boxes to sortation stations (Enright and Wurman, 2011; Y. Liu et al., 2019). They can also transport palletised products with system adjustments as they can carry up to 1300 kgs of weight (Azadeh et al., 2019) (Rating: 3).

Scalability. These systems could easily increase or decrease their capacity by adding or removing robots and shelves when the workload varies (Boysen et al., 2019) (Rating: 2).

Time to Implement. Barcode installation and special shelf placement in a dedicated area require a few months (Geek+, n.d.) (Rating: 2).

3.3.2.2 Laser-Guided Robots

Laser-guided robots are generally used to carry pallets in warehouse operations and only require mirrors in strategic locations to help them map and navigate freely across that environment in an R2G setting (Ferrara et al., 2014; Ly, 2019).

Mobile Robot Cost. As they navigate on predefined paths, AGVs with forks are generally preferred for laser-guided operations (Rating: 2).

Flexibility of the Infrastructure. This system takes advantage of mirrors placed in an area, and they are only able to adapt to a new process/layout with a new setup (Ferrara et al., 2014) (Rating: 2).

Flexibility in Material Handling. Laser-guided mobile robots can only carry pallets (Ferrara et al., 2014; Ly, 2019; Polten and Emde, 2020) (Rating: 1).

Scalability. For similar reasons, they are adaptable to varying workloads just like barcode-guided robots. However, they are big vehicles and adding too many could decrease the warehouse space available for navigation (Polten and Emde, 2020) (Rating: 2).

Time to Implement. Installation of mirrors and the integration of the system could take several months even though it is a low-medium level construction (Banker, 2018) (Rating: 2).

3.3.3 Freeway Robots

Freeway robots do not generally require construction, and they move in the warehouse autonomously, without limitations. Owing to their ability to map the warehouse with its onboard intelligence, AMRs are the only choice in these systems (Wior et al., 2018). There are three types of freeway robot systems: autonomous forklifts, human-collaborated robots, and mobile picking robots.

3.3.3.1 Autonomous Forklifts

Just like laser-guided robots, autonomous forklifts are generally used to carry pallets in warehouse operations in an R2G setting.

Mobile Robot Cost. Even though it is not as expensive as a gripping function, these robots have forks that lift pallets autonomously (Rating: 1).

Flexibility of the Infrastructure. They do not need any fixed infrastructure, making them highly flexible to adapt to layout and process alterations (Rating: 3).

Flexibility in Material Handling. Autonomous forklifts mainly carry pallets (Draganjac et al., 2016; Li et al., 2019) (Rating: 1).

Scalability. Even though they are oversized vehicles like laser-guided robots, they are somewhat suitable for capacity adjustment since they can scale up or down with more or less mobile robots (Rating: 3).

Time to Implement. They have a relatively short installation time as they require no construction, and they are ready to operate as soon as they are in the warehouse (“Forklift” 2021) (Rating: 3).

3.3.3.2 Human Collaborated Robots

Human-collaborated mobile robots operate with human pickers in a P2G context. Robots either travel with a human picker (fixed-assigned) or to human pickers who are waiting for them in the aisles of the warehouses (free-floating). The picker picks the products from the picklist and puts them onto the robot in the fixed-assigned scenario. Once the robot reaches the capacity or the order list is complete – whichever is earlier, it returns to the packing station and another robot is requested to meet the picker. In the free-floating scenario, human pickers stand in the aisles of the warehouse, and mobile robots travel in the warehouse according to their picking list. Once they request a product, they travel to the correct aisle and wait for the picker to load the product. When they reach their capacity, they return to the packing station and unload the products (Boysen et al., 2019).

Mobile Robot Cost. Although closely following a human worker necessitates AMRs, gripping functionality is not required (Rating: 2)

Flexibility of the Infrastructure. These robots do not have any fixed infrastructure, so they are adaptable to layout or process adjustments (Rating: 3).

Flexibility in Material Handling. They can collect small products or boxes, but they cannot operate with bulky palletised-products as human workers cannot lift them (Rating: 2).

Scalability. They are suitable for a chaotic warehouse setting since they can easily coordinate and scale with more mobile robots, but they also require an additional human workforce (Rating: 2).

Time to Implement. They have a short implementation time ranging from days to a few weeks as they become operational immediately upon installation (Locus, n.d.). The human-collaborated mobile robot system is highly adaptive and does not require a re-layout while transforming manually operated order picking in conventional warehouses (De Koster, 2018; Wang et al., 2019).

3.3.3.3 Mobile Picking Robots

Mobile picking robots are relatively new and popular because they can do the picking on their own in the R2G setting. This feature removes human errors and human costs in the order picking operation. They have compartments or tote bins on them, and they put the products they pick into these spaces. Once they reach their capacity, they return to the packing area to unload (Bogue, 2016; Huang et al., 2015).

Mobile Robot Cost. This system requires the robot to have gripping functionality and high-level onboard intelligence, which increases the costs of robots (Rating: 1).

Flexibility of the Infrastructure. Like human-collaborated robots, these robots do not have any fixed infrastructure, so they are adaptable to layout or process adjustments (Rating: 3).

Flexibility of Material Handling. They have limited flexibility in terms of materials they can transport because of materials' weight (a few kg) and shape (boxes or products that have edges) requirements (Kimura et al., 2015). Moreover, the picking areas of the robots should be structured for correct and efficient picking

(Huang et al., 2015). Yet, there are ongoing object detection studies to correctly identify products on an unstructured shelf (Bormann et al., 2019) (Rating: 1).

Scalability. They are suitable for a chaotic warehouse setting since they can coordinate and scale quickly with more mobile robots without any additional needs (Huang et al., 2015) (Rating: 3).

Time to Implement. They need weeks rather than months to implement as they become operational immediately upon installation (Zero to automated in weeks not months., n.d.) (Rating: 3).

3.3.4 Hybrid Systems

Hybrid systems combine at least one mobile robot system with other solutions. These solutions might be preferable to remove the disadvantage of a specific system or take advantage of a higher level of automation. The literature reveals three types of hybrid systems, all of which operate in the R2G method: 1) AS/RS, conveyors, and linear route robots; 2) picker and transport robots; 3) laser-guided robots and pallet shuttles.

3.3.4.1 AS/RS, Conveyors, and Linear Mobile Robots

These systems are generally helpful if the warehouse traffic consists mainly of pallets or similar handling units according to the capability of the AS/RS. In this system, when the AS/RS retrieves the required pallet, they are taken by mobile robots and put on a conveyor for further processing (S. Liu, 2018).

Mobile Robot Cost. AGVs suffice to carry the products or pallets taken from the AS/RS or conveyors (Rating: 3).

Flexibility of the Infrastructure. The system is fixed and is not adaptive to any process or layout changes due to its infrastructure (Rating: 1).

Flexibility of Material Handling. Together with carrying different sizes of products, an AS/RS can only take one type of handling unit due to its physical build (Bauters et al., 2016) (Rating: 1).

Scalability. The system is not scalable as it would need new construction to increase the system capacity (Roy et al., 2019; Wurman et al., 2008) (Rating: 1).

Time to Implement. It takes between six months and a year to construct the system to become operable (Cribley, 2014) (Rating: 1).

3.3.4.2 Picker & Transport Robot

These solutions are akin to the human-collaborated system. Picker robots with gripping functionality to fetch and lift small products replace human pickers, and transport robots carry products placed into tote bins or pallets on them to completely automate the picking operation in an R2G context (Bogue, 2016; Kimura et al., 2015; Lee and Murray, 2019).

Mobile Robot Cost. For picking, AMRs with gripping functionality and for transportation, AMRs with material handling units are necessary. For this reason, mobile robot costs are relatively high (Rating: 1).

Flexibility of the Infrastructure. Like mobile picking robots, these robots do not have any fixed infrastructure, so they are adaptable to layout or process adjustments (Rating: 3).

Flexibility of Material Handling. This system is not flexible in terms of product types or product handling units that can be carried. For instance, the picking robot of Fetch Robotics could lift products that weigh up to 6 kg, and its arm has a reach of 2 m (Bogue, 2016) (Rating: 1).

Scalability. These systems are scalable with more mobile robots, ensuring their robustness against malfunctions (Huang et al., 2015) (Rating: 3).

Time to Implement. The system requires weeks to implement as robots could operate as soon as they are placed in the warehouse with a structured picking area and require no construction (Zero to automated in weeks not months., n.d.) (Rating: 3).

3.3.4.3 Laser-Guided Robots & Pallet Shuttles

These systems differ from a laser-guided mobile robot system in automating pallet movements in shelves from the face to the interior with pallet shuttles in an R2G context. Pallets are stored on rails, narrow aisles are removed, and pallet storing is optimised with the help of these pallet shuttles (Ferrara et al., 2014).

Mobile Robot Cost. AGVs are generally preferred for these systems, similar to the case with laser-guided robot solutions (Rating: 3).

Flexibility of the Infrastructure. Shelving units are fixed infrastructures that are hardly adaptable to process or layout alterations (Rating: 1).

Flexibility of Material Handling. This system only works with pallets or similar handling units, which decreases flexibility in material handling (Rating: 1).

Scalability. There is high-level construction work for the shelves that hold pallet shuttles and light construction work due to the laser-guided robot system structure that prevents rapid capacity alteration (Rating: 1).

Time to Implement. It may take several months to implement this solution due to the high-level construction work (Rating: 1).

Based on the system evaluations above, Table 3-3 summarises the ratings of mobile robot systems concerning each criterion. As the ratings of mobile robot systems regarding the five main evaluation criteria are explained, decision-makers can now select the appropriate solution for themselves using a decision-making approach. The following section illustrates strategies for system selection using Table 3-3.

Table 3-3 Rating table

Mobile Robot Systems (System Method)	**Mobile Robot Cost**	**Flexibility of Infrastructure**	**Flexibility in Handling**	**Scalability**	**Time to Implement**
Rail or Wire -Using Robots (P2G)	3	1	3	2	2
Barcode-Guided Robots (G2P)	2	2	3	2	2

Laser-Guided Robots (R2G)	2	2	1	2	2
Autonomous Forklifts (R2G)	1	3	1	3	3
Human-Collaborated Robots (P2G)	2	3	2	2	3
Mobile Picking Robots (R2G)	1	3	1	3	3
AS/RS, Conveyors, Linear Route Robots (R2G)	3	1	1	1	1
Picker & Transport Robots (R2G)	1	3	1	3	3
Laser-Guided Robots & Pallet Shuttles (R2G)	3	1	1	1	1

3.4 Mobile Robot System Selection

This section uses two independent mobile robot system assessment approaches using multiple decision criteria: the ‘Equal Weight’ approach and FUCOM. The ‘Equal Weight Approach’ uses a scenario and demonstrates multiple evaluation criteria for targeted decision-making. This approach is considered for its ease of use and for establishing a benchmark for other decision methods. Then, FUCOM is applied to the same set of criteria using an alternative methodology.

3.4.1 The ‘Equal Weight’ Approach

As the first demonstration approach, all five criteria were assumed to have equal weight in the decision-making process. The rationale is further explained with a realistic scenario with a step-by-step decision tree to provide a guided example of the approach. The approach towards the scenario is not limited to mobile robot systems mentioned in this paper but can include any others as it is based on the evaluation criteria rather than being system-specific (Figure 3-2).

3.4.1.1 Mobile Robot Selection Scenario: a Logistics Service Provider in E-commerce Fulfilment

The company is a logistics service provider in the e-commerce fulfilment market and serves several large e-commerce retailers. The upper management of the company is confident that e-commerce will continue to grow due to customers’ tendency to buy online, which has further increased during the Covid-19 pandemic. Hence, they want to increase the throughput of their warehouse and are seeking a scalable automation solution. The current portfolio includes small- to medium- sized products handled through manual case picking and broken-case picking. The company is not looking to expand their product portfolio through bulky products. The company might expand its operational area by purchasing the adjacent warehousing space in the logistics park if they see the targeted throughput growth. Thus, the upper management would like the system to adapt to potential layout alterations. Even though the upper management is motivated to implement a mobile robot system, considering the company's financial instability, they prefer an affordable solution. Finally, they want to implement the solution as soon as possible to recruit new customers.

Evaluation Criteria	System Requirements	Logic and Explanations
Scalability	…and are seeking a scalable automation solution…	Systems involve AS/RS and pallet shuttles require high level of construction to scale.
Flexibility in Material Handling	…current portfolio includes small- to medium- sized products handled through manual case picking and broken-case picking…	Laser Guided Robots and Autonomous Forklifts are generally carry pallets and they are not useful in picking e-commerce products.
Flexibility of Infrastructure	…adapt to potential layout alterations…	In terms of infrastructure, among the remaining solutions, linear route robots are not flexible to rearrange without construction.
Mobile Robot Cost	…they prefer an affordable solution…	Mobile picking robots and picker & transport robots require rather expensive investment compared to other alternatives.
Time to Implement	…they want to implement the solution as soon as possible…	Human collaborated robots become operational within few weeks; without any re-layouting and extra requirements.

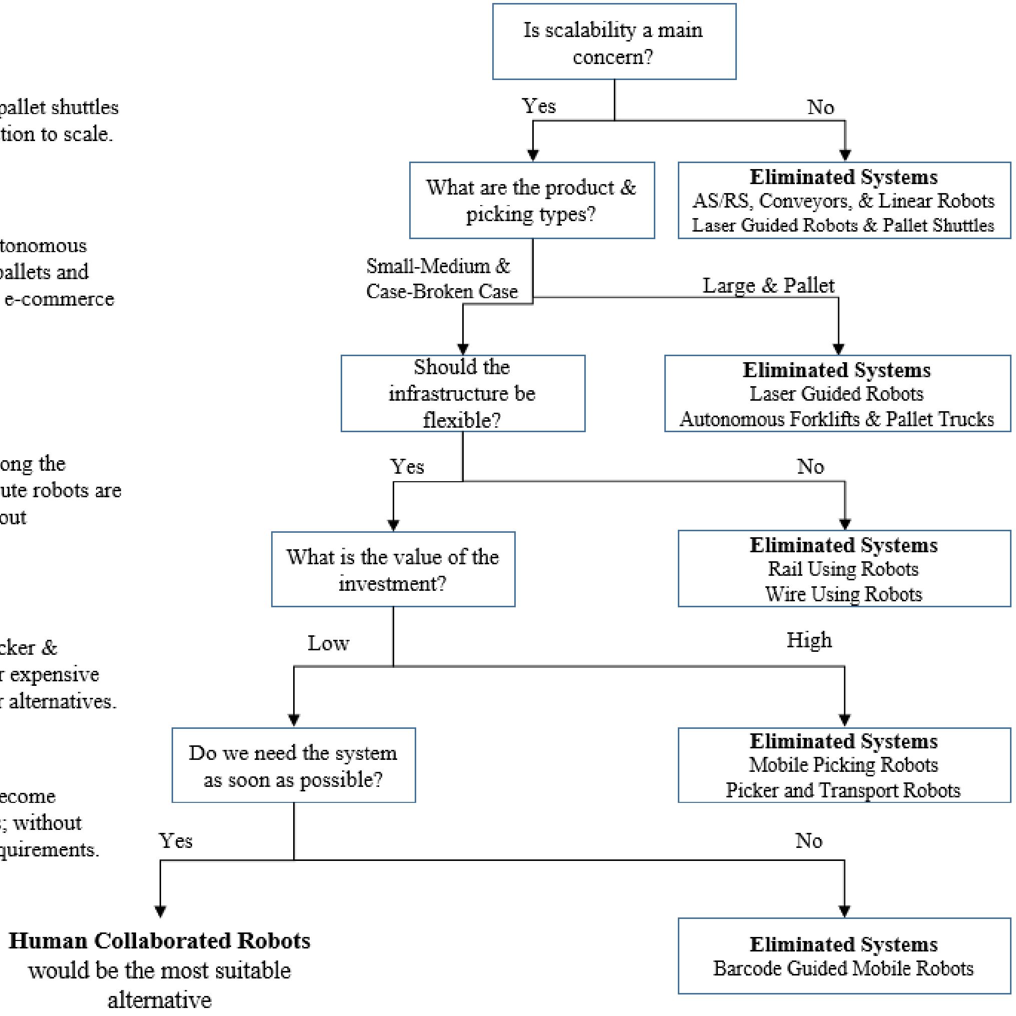


Figure 3-2 Decision tree of the scenario with explanation

3.4.2 FUCOM Approach

In case decision problems are characterised by criteria with differing degrees of importance, criteria should be allowed to have varying weights to reflect the decision-maker's preferences while minimising subjectivity in the process. As an alternative and independent assessment of mobile robot systems based on expert evaluations, FUCOM determines values for the weight coefficients of all criteria by performing consistent comparisons.

Initially, the list of evaluation criteria is prepared in alphabetical order as C1: Flexibility in infrastructure (max), C2: Flexibility in handling (max), C3: Mobile robot cost (min), C4: Scalability (max), C5: Time to implement (min).

Then, as the FUCOM process suggests, the predefined set of criteria is ranked by a supply chain expert (Decision-Maker 1):

C2 > C1 > C3 > C5 > C4

Once criteria are ranked, the decision-maker determines their importance coefficients with pairwise comparisons based on a scale [1,9]. The pairwise priority comparison is always made with respect to the 1st-ranked C2 criterion (Table 3-4).

Table 3-4 Priorities of criteria for decision-maker 1

Criterion	C_2	C_1	C_3	C_5	C_4
$\boldsymbol{\varpi}_{C_{j(k)}}$	1	2	3	5	7

Based on obtained priorities, comparative priorities are determined:

$$\phi_{C_2/C_1} = 2/1 = 2;\ \phi_{C_1/C_3} = 3/2 = 1.5;\ \phi_{C_3/C_5} = 5/3 = 1.\overline{6};\ \phi_{C_5/C_4} = 7/5 = 1.4$$

The final values of the weight coefficients should meet:

$$\frac{w_2}{w_1} = 2;\ \frac{w_1}{w_3} = 1.5;\ \frac{w_3}{w_5} = 1.\overline{6};\ \frac{w_5}{w_4} = 1.4$$

In addition to the previous condition, the final values of the weight coefficients should meet the mathematical transitivity condition:

$\frac{w_2}{w_3} = 2 * 1.5 = 3;$ $\frac{w_1}{w_5} = 1.5 * 1.\bar{6} = 2.4;$ $\frac{w_3}{w_4} = 1.\bar{6} * 1.4 = 2.\bar{3}$

Using Expression (5), our final model to determine the weight coefficients of the Decision-Maker 1 is as follows:

$$\min \chi$$

s.t.

$$\left|\frac{w_2}{w_1} - 2\right| \leq \chi, \left|\frac{w_1}{w_3} - 1.5\right| \leq \chi, \left|\frac{w_3}{w_5} - 1.\bar{6}\right| \leq \chi, \left|\frac{w_5}{w_4} - 1.4\right| \leq \chi,$$

$$\left|\frac{w_2}{w_3} - 2 * 1.5\right| \leq \chi, \left|\frac{w_1}{w_5} - 1.5 * 1.\bar{6}\right| \leq \chi, \left|\frac{w_3}{w_4} - 1.\bar{6} * 1.4\right| \leq \chi,$$

$$\sum_{j=1}^{5} w_j = 1, \forall_j$$

$$w_j \geq 0, \forall_j$$

By solving this nonlinear model, we obtain the final values of weight coefficients for flexibility in infrastructure, flexibility in handling, mobile robot cost, scalability, and time to implement as $(0.23, 0.46, 0.15, 0.07, 0.09)^T$ and the deviation from a full consistency, $\chi = 0.00$.

These steps were repeated with the other supply chain experts (Decision-Maker 2,3,4,5) (Table 3-5). It is assumed that the experts have comparable expertise and knowledge of the warehouse operations; hence, the average of individual weights was used to find the final weights of the criteria. The average resulting weights from the five decision-makers are Flexibility in infrastructure: 0.16; Flexibility in material handling: 0.2; Mobile robot cost: 0.3; Scalability: 0.2; and Time to implement: 0.14.

Table 3-5 Decision-makers and the FUCOM details

	Decision-Maker 1	**Decision-Maker 2**	**Decision-Maker 3**	**Decision-Maker 4**	**Decision-Maker 5**
Criterion Ranking	$C_2 > C_1 > C_3 > C_5 > C_4$	$C_3 > C_5 = C_1 = C_2 = C_4$	$C_4 > C_1 > C_3 > C_2 = C_5$	$C_3 > C_4 > C_2 > C_1 > C_5$	$C_3 > C_2 = C_4 = C_5 > C_1$
Priorities of Criteria	1 – 2 – 3 – 5 – 7	1 – 2 – 4 – 4 – 4	1 – 2 – 3 – 5 – 5	1 – 2 – 3 – 3.5 – 4	1 – 2 – 2 – 2 – 3
Weight Coefficients	0.23 – 0.46 – 0.15 – 0.07 – 0.09	0.44 – 0.22 – 0.11 – 0.11 – 0.11	0.45 – 0.22 – 0.15 – 0.09 – 0.09	0.42 – 0.21 – 0.14 – 0.12 – 0.10	0.35 – 0.18 – 0.18 – 0.18 – 0.12
Deviation from Consistency	0.00	0.00	0.00	0.00	0.00
Average Weight Coefficients	$C_1 – C_2 – C_3 – C_4 – C_5$ 0.16 – 0.20 – 0.30 – 0.20 – 0.14				

As we multiply the average resulting weights of these criteria with the ratings for the mobile robot systems (Table 3-3) and sum the scores obtained from each criterion, a ranking of the mobile robot systems is produced. After the calculation (Appendix B.2), linear route mobile robots appear to be the best alternative for a generic warehouse, followed by human-collaborated robots and barcode-guided robots (Table 3-6). Compared to the outcome of the benchmark method, the Equal Weight' approach, the two runner-up systems (human-collaborated robots and barcode-guided robots) are the final candidates to choose from (Figure 3-2) in the 'Equal Weight' approach.

Table 3-6 Mobile robot systems and their rankings with weighted criteria

Mobile Robot Systems	**Results**
Rail or Wire -Using Robots	**2.34**
Human-Collaborated Robots	2.30
Barcode-Guided Robots	2.20
Autonomous Forklifts	2.00
Mobile Picking Robots	2.00

Picker & Transport Robots	2.00
Laser-Guided Robots	1.80
AS/RS, Conveyors, Linear Route Robots	1.61
Laser-Guided Robots & Pallet Shuttles	1.61

3.5 Discussion

3.5.1 Discussion of Evaluation Criteria Weights

Experts rated mobile robot cost the highest (0.3) among evaluation criteria which align with the findings of Horňáková et al., (2019) but conflicting with the findings of Zavadskas et al., (2018). Rating the ‘mobile robot cost’ criterion the highest is not surprising considering the high robot costs (especially AMRs) and uncertainty of the return on investment in warehouse automation. After mobile robot cost, scalability and flexibility in material handling share the highest importance (0.2 each). This decision reflects the massive increase in e-commerce orders and the growth potential it offers. Time to implement mobile robot systems receives the lowest priority (0.14) which also aligns with the findings of Horňáková et al., (2019). Even though it is surprising in the fast-paced and agile supply chain environment that the warehouses should adapt to, time to implement might be interpreted as a minor detail in a strategic decision compared to other criteria. Yet, the weights of the criteria are for a generic warehouse and could change in the presence of a scenario, similar to the one in the ‘Equal Weight’ approach, and specific expectations. For instance, if the warehouse is operating with small-sized products, forklift-containing solutions would directly be eliminated from picking operations.

3.5.2 Discussion of Mobile Robot System Ranking Through FUCOM

The application presented in this paper is a demonstration and the proof of concept of a mobile robot system selection strategy. As it can be further customised with additional criteria and/or sensitivity analyses, it offers needed guidance for decision-makers.

Considering deviation consistency values being ‘0’ or a negligible positive value, it can be concluded that the results are reliable with high validity in terms of methodology. Hence, FUCOM is applicable to demonstrate an evaluation of mobile robot systems regarding the predefined set of evaluation criteria.

Since rail or wire-guided robots operate with AGVs and can handle various types of material, it appears as the best alternative in line with allocated criteria weights. It is not surprising that human-collaborated robots and barcode-guided robots are first and second runner-up. They are the only two solutions without having ‘1’ as a rating in any criterion. Hybrid solutions are not performing well in the ranking which might be because they are suffering from the weaknesses of every sub-system in the solution.

As an alternative to this paper’s FUCOM approach, decision-makers could also rate the potential mobile robot solutions using the set of criteria in Table 3-3 (Erceg and Mularifović, 2019; Zavadskas et al., 2018). This paper’s findings can provide a starting evaluation for managers considering deploying mobile robots in warehouses. The assessment of the alternative solutions is robust as it is based on their functionality and additional information obtained from the literature review. However, the researcher believes mobile robot systems are complex and difficult to assess without detailed preliminary research. FUCOM is also used in group decision-making processes in the supply chain to form a consensus among decision-makers (Fazlollahtabar et al., 2019). Nevertheless, there is a threat of manipulation (opinion leaders influencing others) in that approach that directed this study towards individual evaluation processes.

3.5.3 Discussion of Further Evaluation Criteria

The list of evaluation criteria enables companies to assess and select mobile robot solutions concerning their specific targets and expectations. Yet, there are many other criteria that a decision-maker or decision-making unit might consider while making large financial investments. Below are further criteria that the decision-makers could consider in their decision-making process supported by the ideas from the reviewed papers:

Downtime/reliability/cost of maintenance: Even though a mobile robot system does not get interrupted by a robot's failure, the overall warehouse throughput could decrease by up to 10% with such failures (Lienert et al., 2019). Hence, a potential robot and mission failure map with routine maintenance should be developed with action strategies (Yan et al., 2017). In this way, preventive maintenance would be preserved, and the cost would be minimised.

Ergonomics: Human workers are now travelling less in the warehouse environment due to mobile robot presence for non-value-adding tasks, making it easier to recruit pickers (Hanson et al., 2018). Yet, the design of workplaces and actions against large-sized and weighty products in picking operations remain significant in terms of ergonomics (Boysen et al., 2019; Moeller et al., 2016).

Supplier existence/capability/financial strength: By withdrawing Kiva robots from the market, Amazon unintentionally triggered an intense warehouse robot development effort, which created many start-ups competing for the market share (Bogue, 2016). Because most companies access such technologies through purchasing, supplier availability and choice become one of the most crucial decision points before implementation. If the technology supplier is not technically and financially capable enough to handle logistics customers, the whole automation attempt might collapse.

Human safety: Even though mobile robots significantly decrease the threat towards human life by reducing manual labour (Bechtsis et al., 2017), the probability of a robot-human collision raises concerns as they begin to operate in the same environment together with AMRs (Raineri et al., 2019). Thus, a risk assessment study should take place, and precautions against identified risks should be taken (Inam and Raizer, 2018).

Pick rate/throughput: This key performance index could be the most helpful metric for a warehouse (Boysen et al., 2019). However, it is not easy to calculate a specific throughput rate for a mobile robot solution. There are many variables such as functional layout, number of workstations or pick stations, fleet size, shelf size, product sizes, path planning and task allocation algorithms, conflict avoidance strategies etc. Hence, simulations should be run for various scenarios to provide throughput or pick rates as outputs for easier decision-making (Tsolakis et al., 2019).

Pick accuracy: Following the pick rate, pick accuracy is another significant metric to avoid interruptions in operations and decrease returns. To accelerate robot picking speed and accuracy research, Amazon initiated Amazon Picking Challenge in 2015. In systems where robots perform the picking, advanced computer vision techniques and artificial intelligence (Wen et al., 2018) is used, whereas, in scenarios where human workers carry out the picking, pick-to-light systems are applied to increase pick accuracy (Bauters et al., 2016; Hanson et al., 2018).

Future-proof solution: Future-proof solution could be explained through the criteria offered in this paper. For instance, having flexibility in infrastructure makes the system future-proof against potential process or layout alterations. AMRs, rather than AGVs, make the solution more flexible in terms of robot navigation and, thus, future-proof. From another point of view, flexibility in material handling makes the system ready to handle various types of materials or material handling units. However, it can be further extended to other criteria such as compatibility with other automation solutions or technologies.

Personnel training: Even though the literature brings almost no research on this subject, supply chain experts raise the importance of operational worker and engineer training to utilise the system fully within the warehouse. Operational human worker training times for mobile robot systems are shorter than training times for manual warehouse operations (Hanson et al., 2018). Yet, they should be communicated, trained, and incentivised potentially via a change management team (Moeller et al., 2016) for increased efficiency and throughput (Azadeh et al., 2019; Boysen et al., 2019).

Even though these additional criteria were not incorporated in the selection model with primary evaluation criteria defined in this paper, they can also be employed by different decision-makers if they become relevant in specific scenarios. Hence, these criteria are explained and supported through the SLR and the insights of supply chain experts so that they can be included in the decision-making process with the correct focus.

3.6 Conclusion

This study contributes to knowledge with a clear typology of mobile robots in warehouse operations and evaluates the characteristics of ten mobile robot systems in this regard. Moreover, it rates these systems according to a list of criteria and a rating system and supports the practicality of the criteria through demonstrations and methods. In combination, these outcomes form this paper's key contribution, which could also aid warehouse decision-makers when they need to automate their warehouse. The approach this study develops is not only valid for mobile robot automation but could potentially become a way of assessing other types of warehouse equipment and automation alternatives.

As with any study, there are limitations in this review and analysis. The research is formed using academic databases only and focused on studies from 2000 onwards. Thus, its outcomes might not wholly reflect available mobile robot systems in the picking operation. Further, even though the reliability of FUCOM is maintained, it could involve more criteria, a range of operations scenarios expected to appear in the warehouse environment, and decision-makers for higher validity of the results.

Mobile robots are key technologies for improving warehouse efficiency and for coping with the increasingly challenging demands from customers by being flexible, scalable, and sometimes adaptable to existing solutions. However, implementing mobile robots in warehouses involves a plethora of complex decisions, and failures such as the implementation of unsuitable mobile robot systems or overlooking key decision factors could lead to costly mistakes. Hence, warehouse managers require guidance and a tailored managerial decision framework that would inform, support, and prescriptively guide them in implementing mobile robots. In terms of future research, this study forms a basis for a more comprehensive managerial decision framework to integrate and apply mobile robot solutions at the strategic level in warehouses.

3.7 References to Chapter 3

Abbas, A. S., Mohamed, T. A., and Hazem, M. (2018). Optimization of Warehouse Material Handling Parameters to Enhance the Efficiency of Automated Sorting and Storage Systems. 11(1), 2018.

Adobe Holiday Shopping Trends. (2019). Adobe Analytics. https://www.adobe.com/content/dam/www/us/en/experience-cloud/digital-insights/pdfs/adobe_analytics-holiday-predictions-2019.pdf?promoid=NV3KR4X2&mv=other

AGV Weasel. (n.d.). SSI Schaefer. Retrieved February 21, 2021, from https://www.ssi-schaefer.com/en-us/products/conveying-transport/automated-guided-vehicles/fahrerloses-transportsystem-weasel-53020

Azadeh, K., De Koster, R. B. M., and Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. In Transportation Science (Vol. 53, Issue 4). https://doi.org/10.1287/trsc.2018.0873

Baker, P. (2006). Designing distribution centres for agile supply chains. International Journal of Logistics Research and Applications, 9(3), 207–221. https://doi.org/10.1080/13675560600859136

Banker, S. (2018). Laser Guided Vehicles Navigate With Precision. https://www.forbes.com/sites/stevebanker/2018/08/29/laser-guided-vehicles-navigate-with-precision/?sh=41e5e5465091

Bartholdi, J. J., and Hackman, S. T. (2019). Warehouse & Distribution Science. In Available on line at:/http://www. tli. gatech. edu/ … (Issue August).

Bauters, K., De Cock, K., Hollevoet, J., Dobbelaere, G., and Van Landeghem, H. (2016). A simulation model to compare autonomous vehicle based warehouses with traditional AS/RS systems. European Simulation and Modelling Conference 2016, ESM 2016, 451–460.

Bechtsis, D., Tsolakis, N., Vlachos, D., and Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated

Guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Bogue, R. (2016). Growth in e-commerce boosts innovation in the warehouse robot market. Industrial Robot, 43(6), 583–587. https://doi.org/10.1108/IR-07-2016-0194

Bormann, R., de Brito, B. F., Lindermayr, J., Omainska, M., and Patel, M. (2019). Towards Automated Order Picking Robots for Warehouses and Retail. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11754 LNCS, 185–198. https://doi.org/10.1007/978-3-030-34995-0_18

Boysen, N., De Koster, R. B. M., and Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. In European Journal of Operational Research (Vol. 277, Issue 2, pp. 396–411). Elsevier B.V. https://doi.org/10.1016/j.ejor.2018.08.023

Cribley, D. (2014). 9 Steps to Determining if an ASRS is Right For You.

De Koster, R. B. M. (2018). Automated and robotic warehouses: developments and research opportunities. Logistics and Transport, 2(38De Koster, R. B. M. (2018). Automated and robotic warehouses: developments and research opportunities. Logistics and Transport, 2(38), 33–40. https://doi.org/10.26411/83-1734-2015-2-38-4–18), 33–40. https://doi.org/10.26411/83-1734-2015-2-38-4-18

Đorđević, Stojić, Stević, Pamučar, Vulević, and Mišić. (2019). A New Model for Defining the Criteria of Service Quality in Rail Transport: The Full Consistency Method Based on a Rough Power Heronian Aggregator. Symmetry, 11(8), 992. https://doi.org/10.3390/sym11080992

Draganjac, I., Miklic, D., Kovacic, Z., Vasiljevic, G., and Bogdan, S. (2016). Decentralized Control of Multi-AGV Systems in Autonomous Warehousing Applications. IEEE Transactions on Automation Science and Engineering, 13(4), 1433–1447. https://doi.org/10.1109/TASE.2016.2603781

Durmić, E. (2019). The Evaluation of the Criteria for Sustainable Supplier Selection by Using the FUCOM Method. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901085d

Enright, J. J., and Wurman, P. R. (2011). Optimization and coordinated autonomy in mobile fulfillment systems. AAAI Workshop - Technical Report, WS-11-09, 33–38.

Erceg, Ž., and Mularifović, F. (2019). Integrated MCDM model for processes optimization in the supply chain management in the wood company. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901015e

Fan, Z., Gu, C., Yin, X., Liu, C., and Huang, H. (2018). Time window based path planning of multi-AGVs in logistics center. Proceedings - 2017 10th International Symposium on Computational Intelligence and Design, ISCID 2017, 2, 161–166. https://doi.org/10.1109/ISCID.2017.40

Fazlollahtabar, H., Smailbašić, A., and Stević, Ž. (2019). FUCOM method in group decision-making: Selection of forklift in a warehouse. Decision Making: Applications in Management and Engineering, 2(1), 49–65. https://doi.org/10.31181/dmame1901065f

Ferrara, A., Gebennini, E., and Grassi, A. (2014). Fleet sizing of laser guided vehicles and pallet shuttles in automated warehouses. International Journal of Production Economics, 157(1), 7–14. https://doi.org/10.1016/j.ijpe.2014.06.008

Füßler, D., Boysen, N., and Stephan, K. (2019). Trolley line picking: storage assignment and order sequencing to increase picking performance. OR Spectrum, 41(4), 1087–1121. https://doi.org/10.1007/s00291-019-00566-9

Geek+. (n.d.). Geek+. Retrieved February 21, 2021, from https://www.geekplus.com/

Hanson, R., Medbo, L., and Johansson, M. I. (2018). Performance Characteristics of Robotic Mobile Fulfilment Systems in Order Picking

Applications. IFAC-PapersOnLine, 51(11), 1493–1498. https://doi.org/10.1016/j.ifacol.2018.08.290

Horňáková, N., Jurík, L., Hrablik Chovanová, H., Cagáňová, D., and Babčanová, D. (2019). AHP method application in selection of appropriate material handling equipment in selected industrial enterprise. Wireless Networks. https://doi.org/10.1007/s11276-019-02050-2

Huang, G. Q., Chen, M. Z. Q., and Pan, J. (2015). Robotics in ecommerce logistics. HKIE Transactions Hong Kong Institution of Engineers, 22(2), 68–77. https://doi.org/10.1080/1023697X.2015.1043960

Inam, R., and Raizer, K. (2018). Risk Assessment for Human-Robot Collaboration in an automated warehouse scenario.

Jaghbeer, Y., Hanson, R., and Johansson, M. I. (2020). Automated order picking systems and the links between design and performance: a systematic literature review. International Journal of Production Research, 0(0), 4489–4505. https://doi.org/10.1080/00207543.2020.1788734

Kattepur, A., Rath, H. K., Simha, A., and Mukherjee, A. (2018). Distributed optimization in multi-agent robotics for industry 4.0 warehouses. Proceedings of the ACM Symposium on Applied Computing, 808–815. https://doi.org/10.1145/3167132.3167221

Kimura, N., Ito, K., Fuji, T., Fujimoto, K., Esaki, K., Beniyama, F., and Moriya, T. (2015). Mobile dual-arm robot for automated order picking system in warehouse containing various kinds of products. 2015 IEEE/SICE International Symposium on System Integration (SII), 332–338. https://doi.org/10.1109/SII.2015.7404942

Lee, H. Y., and Murray, C. C. (2019). Robotics in order picking: evaluating warehouse layouts for pick, place, and transport vehicle routing systems. International Journal of Production Research, 57(18), 5821–5841. https://doi.org/10.1080/00207543.2018.1552031

Li, M. P., Sankaran, P., Kuhl, M. E., Ptucha, R., Ganguly, A., and Kwasinski, A. (2019). Task Selection by Autonomous Mobile Robots in A Warehouse Using

Deep Reinforcement Learning. In Proceedings - Winter Simulation Conference (Vols. 2019-Decem). https://doi.org/10.1109/WSC40007.2019.9004792

Lienert, T., Stigler, L., and Fottner, J. (2019). Failure-Handling Strategies For Mobile Robots In Automated Warehouses. ECMS 2019 Proceedings Edited by Mauro Iacono, Francesco Palmieri, Marco Gribaudo, Massimo Ficco, 199–205. https://doi.org/10.7148/2019-0199

Liu, S. (2018). Research on scheduling policy of automated warehouse system. ACM International Conference Proceeding Series, 1–5. https://doi.org/10.1145/3207677.3277965

Liu, Y., Ji, S., Su, Z., and Guo, D. (2019). Multi-objective AGV scheduling in an automatic sorting system of an unmanned (intelligent) warehouse by using two adaptive genetic algorithms and a multi-adaptive genetic algorithm. PLoS ONE, 14(12). https://doi.org/10.1371/journal.pone.0226161

Locus. (n.d.). Locus Robotics. Retrieved February 21, 2021, from https://locusrobotics.com/why-locus/deployment/

Ly, G. B. (2019). Storage Assignment Policy and Route Planning of AGVS in Warehouse Optimization. In Proceedings of 2019 International Conference on System Science and Engineering, ICSSE 2019.

Marchet, G., Melacini, M., and Perotti, S. (2015). Investigating order picking system adoption: a case-study-based approach. International Journal of Logistics Research and Applications, 18(1), 82–98. https://doi.org/10.1080/13675567.2014.945400

Moeller, K., Gabel, J., and Bertagnolli, F. (2016). FISCHER FIXING SYSTEMS: MOVING FORWARD WITH THE WORKFORCE - CHANGE COMMUNICATION AT THE GLOBAL DISTRIBUTION CENTER. Journal of Information Technology Education: Discussion Cases, 5(September 2017), 01. https://doi.org/10.28945/3457

Pamučar, D., Stević, Ž., and Sremac, S. (2018). A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). Symmetry, 10(9), 393. https://doi.org/10.3390/sym10090393

Pittaway, L., Robertson, M., Munir, K., Denyer, D., and Neely, A. (2004). Networking and innovation: A systematic review of the evidence. International Journal of Management Reviews, 5–6(3–4), 137–168. https://doi.org/10.1111/j.1460-8545.2004.00101.x

Polten, L., and Emde, S. (2020). Scheduling automated guided vehicles in very narrow aisle warehouses. Omega (United Kingdom). https://doi.org/10.1016/j.omega.2020.102204

Raineri, M., Perri, S., and Guarino Lo Bianco, C. (2019). Safety and efficiency management in LGV operated warehouses. Robotics and Computer-Integrated Manufacturing, 57, 73–85. https://doi.org/10.1016/j.rcim.2018.11.003

Roy, D., Nigam, S., De Koster, R. B. M., Adan, I., and Resing, J. (2019). Robot-storage zone assignment strategies in mobile fulfillment systems. Transportation Research Part E: Logistics and Transportation Review, 122, 119–142. https://doi.org/10.1016/j.tre.2018.11.005

Schmidt, T., and Schulze, F. (2009). Future approaches to meet complexity requirements in material handling systems. FME Transactions, 37(4), 159–166.

Sharma, M., Luthra, S., Joshi, S., and Kumar, A. (2021). Accelerating retail supply chain performance against pandemic disruption: adopting resilient strategies to mitigate the long-term effects. Journal of Enterprise Information Management, 34(6), 1844–1873. https://doi.org/10.1108/JEIM-07-2020-0286

Tranfield, D., Denyer, D., and Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review* Introduction: the need for an evidence- informed approach. British Journal of Management, 14, 207–222.

Tsolakis, N., Bechtsis, D., and Srai, J. S. (2019). Intelligent autonomous vehicles in digital supply chains: From conceptualisation, to simulation modelling, to real-world operations. Business Process Management Journal, 25(3), 414–437. https://doi.org/10.1108/BPMJ-11-2017-0330

Wang, K., Yang, Y., and Li, R. (2019). Travel time models for the rack-moving mobile robot system. International Journal of Production Research. https://doi.org/10.1080/00207543.2019.1652778

Wen, J., He, L., and Zhu, F. (2018). Swarm Robotics Control and Communications: Imminent Challenges for Next Generation Smart Logistics. IEEE Communications Magazine, 56(7), 102–107. https://doi.org/10.1109/MCOM.2018.1700544

Wior, I., Jerenz, S., and Fay, A. (2018). Automated transportation systems subject to interruptions in production and intralogistics - a survey and evaluation. International Journal of Logistics Systems and Management, 30(4), 421. https://doi.org/10.1504/IJLSM.2018.093581

Wurman, P. R., DAndrea, R., and Mountz, M. (2008). Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses.

Yan, R., Jackson, L. M., and Dunnett, S. J. (2017). Automated guided vehicle mission reliability modelling using a combined fault tree and Petri net approach. International Journal of Advanced Manufacturing Technology, 92(5–8), 1825–1837. https://doi.org/10.1007/s00170-017-0175-7

Yoshitake, H., Kamoshida, R., and Nagashima, Y. (2019). New Automated Guided Vehicle System Using Real-Time Holonic Scheduling for Warehouse Picking. IEEE Robotics and Automation Letters, 4(2), 1045–1052. https://doi.org/10.1109/LRA.2019.2894001

Zavadskas, E. K., Nunić, Z., Stjepanović, Ž., and Prentkovskis, O. (2018). Novel Rough Range of Value Method (R-ROV) for selecting automatically guided vehicles (AGVs). Studies in Informatics and Control, 27(4), 385–394. https://doi.org/10.24846/v27i4y201802

Zero to automated in weeks not months. (n.d.). InVia Robotics. Retrieved February 21, 2021, from https://www.inviarobotics.com/implementation/

Zou, B., Xu, X., Gong, Y. (Yale), and De Koster, R. B. M. (2018). Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system. European Journal of Operational Research, 267(2), 733–753. https://doi.org/10.1016/j.ejor.2017.12.008Azadeh, K., De Koster, R. B. M., and Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. In Transportation Science (Vol. 53, Issue 4). https://doi.org/10.1287/trsc.2018.0873

Bauters, K., De Cock, K., Hollevoet, J., Dobbelaere, G., and Van Landeghem, H. (2016). A simulation model to compare autonomous vehicle based warehouses with traditional AS/RS systems. European Simulation and Modelling Conference 2016, ESM 2016, 451–460.

Bechtsis, D., Tsolakis, N., Vlachos, D., and Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Benady, D. (2016). Will a robot take my job? DHL. https://www.dhl.com/global-en/home/about-us/delivered-magazine/articles/2016/issue-3-2016/will-a-robot-take-my-job.html

Bogue, R. (2016). Growth in e-commerce boosts innovation in the warehouse robot market. Industrial Robot, 43(6), 583–587. https://doi.org/10.1108/IR-07-2016-0194

Boysen, N., De Koster, R. B. M., and Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. In European Journal of Operational Research (Vol. 277, Issue 2, pp. 396–411). Elsevier B.V. https://doi.org/10.1016/j.ejor.2018.08.023

Durmić, E. (2019). The Evaluation of the Criteria for Sustainable Supplier Selection by Using the FUCOM Method. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901085d

Erceg, Ž., and Mularifović, F. (2019). Integrated MCDM model for processes optimization in the supply chain management in the wood company. Operational Research in Engineering Sciences: Theory and Applications, 2(1). https://doi.org/10.31181/oresta1901015e

Fazlollahtabar, H., Smailbašić, A., and Stević, Ž. (2019). FUCOM method in group decision-making: Selection of forklift in a warehouse. Decision Making: Applications in Management and Engineering, 2(1), 49–65. https://doi.org/10.31181/dmame1901065f

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

Horňáková, N., Jurík, L., Hrablik Chovanová, H., Cagáňová, D., and Babčanová, D. (2019). AHP method application in selection of appropriate material handling equipment in selected industrial enterprise. Wireless Networks. https://doi.org/10.1007/s11276-019-02050-2

Inam, R., and Raizer, K. (2018). Risk Assessment for Human-Robot Collaboration in an automated warehouse scenario.

Lienert, T., Stigler, L., and Fottner, J. (2019). Failure-Handling Strategies For Mobile Robots In Automated Warehouses. ECMS 2019 Proceedings Edited by Mauro Iacono, Francesco Palmieri, Marco Gribaudo, Massimo Ficco, 199–205. https://doi.org/10.7148/2019-0199

Moeller, K., Gabel, J., and Bertagnolli, F. (2016). FISCHER FIXING SYSTEMS: MOVING FORWARD WITH THE WORKFORCE - CHANGE COMMUNICATION AT THE GLOBAL DISTRIBUTION CENTER. Journal of Information Technology Education: Discussion Cases, 5(September 2017), 01. https://doi.org/10.28945/3457

Pamučar, D., Stević, Ž., and Sremac, S. (2018). A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). Symmetry, 10(9), 393. https://doi.org/10.3390/sym10090393

Raineri, M., Perri, S., and Guarino Lo Bianco, C. (2019). Safety and efficiency management in LGV operated warehouses. Robotics and Computer-Integrated Manufacturing, 57, 73–85. https://doi.org/10.1016/j.rcim.2018.11.003

Sharma, M., Luthra, S., Joshi, S., and Kumar, A. (2021). Accelerating retail supply chain performance against pandemic disruption: adopting resilient strategies to mitigate the long-term effects. Journal of Enterprise Information Management, 34(6), 1844–1873. https://doi.org/10.1108/JEIM-07-2020-0286

Tsolakis, N., Bechtsis, D., and Srai, J. S. (2019). Intelligent autonomous vehicles in digital supply chains: From conceptualisation, to simulation modelling, to real-world operations. Business Process Management Journal, 25(3), 414–437. https://doi.org/10.1108/BPMJ-11-2017-0330

Wen, J., He, L., and Zhu, F. (2018). Swarm Robotics Control and Communications: Imminent Challenges for Next Generation Smart Logistics. IEEE Communications Magazine, 56(7), 102–107. https://doi.org/10.1109/MCOM.2018.1700544

Yan, R., Jackson, L. M., and Dunnett, S. J. (2017). Automated guided vehicle mission reliability modelling using a combined fault tree and Petri net approach. International Journal of Advanced Manufacturing Technology, 92(5–8), 1825–1837. https://doi.org/10.1007/s00170-017-0175-7

Zavadskas, E. K., Nunić, Z., Stjepanović, Ž., and Prentkovskis, O. (2018). Novel Rough Range of Value Method (R-ROV) for selecting automatically guided vehicles (AGVs). Studies in Informatics and Control, 27(4), 385–394. https://doi.org/10.24846/v27i4y201802

4 Mobile Robot System Implementation in Warehouses: an Adoption Framework

Abstract

Mobile robot systems (MRS) are automation solutions in warehouses that make order fulfilment agile, flexible, and scalable to cope with customer orders' increasing volumes and complexities. The purpose of this paper is to explore the MRS adoption journey using the innovation diffusion theory (IDT) and technology-environment-organisation (TOE) framework as theoretical lenses. It also aims to examine the relationship between the managerial decisions taken in the journey and the TOE factors affecting those decisions.

A theory elaborating case study involving eight warehouses of four organisations implementing or planning to implement mobile robot systems provides evidence on the application of these solutions in warehouse operations. Thirty-six semi-structured interviews, relevant documents, and observations are triangulated to validate the results.

Phases and stages of MRS adoption are identified along with an exhaustive list of managerial decisions and TOE factors affecting the adoption journey. It is found that MRS adoption is a cyclical process with the presence of continuous learning. It is also evident that managerial decisions shape the entire process, while TOE factors influence and sometimes dictate managerial decisions.

This study has three key contributions. It elaborates on IDT and includes the ‘assimilation & learning’ phase that affects the ongoing and future implementation planning. Secondly, it illustrates the interaction of managerial decisions and contextual factors and how they affect MRS implementation. Finally, it develops an empirically validated MRS adoption framework for warehouse managers.

Keywords mobile robot automation, TOE framework, technology adoption, multiple case studies, innovation diffusion

4.1 Introduction

Fulfilling customers' orders swiftly and efficiently whilst managing the increasing complexity and variability of these orders is an ongoing challenge in supply chains. Retail sectors, such as consumer electronics, clothing and footwear, grocery, or pharmaceuticals, are characterised by large assortments of small products. The increasing tendency of customers to buy online leads to thousands of daily orders, which, coupled with thousands of different products, can make the warehouse environment chaotic and complicate operations such as receiving, picking, sorting, and packing.

Due to intense competition and the complexity of orders, companies are constantly trying to adopt new technologies. Innovative technologies such as mobile robots promise more efficient and faster operations than manually operated warehouses and could be applied to most individual warehouse operations (Wurman et al., 2008).

Owing to the successes of early adopters (i.e., Amazon, Alibaba, Ocado, and JD.com), mobile robot adoption in warehouses had a spectacular boost. Grey Orange, Hikvision, Geek+, IAM Robotics, 6 River Systems, Magazino, and many other start-up companies began developing various mobile robot systems for warehouses using automated guided vehicles (AGV) and autonomous mobile robots (AMR). Industry forecasts estimate that more than 50,000 warehouses, up from 4,000 in 2018, will use over 4 million mobile robots globally by 2025 (ABI Research, 2019). Paper 2 explains and evaluates mobile robot systems emerging from practice and academia.

Mobile robot systems (MRS) seem promising for improving warehouse efficiency and coping with the increasingly challenging demand from customers. However, there is a lack of a tailored managerial decision framework that would aid decision-makers in the integration and implementation of warehouse mobile robot systems. Although lots of research (Fazlollahtabar and Saidi-Mehrabad, 2015; Lamballais et al., 2017; Merschformann et al., 2019; Roy et al., 2019; Vivaldini et al., 2015) have been conducted, most of them fail to integrate managerial decisions and are mainly took an optimisation perspective (Benzidia et al., 2019; Boysen et al., 2019; Jaghbeer et al., 2020). Many review papers attempted to respond to this gap and offered decision frameworks (Bechtsis et al., 2017; Fragapane et al., 2021; Jaghbeer et al., 2020; Le-Anh and De Koster, 2006). Providing a fragmented list of managerial decisions, these reviews are not focused on the process of innovation diffusion at the organisational level. Paper 1 addressed this lack of knowledge and provided a conceptual managerial decision framework with thirteen strategic, tactical, and operational focus areas stemming from the literature to support implementation decisions of mobile robot systems in warehouses. It also concluded that further study is necessary with the participation of experts and practitioners to explain the MRS adoption process elaborating on the conceptual framework with more focus areas and/or decision questions. Shamout et al. (2022) concentrate on MRS adoption but only focus on the factors affecting the decision to adopt such technologies rather than the implementation journey as a whole.

Since the current body of literature only partially identifies managerial decisions and fails to deliver a holistic approach to investigating the implementation process of MRS adoption, this paper aims to fill these gaps. The main objective of this empirical study is to understand the mobile robot system adoption journey in warehouses explaining the managerial decisions and factors affecting those decisions. The following research question and its sub-questions are formed:

Research Question 1. How do managerial decisions affect the process of adopting MRS in warehouses?

Research Question 2. How do technological, organisational, and environmental factors affect managerial decisions in adopting MRS in warehouses?

The outline for the rest of the paper is as follows. The next chapter will focus on the theoretical background of innovation adoption in extant literature. It will present the theoretical framework of the study. The methodology chapter will explain the case study methodology adopted by this paper with the descriptive information of the data collected. The findings chapter will analyse the data collected on the MRS adoption process. The discussion chapter will include an example from one sub-case to represent the proposed MRS adoption framework and discuss the significance of learning in innovation adoption. Finally, the conclusion chapter will mention the theoretical contribution of the study as well as the managerial implications and research limitations.

4.2 Theoretical Background

There are a lot of papers concentrating on innovation adoption in supply chain management (SCM). However, to the researcher’s knowledge, the main focus is on information systems (IS) technologies such as Blockchain (Hartley et al., 2022; Vu et al., 2022; Wong et al., 2020), big data analytics (Lai et al., 2018), e-SCM (I.-L. Wu and Chuang, 2010), information & communication technologies (Evangelista et al., 2013), and cloud computing (Y. Wu et al., 2013). Only two studies are based on the adoption of mobile robots; one in healthcare logistics (Benzidia et al., 2019) and the other in SCM (Shamout et al., 2022). Many of these papers approach innovation adoption using the innovation diffusion theory of (Rogers, 2003). Therefore, to observe and analyse organisations’ journey of integrating MRS into their warehouses, this paper adopts innovation diffusion theory (IDT) as a theoretical lens (Rogers, 2003).

Other theoretical works such as the Technology Acceptance Model (TAM) (Davis, 1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) could also be relevant. However, to respond to the call to conduct research focused on automation in SCM from an organisational perspective (P. Baker and Halim, 2007; Benzidia et al., 2019), this paper intends to observe MRS adoption from an organisational perspective. Yet, TAM and UTAUT are applied to research focused on the user-level. Therefore, IDT was evaluated as a better alternative in the scope of this paper.

Innovation is “an idea, practice, or object perceived as new by an individual or other unit of adoption” (Rogers, 2003, p. 12) and the two broad phases of innovation are initiation and implementation (p. 420). In the initiation phase, sometimes perceived needs trigger the innovation adoption process in an organisation, and sometimes perceived benefits of the innovation create a need for it (Rogers, 2003). The implementation phase has the stages of redefining/restructuring (preparing for the implementation), clarifying (understanding the innovation), and routinising (innovation becomes a regular activity for the organisation).

The initiation and implementation phases are divided by the adoption decision. There are similar structures (initiation, adoption decision, implementation) in many papers adopting IDT in SCM (Mathauer and Hofmann, 2019; Sternberg et al., 2021; Vu et al., 2022; Zhu et al., 2006). Mathauer and Hofmann (2019) model the technology adoption of logistics companies and suggests that decision to adopt encompasses the technology access decision (TAD). Even though Rogers (2003) put more emphasis on the initiation and implementation phases, Mathauer and Hofmann (2019) state that the decision to adopt phase is the most significant stage due to its central position and interrelatedness with other phases.

Three main options to access an innovation or a technology are Make, Buy, and Ally (Mathauer and Hofmann (2019). The ‘Make’ option is preferred if the company is keen to build the entire mobile robot solution (Capron and Mitchell, 2010; White, 2000). This option also covers mergers and acquisitions to access the technology. Even though ‘Make’ companies have total flexibility and control over the MRS, they lose an outsider perspective (potentially the technology provider/supplier’s) on managerial decisions (Gnekpe and Coeurderoy, 2017). The ‘Ally’ option is reasonable if companies are knowledgeable and interested in the technology but prefer to outsource or co-develop the solution, at least initially (Borah and Tellis, 2013). ‘Ally’ companies are expected to ask for customisations on the technology or even invest in the supplier (Mudambi and Tallman, 2010). ‘Buy’ companies, on the other hand, mainly rely on the knowledge of a supplier as they only want the solution off the shelf and benefit from its advantages (Capron and Mitchell, 2010) (Figure 4-1).

Technology Access Decision			
Type	**Make (In-house)**	**Ally (Partnership)**	**Buy (Purchase)**
How?	Build the mobile robot system in-house or acquire the technology provider for the same aim.	Invest in or co-develop with the technology provider.	Purchase the whole solution from the technology provider. Plug and play.
Why?	Possesses the total control and flexibility over the system being developed.	Interested in the solution, takes part in the integration, and asks for customisations.	Only interested in the outcome of the solution.
Example	Amazon-Kiva	Alibaba-Quicktron	Nike-Geek+

Figure 4-1 Technology access decision

This study divides MRS adoption into initiation, the decision to adopt, and the implementation phases. As mentioned earlier, it also uses adoption decisions (make, buy, ally) and keeps the technology access decision as a stage in the 'decision to adopt' phase. Further, it uses the managerial decision framework offered in Paper 1 to cover the managerial decisions (decision focus areas) being considered during the MRS adoption process.

Finally, integrating Technology-Organization-Environment (TOE) framework (Tornatzky and Fleischer, 1990) to IDT to explain both the innovation adoption process in organisations and factors affecting the adoption process is a common approach both in the wider literature (Ahmed and Kassem, 2018; Low et al., 2011; Zhu et al., 2006) and more specifically in SCM (Mathauer and Hofmann, 2019; Shamout et al., 2022; Vu et al., 2022; Wei et al., 2015; I.-L. Wu and Chuang, 2009; X. Wu and Subramaniam, 2011). The TOE framework has three contexts: technology, organisation, and environment. The technology context of the framework includes the characteristics of the technology/innovation planning to be adopted, such as relative advantage, complexity, and cost. Organisation context contains the characteristics of the organisation that is planning to adopt the technology, such as size, worker profile, and innovativeness of the organisation. Finally, the environmental context includes the characteristics of the external part of the organisation, such as government and its legislations, competitive pressure, and supplier relationships (J. Baker, 2012; Tornatzky and

Fleischer, 1990). These characteristics are also named factors and affect innovation's adoption process through managerial decisions (J. Baker, 2012).

This study builds on these ideas and proposes a theoretical framework to be elaborated, forming a theoretical basis for the case study (Figure 4-2). By integrating IDT, TAD, the managerial decision framework from Paper 1, and TOE at the organisational level this study seeks a comprehensive understanding of the MRS adoption process. The next chapter explains the case study.

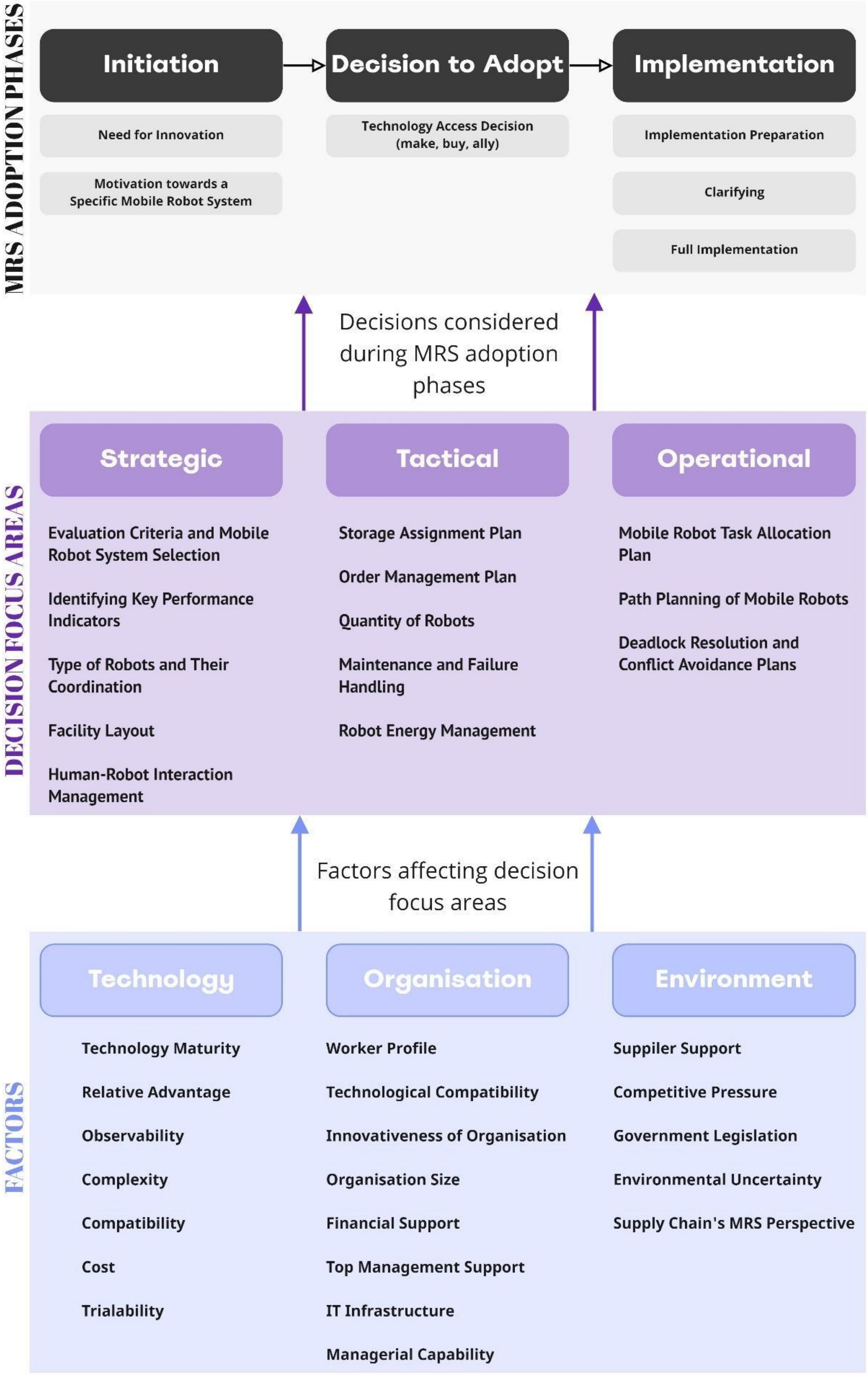


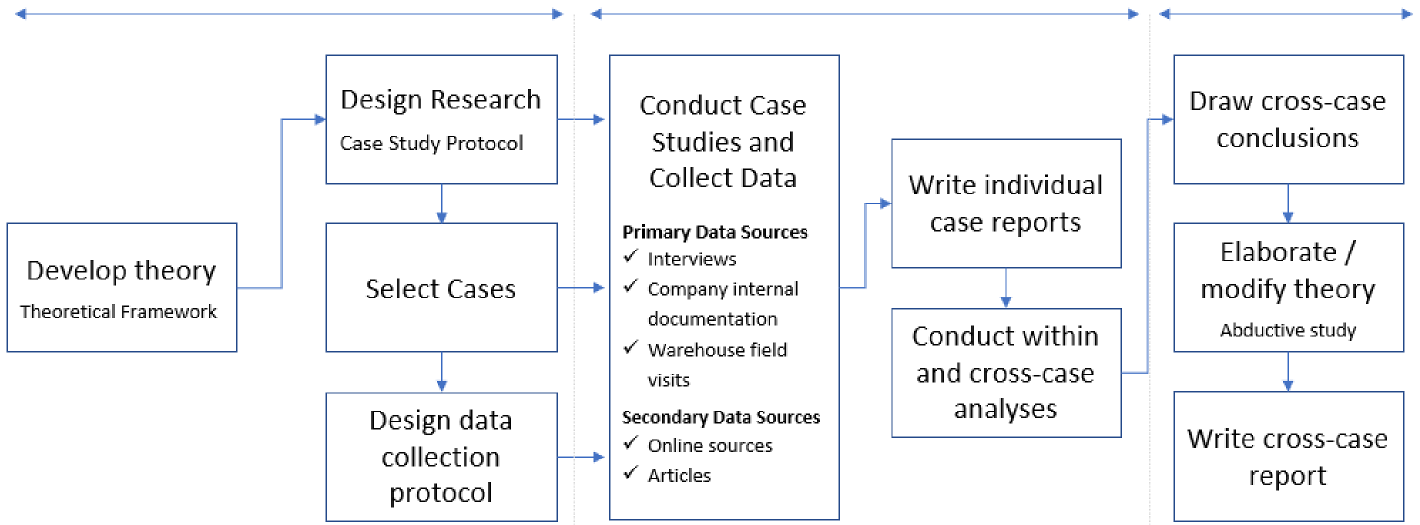
Figure 4-2 Theoretical framework

4.3 Methodology

4.3.1 Research Strategy

The case study methodology is selected as it aims to explain a contemporary phenomenon by taking a comprehensive approach (Gerring, 2006, p. 17; Yin, 2018, p. 3). To fulfil this aim, the study will be in-depth within its real-life context (cases from Norway, Denmark, the United Kingdom - UK, and Turkey), therefore, considering all the complexities in practice and not abstracting the phenomena. This way, it will provide findings which are highly relevant to practice. The research question and sub-questions also direct the study towards a case study as they are generally built on ‘why’ and ‘how’ questions (Yin, 2018).

This theory-elaborating case research has an abductive approach that allows the researcher to (a) initiate data collection with a conceptual model as a theory base; (b) seek information that would potentially adjust or develop the initial theory (Ketokivi and Choi, 2014). To maintain the quality and rigour of the case study, a case study framework was constructed including four main criteria: construct validity, internal validity, external validity, and reliability (Figure 4-3).



	Define and Design	Prepare, Collect, and Analyse	Analyse and Conclude
Construct Validity	➢ Feedback from peer researchers on case study and interview protocols	➢ Multiple perspectives and sources of evidences collected ➢ Data and patterns supported from multiple informants and/or data sources for the same phenomena (triangulation)	➢ Case reports reviewed with key informants to compare and contrast views ➢ Chain of evidence is maintained
Internal Validity	➢ Data collection protocol to ensure that linkages will be developed ➢ A particular type of causal analysis (TAD) is formed to support internal validity	➢ Data displayed in a structure to facilitate establishing cross-case analysis and causal relationships	➢ Different causal linkages are pursued when coding and analysis (phases – decisions, decisions – factors) ➢ Rival theoretical explanations discussed
External Validity	➢ Cases selected according to three dimensional criteria for analytical generalisation (TAD, country, company type) ➢ Multiple informants from different levels in the company are involved	➢ Cases described in detail to enable comparison with different contexts	➢ Results presented to peer researchers and practitioners to ensure validity
Reliability	➢ A case study protocol prepared to standardise data collection across the cases	➢ A case study database developed to preserve the data generated from data sources and within & cross-case findings	➢ Case study database updated iteratively to ensure complete documentation

Figure 4-3 Case study framework. Adopted from: Yin, 2018

Table 4-1 Descriptive information about cases

	Organisation 1	Organisation 2	Organisation 3	Organisation 4
General Info				
Country	Turkey	Denmark	United Kingdom	Norway
Type	Logistics Service Provider	Grocery Retailer	Logistics Service Provider	Grocery Retailer
# of Warehouses	1	1	2	4
Implementation Status	Implementation Preparation	Implementation Preparation	Fully Implemented	Fully Implemented (One exception at prep.)
Units of Analysis (TAD)				
Make	1	-	-	-
Buy	-	-	1	3
Ally	-	1	1	1
Data Collection				
Interviews	14 (P1-14)	6 (P15-20)	3 (P26-28)	14 (P21-25 & P29-37)
Documents	6	8	12	4
Observations	3	-	1	-

4.3.2 Data Collection

A case study protocol is prepared to ensure the replicability and reliability of the case study (Yin, 2018). This protocol includes: (a) an overview of the case study (aim, research questions, theoretical framework); (b) data collection procedures (list of contact persons from each company, details of people to be interviewed, documents to be reviewed - Table C-3, observations); and (c) protocol questions (questions asked to the researcher to clarify which data to be collected - Table C-1).

Multiple sources of evidence (interviews, documents, observations) were collected to ensure construct validity through method (sources of evidence) and data (multiple informants and/or documents) triangulation (Jick, 1979; Given, 2008; Saunders et al., 2012) (Table 4-1). Semi structured interviews (Table C-2) were conducted to provide flexibility to the respondent and allow new themes to emerge if they are missing from the theoretical framework (Eisenhardt, 1989; Given, 2008). Thirty-six interviews averaging 63 minutes/interview were conducted with 37 informants/interviewees between November 2021 and July 2022 (Table 4-2). 66% of the informants are mid-senior level managers, including CEOs, technical managers, warehouse managers, and project managers, whereas 22% are blue-collar employees or operational leads, and 11% are from robotics teams. Only three interviews were conducted in case 3 as they were highly involved and knowledgeable. Further, there are many documents to collect evidence from, which were also helpful for validity in case 3.

Documents collected were formed of implementation or MRS documents that organisations allowed researchers to access, articles about these implementations, and online sources as well as photos and videos (Table C-4). Online sources helped researchers triangulate the TAD. Implementation documents and articles helped triangulate the implementation status, phases, and decisions taken throughout the journey. Finally, in the instances the organisations and covid-19 allowed, the warehouses were visited to observe the implementation and how these systems are being controlled in a daily routine (Table C-5).

Table 4-2 Overview of Interviews

Person #	Interviewee Role	Years of Experience	Case & Organisation #	Warehouse Location	Warehouse Industry	TAD	Length of Interview (min)
P1	CEO	15+	1	Turkey	E-commerce	Make	53
P2	Ex Robotics Lead	15+	1	Turkey	E-commerce	Make	102
P3	Robotics Lead	10-15	1	Turkey	E-commerce	Make	87
P4	Ex Robotics Lead	5-10	1	Turkey	E-commerce	Make	105
P5	Ex CEO Office	5-10	1	Turkey	E-commerce	Make	21
P6	Robotics Team	15+	1	Turkey	E-commerce	Make	63
P7	Robotics Team	5-10	1	Turkey	E-commerce	Make	25
P8	IT Support Lead	10-15	1	Turkey	E-commerce	Make	44
P9	Warehouse Manager	15+	1	Turkey	E-commerce	Make	42
P10	Robotics Team	5-10	1	Turkey	E-commerce	Make	65
P11	Operational Lead	5-10	1	Turkey	E-commerce	Make	18
P12	Operational Lead	5-10	1	Turkey	E-commerce	Make	15

P13	Blue-collar Employee	5-10	1	Turkey	E-commerce	Make	11
P14	Customer Success Lead	5-10	1	Turkey	E-commerce	Make	49
P15	Country Logistics Manager	15+	2	Denmark	Grocery Retail	Ally	57
P16	Global Logistics Manager	15+	2	Denmark	Grocery Retail	Ally	50
P17	Project Manager	15+	2	Denmark	Grocery Retail	Ally	72
P18	Operational Lead	15+	2	Denmark	Grocery Retail	Ally	25
P19	Blue-collar Employee	10-15	2	Denmark	Grocery Retail	Ally	31
P20	Blue-collar Employee	15+	2	Denmark	Grocery Retail	Ally	42
P21	Group Logistics Manager	15+	4	Norway	Grocery Retail	Buy, Ally	62
P22	Warehouse Manager	15+	4	Norway	Grocery Retail	Ally	90
P23	Supplier Robotics Team	0-5	4	Norway	Grocery Retail	Ally	61
P24	Warehouse Logistics Coordinator	15+	4	Norway	Grocery Retail	Ally	76
P25	Blue-collar Employee	10-15	4	Norway	Grocery Retail	Ally	37

P26	Lead of Digitalisation	15+	3	United Kingdom	Automotive, E-commerce	Buy, Ally	105
P27	Project Manager	10-15	3	United Kingdom	Automotive	Buy	95
P28	Operational Lead	15+	3	United Kingdom	Automotive	Buy	90
P29	Warehouse Manager	15+	4	Norway	Grocery Retail	Buy	83
P30	Project Manager	15+	4	Norway	Grocery Retail	Buy	89
P31	Technical Manager	15+	4	Norway	Grocery Retail	Buy	89
P32	Warehouse Manager	15+	4	Norway	Grocery Retail	Buy	78
P33	Projects Lead	15+	4	Norway	Grocery Retail	Buy	100
P34	Project Manager	15+	4	Norway	Grocery Retail	Buy	80
P35	Warehouse Logistics Coordinator	15+	4	Norway	Grocery Retail	Buy	43
P36	Warehouse Manager	15+	4	Norway	Grocery Retail	Buy	125
P37	Warehouse Logistics Coordinator	15+	4	Norway	Grocery Retail	Buy	63

4.3.3 Data Analysis

All the data collected from the interviews were transcribed and coded (Table 4-3) together with the documents and observation memos. As a general approach, the theoretical framework and data were visited multiple times to ensure the alterations and additions being made to the existing framework.

A priori coding structure (Table C-6) was used as an existing theoretical framework (Figure 4-2). The first step was a within-case analysis (Figure C-1; Figure C-2) to better understand the case implications for the MRS adoption process. Then, a cross-case analysis was conducted to identify generalisable patterns among cases. Through theory elaboration (with codes emerging from the evidence), the theoretical framework was elaborated and finalised.

Table 4-3 Example of coding

Quotes	Sub-code	Code	Category	Theme
We gradually increased it over about six or seven weeks. We went from two to ten aisles. Phase by phase, just doing a bit more each week. – P26, Lead of Digitalisation	After implementation prep, before full implementation	Testing (Gradual Implementation)	Implementation	Phases
The next level now is to get the AGV to also handle the second wrap line. Also, next year, probably, will have a third line. We are moving slowly towards a point where all these three lines are being handled by AGVs. – P33, Projects Lead				
Maybe we can use it with one customer at first. We have a mezzanine floor at the second floor, and I think we can allocate that floor entirely to the robots. – P9, Warehouse Manager				
Most providers we see delivering hardware trucks or forklifts now also deliver AGVs. But they are not delivering at the nice enough level on IT safety. – P21, Group Logistics Manager	IT Safety	Supplier Selection and Management	Strategic Decisions	Decision Focus Areas
It is very important that the supplier can ensure us with the people that have been working in similar projects before. – P36, Warehouse Manager	Supplier Experience			

They (the supplier) are not big enough and they do not have the power to run several projects at the same time, with a nice speed. – P21, Group Logistics Manager	Supplier Size			
We have been looking at more complex solutions too. But I do not think they (AMRs) are good enough yet because with obstacles they use too much time or wave around looking for the other way. It is nice on paper but in the practical life it does not give that much yet. When this develops, it will probably be the solution to go for. – P21, Group Logistics Manager	Affects to evaluation criteria and MRS selection (AGV vs AMR)	Technology Maturity	Technological Factors	Factors
I think we are entering into something that works in some cases, but it is not really mature yet. We had hard times finding (MRS solutions that work with) operations like ours within the conditions we work with, the temperature and all that is. – P15, Country Logistics Manager	Affects to Supplier Selection and Management (TAD - buy to ally)			
It was a choice of different suppliers that could provide an automated forklift that could lift up to 11 meters high and could navigate accurately and safely through the warehouse. So, you are into really a choice of probably three or four different providers. – P26, Lead of Digitalisation	Affects to Supplier Selection and Management			

4.4 Findings

This chapter is divided into four sections. The first section elaborates on the existing managerial decision framework that was introduced in Paper 1, with new decisions and extensions of existing decisions. Then, the MRS adoption phases are introduced to cover the whole journey of MRS implementation. The next section introduces factors affecting the MRS adoption process and categorises them as technological, organisational, and environmental. Finally, the last section combines these outputs to create an MRS adoption framework that takes its foundation from the theoretical framework.

4.4.1 Extensions on the Managerial Decision Framework (Decision Focus Areas)

Using the insights of the case study, the managerial decision framework presented in Paper 1 was elaborated with new decisions or sub-focus areas in existing decisions.

4.4.1.1 Supplier/Technology Provider Selection and Management

When accessing mobile robot systems (MRS), one of the fundamental decisions is selecting and building communication with the MRS supplier. Emerging from the interviewees' insights, this paper deduces several supplier characteristics decision-makers should consider during the supplier selection process (Table 4-4).

Table 4-4 Emergent MRS supplier characteristics and explanations

Quotes	**Emergent Characteristic**	**Explanation**
They (the supplier) are not big enough and they do not have the power to run several projects at the same time, with a nice speed. – P21, Group Logistics Manager	**Supplier Size**	The supplier's size determines the communication quality and responsiveness.
It is very important that the supplier can ensure us with the people that have been working in similar projects before. – P36, Warehouse Manager	**Supplier Experience**	Decision-makers prefer experienced suppliers.
We looked into this (MRS) because they are very interesting and exciting. But they are unavailable for us because they (suppliers) do not have a license to sell them in other countries. – P33, Projects Lead	**Country Presence – office, service, licensing**	A critical characteristic for a potential supplier is their country presence for the customer organisations. If they do not have a license to sell their technology in a country, there is no way to get that MRS.
My feeling is that our supplier has many engineers but not enough people who understand logistics. A lot of ideas, but say half of those ideas, maybe not, worked for us. (…) Short meetings every third week because the supplier works on, I think they call Sprint. And every task they have is three weeks long. And then, they make a status check after three weeks but only for 10-15 minutes. – P24, Warehouse Logistics Coordinator	**Supplier Structure**	As there are many start-up MRS suppliers, they are generally focused on the technology aspect of the MRS. Yet, they sometimes miss to match the product with the actual operations or have communication issues with logistics companies that want to automate their warehouses.
We are able to make changes to their (information technology - IT) system to meet our requirements both when it comes to	**Software Integrability**	Software integration with a warehouse management system (WMS) or similar organisation software can

security and integration. Very important issues. – P36, Warehouse Manager		quickly become a pain point. Therefore, supply chain experts would like an easy-to-adjust MRS management software.
Most providers we see delivering hardware trucks or forklifts now also deliver AGVs. But they are not delivering at the nice enough level on IT safety. – P21, Group Logistics Manager	**IT Safety**	IT safety is a crucial point when it comes to preventing cyber-attacks. As it is not the primary concern of MRS developers, it can put the buyer organisation at risk.

Finally, as the lead of digitalisation (P26) suggests, decision-makers should either align their support contract with their customer/operational contracts (if they have customers) or find a way to redeploy these mobile robots in another warehouse (if they have other warehouses).

It should be noted that this decision has different content in ‘make’ TAD, which will be mentioned in the ‘Software & Hardware Development of Robots’ decision.

4.4.1.2 Software & Hardware Development of Robots

Integration of MRS into the organisation is a crucial decision, and the development the organisation needs to undertake can be divided into software and hardware.

Regardless of TAD, software development is a crucial part of this decision. The organisation should be able to integrate its relevant IT structure (i.e., WMS, servers) into the MRS for robot coordination and communication purposes. P36 mentioned the significance of software development capability in MRS implementations.

> *It is an IT project more than a truck project. – P36, Warehouse Manager*

P21 talked about their intention (also a request from suppliers) to standardise the software side of MRS implementation.

> *We have a quite big IT organisation and they have developed (something) called a standardised interface for automation but also for the AGV part. We will be more or less telling our (technology) providers to adjust to that interface.*
> *– P21, Group Logistics Manager*

Software development gets more intense for ‘make’ organisations, and hardware development appears as a sub-focus area. P2 discussed the difficulties they faced in finding human resources for such projects.

> *Human resource. To find the human resource, and then to keep their belief in the project and the company at a certain level. These were the biggest difficulties for me and the biggest problem with the managerial approach. – P2, Operational Excellence Lead (Ex-Robotics Lead)*

On top of the difficulties developing hardware within the organisation, P3 mentioned the necessity of building a supply chain structure while developing such complex hardware.

> *Our robot has more than five thousand components. This also raises the necessity of a critical supply chain management for these components. – P3, Robotics Lead*

Therefore, the supply chain structure building focus area reflects the ‘Supplier Selection and Management’ decision for ‘make’ organisations.

4.4.1.3 Facility Layout

As a minor extension of facility layout decisions, floor quality appeared to be a significant sub-focus area. The project manager (P17) stated they require a floor renovation before implementation. P28 mentioned their experience with floor quality for MRS.

> *Have you got suitable flooring? If your flooring looks like it has been part of a minefield, then these AGVs are not going to operate to the best of their ability. – P28, Operational Lead*

4.4.1.4 Human-Robot Interaction

This decision was extensively discussed in Paper 1. However, the worker training aspect of human-robot interaction appears to be a challenging part of this decision. Two primary purposes of human training are retaining human safety and ensuring smooth robot traffic.

> *Even though we had some incidents with people walking up in front of AGVs, and we had a lot of issues with that, there were no major accidents. We had to train our operators working together with these AGVs and that was the major problem in the beginning. – P29, Warehouse Manager*

Managers should also ensure that manual workers accurately place products that will be contacted with the mobile robots, as these robots are inflexible when handling a product placed inaccurately.

> *If a person has played the pallet there and it is not 100% aligned, you will get stuck. We spend a lot of hours just moving pallets by, for instance, two centimetres. We are just teaching everybody that: Yes, you have to be accurate – P34, Project Manager*

The workforce might require extra training and supervision if managers introduce a complex operation.

> *It was quite difficult to explain to colleagues that sometimes you stand still, sometimes you walk to the next one (order), and sometimes you follow the bot (mobile robot). You have got to train them and coach them. (...) I think there is a lot of learning about the way that we had to train our colleagues to work differently – P26, Lead of Digitalisation*

4.4.1.5 Maintenance and Failure Handling

Spare parts should be a significant sub-focus area for maintenance and failure handling. Deciding on spare parts inventory indirectly increases robots' uptime. In case of missing spare parts in a breakdown, the organisation must order and wait for those parts to fix the robot. Along with inventory preparation, spare part availability is another consideration point in spare part management. P35 mentioned that they had to wait for the missing spare parts as they came from another country.

> *Employees crashed with it (mobile robot), and then we had to change a part. We have waited to get some spare parts from Sweden, and it took a lot of time – P35, Warehouse Logistics Coordinator*

Having a spare part inventory is not sufficient. To prevent unnecessary spending, part quantities should be carefully decided through a learning experience and with the help of an MRS supplier.

> *I think one of our learning points from the project was we have got too broad a catalogue of spare parts. We bought a massive variance of spare parts to store but we spent almost half our budget, for example, on cameras. We have got three or four of those expensive cameras spare. Actually, the cameras are probably never going to break down. We had a lot of the smaller parts like the springs on the fork tip and sensors. If they have caught on the pallet, they can*

> *break off quite easily. We have not got enough of those – P28, Operational Lead*

4.4.1.6 Robot-Human Traffic Management

This decision can be a significant obstacle to efficient MRS flow and reflects how well the human workforce is trained. The significance of this decision can sometimes be underestimated.

> *The interface between manual traffic and those automated trucks is a big lesson learned for us. That is not something to be underestimated in such a project – P36, Warehouse Manager*

P29 said it took a lot of time before they solved robot-human traffic problems.

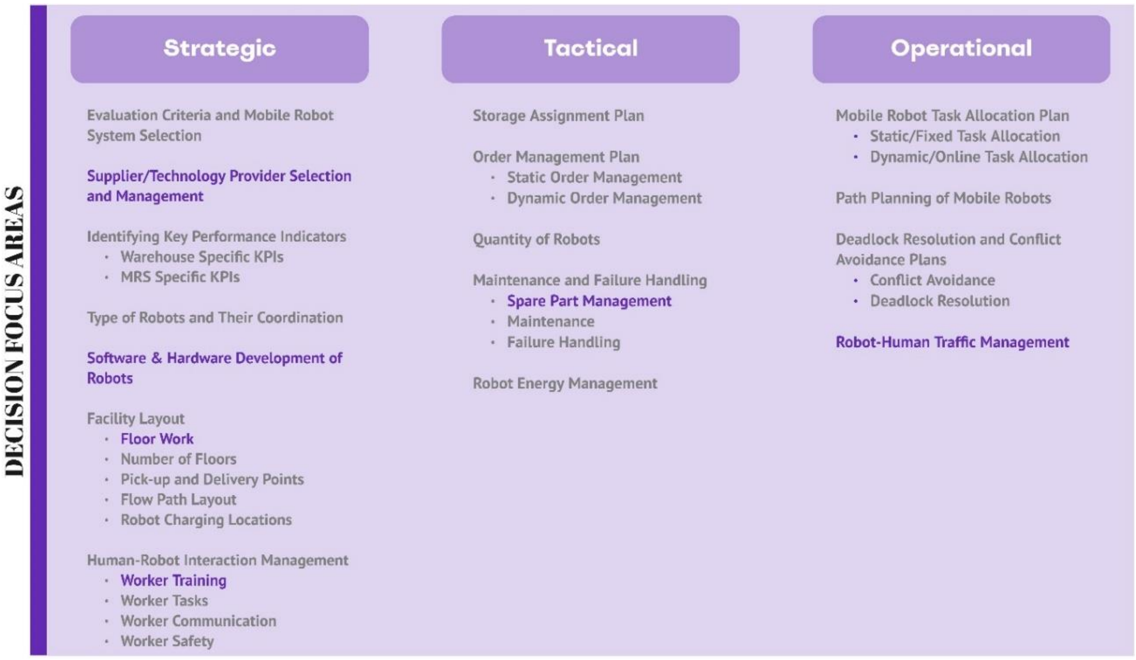
> *It took half a year—no issue at all (now). No, there are no accidents, no incidents. But you have to spend a lot of time, maybe train people twice. – P29, Warehouse Manager*

It should be noted that this decision exists only if robots and human workers operate in the same environment. Even though this is very common in warehouses, many managers tend to separate human workers and mobile robots.

> *They (decision-makers) need to limit the traffic of conventional forklifts in the same area as the AGVs as much as possible. Try to separate the routes as much as possible. – P29, Warehouse Manager*

4.4.1.7 Elaborated Managerial Decision Framework

The elaborated managerial decision framework is shown below as decision focus areas, together with the existing (Paper 1) and new decisions, and their sub-focus areas (Figure 4-4).



DECISION FOCUS AREAS

Strategic

Evaluation Criteria and Mobile Robot System Selection

Supplier/Technology Provider Selection and Management

Identifying Key Performance Indicators
- Warehouse Specific KPIs
- MRS Specific KPIs

Type of Robots and Their Coordination

Software & Hardware Development of Robots

Facility Layout
- **Floor Work**
- Number of Floors
- Pick-up and Delivery Points
- Flow Path Layout
- Robot Charging Locations

Human-Robot Interaction Management
- **Worker Training**
- Worker Tasks
- Worker Communication
- Worker Safety

Tactical

Storage Assignment Plan

Order Management Plan
- Static Order Management
- Dynamic Order Management

Quantity of Robots

Maintenance and Failure Handling
- **Spare Part Management**
- Maintenance
- Failure Handling

Robot Energy Management

Operational

Mobile Robot Task Allocation Plan
- Static/Fixed Task Allocation
- Dynamic/Online Task Allocation

Path Planning of Mobile Robots

Deadlock Resolution and Conflict Avoidance Plans
- Conflict Avoidance
- Deadlock Resolution

Robot-Human Traffic Management

Figure 4-4 Elaborated managerial decision framework with bold purples being new additions. Adopted from: Paper 1

Supply chain experts’ insights were gathered to form a comprehensive overview of mobile robot innovation adoption in warehouses. Their processes are aligned with the three main phases: ' initiation’, ‘decision to adopt’, and ‘implementation’. Yet, another phase emerged, named ‘assimilation & learning’, that supports the previous phases in ongoing and future MRS implementations.

4.4.2 MRS Adoption Phases

4.4.2.1 Initiation

Similar to what is discussed in the literature, MRS adoption starts with identifying a pain point in a warehouse operation, creating a perceived need to adopt MRS. As an example, P16 said they had complaints about picking efficiency.

> *You can implement automation to remove bottlenecks. This one is about picking efficiency. So how good are we at picking our customer orders? – P16, Global Logistics Manager*

In another case, P36 recalled non-value-added transport activities in their consolidation area as their pain points.

> *In the consolidation area, we put our pallets to be consolidated and prepared for the lorries. We have three different areas, and between those areas, there is a lot of internal transport. – P36, Warehouse Manager*

Naturally, operational costs can also be why an organisation wants to automate. In many cases, supply chain experts mentioned labour scarcity. Many wanted to automate their warehouses to eliminate manual operations and decrease their dependency on labour.

> *We have got scarce labour, a real shortage in the market. (…) The impact of that is; whenever you have scarce something, then the price goes up. So, we are paying more and more, and wage inflation is outstripping normal inflation. (…) So, the long-term strategy has to be to do more of this kind of thing (automation). – P26, Lead of Digitalisation*

Choosing an MRS as a potential solution to overcome these pain points is a journey within itself and requires motivation from multiple angles. Managers start considering an automation solution which is then followed by considering mobile robots as automation.

> *Automation is a natural step towards improving the work environment and health & safety of our employees. – P15, Country Logistics Manager*

P26 said they wanted to automate their warehouse because of peaks in their e-commerce business and labour scarcity in the market.

> *E-commerce-type operations have a big peak as you get closer to Christmas, and we simply do not have enough labour to provide the service at times. By having an element of robotics or automation, we can increase our capacity. – P26, Lead of Digitalisation*

P15 mentioned their motivation towards mobile robots and said mobile robots could undertake all inbound transportation missions.

> *I see mobile robots being able to take away all the transport from A to B within our operations. When I look at it, I cannot see why we should have less ambition than that. – P15, Country Logistics Manager*

Decision-makers finally select a specific MRS, such as laser-guided robots, as discussed in the ‘evaluation criteria and mobile robot system selection’ decision. The complexity of the MRS can be a reason for decision-makers, as explained below.

> *The laser-guided system is a basic system that functions well. It has been there for many years and there is no problem using it. – P21, Group Logistics Manager*

To explain their motivation towards barcode-guided robots, P2 mentioned their ideation process. They compared goods-to-person and person-to-goods types of MRS and ended up with a goods-to-person kind of solution.

> *So how can you collect a product? You can direct the user inside the warehouse, which causes a non-value-added time. Or you constantly direct the user to do a value-added operation, but then you need to bring the product to him. – P2, Operational Excellence Lead (Ex-Robotics Lead)*

4.4.2.2 Decision to Adopt

Once the MRS is decided, the decision to adopt phase starts. The main topic for the mobile robot adoption process in this phase is TAD. Most of the sub-cases chose to buy the solution off-the-shelf as their core business is not based on mobile robots.

> *This (MRS) is something we have to buy, like a computer, like your laptop. We have to buy them as well. Not possible to produce in-house. – P29, Warehouse Manager*

Further, decision-makers believe it could take years to develop an MRS in-house.

> *There is a huge risk you might have to wait four or five years until you have something that can run. – P34, Project Manager*

On the other hand, some decision-makers think organisations with warehouses should be capable of developing robotic solutions, an MRS in this case. They believe it will be an integral part of logistics functions and a key to becoming competitive.

> *We can see in-house software teams even in conventional logistics companies. I think, as a founder, it will happen again with robotics. It will become a commodity very soon. When we fast-forward time and look at the future, buying a system will not be enough in terms of productivity and competitiveness. This is why we are doing it in-house as early-adopters. – P1, CEO*

Alternatively, building alliances can be essential for customised products and solutions to operational requirements. Investing in a supplier and directing them towards a customised MRS could be a recipe for the pain points.

> *I think we have ownership of probably 50% of them. (…) Now we are doing this together. We are a pilot for them. And we decided to go from picking 80% of the SKUs to picking only the heavy goods. We said we do not think this (80% of the SKUs target) will work, but if we go for heavy and mostly liquid goods, it will have a great outcome. So, they listened to us there. – P24, Warehouse Manager*

According to TAD, organisations face different steps. Suppose they decide to buy the solution or intend to ally with a supplier for a customised solution. In that case, they get into a supplier selection process which was also discussed in the ‘supplier/technology provider selection and management’ decision.

> *We had to start with this, and this was the company (supplier) could achieve things that other companies could not, such as the heights we needed to come. – P27, Project Manager*

A decision-maker mentioned the brainstorming process they had with the supplier before agreeing. Decision-makers start considering managerial decisions such as key performance indicators, type of robots, layout planning, the number of robots, and energy management at this stage.

> *The AGVs can carry some pallets with a number of movements. (Considering that) We make a layout of the area. And then, we started to discuss this with the supplier for a possible solution. They calculated how many AGVs we need to manage this because they know their (AGVs) charging time, speed, and distances. – P29, Warehouse Manager*

If organisations decide to make the solution, they need to plan the MRS development, which appears to be a massive decision with multiple angles, along with building development and production facilities and creating engineering teams for sub-systems of the MRS.

> *I started to include new friends in the organisation. Mechanical engineers, electronics engineers, harness designers. In addition, we have promoted our competence on the production side. We included production engineers. At the same time, we included computer-aided manufacturing operators, rented a place, and started operating our own production facility there. Afterwards, we included a quality person who would observe the need to set the standard and*

> *take over quality management. Finally, technicians and system designers were included. So, a team was formed from scratch. – P2, Operational Excellence Lead (Ex-Robotics Lead)*

Simulations appear to be an essential stage of the decision to adopt phase, and it precedes the finalised TAD followed by the implementation phase. Indeed, remembering their past failure experiences, some organisations accept to pay money to the supplier for a simulation to make sure the solution works for them in theory.

> *We spent a lot of time on the pre-study because we would like to fail fast. We do not want to start a full-blown project and find out it is not working. Many times, we spent a lot of time and a lot of energy on a huge project and then we got into a car crash. Then it goes backwards and never starts again. So, we actually tried to spend some energy on the pre-study, which will cost us a little bit, but it does not matter because the alternative is that we spent millions without getting anything from the money. – P16, Global Logistics Manager*

As simulation setups are generally the final step before adopting the MRS, many strategic, tactical, and operational level decisions are considered together at this stage.

> *To be able to simulate, we had to set up the infrastructure first anyway. Because mechanical and electronics development is more costly, it costs more to replace it too. But in the software environment, we had to do this kind of (detailed) simulation to see the results by changing the properties of the agent (mobile robots), etc. – P2, Operational Excellence Lead (Ex-Robotics Lead)*

4.4.2.3 Implementation

As soon as the organisation completes their technology access strategy, the implementation phase begins with the preparation. Process planning and redefining workforce roles are two of the critical parts of the implementation preparation. There was a way for the organisations to carry out their warehouse operations, but with MRS, there will be a change.

> *I think the biggest thing is how you will operate differently. There is an existing way of working with manual trucks in this warehouse or picking people pushing trolleys in the other warehouse. And if there were an exception, they would press a certain button on the device, and that would trigger an exception. Those exceptions would be managed by a person who is their first-*

> *line manager. So, there is a defined process that the big thing is how do you redefine that process for the automation system? – P26, Lead of Digitalisation*

Of course, decision-makers should also communicate this innovation implementation decision with the workforce, as previously mentioned in the ‘human-robot interaction’ decision. Continuous information sharing, using various sources of information, from day one to update the human workforce about the project's status would prevent them from alienating from new warehouse processes. Two management people from the same warehouse mentioned worker communication methods.

> *There were rollups where you could scan a barcode to get a news feed about how the project was moving. It is important for us to let our co-workers be informed about what is going on because it would be easier for the project when people know about it all the time. – P33, Projects Lead*
>
> *We took one of the AGVs six months before and placed it in the area before it was operational. – P32, Warehouse Manager*

Along with status and information sharing, the human workforce should be trained for their new roles and the health & safety approach while working in the same environment as the mobile robots.

> *We have a big health and safety engagement piece where we get groups of 10 to 15 people into our main engagement room and run them through. The health and safety team put together quite an extensive awareness pack which ran through everything regarding the AGVs and their responsibilities as operators and working alongside the AGVs. – P28, Operational Lead*

Besides process planning, redefinition of workforce roles, and worker training, the layout should also be planned and organised before mobile robots arrive.

> *We gave them the locations, and they mapped out all the different paths. – P34, Project Manager*

Connected with the planning, there needs to be some actual physical installation before putting the system into use. This process should always be followed and supervised by the organisation by having employees from different levels (i.e., project managers and blue-collar workers).

> *You need to supervise the installation at all times. You need to have a project leader that is always in the field. Staff are following up with the supplier and*

> *also the sub-suppliers. They need to be on-site and look at what they are doing. – P30, Project Manager*

Even though physical installations seem to be the frightening part of the route to implementation, IT integration can also be a complicated process.

> *Through an (IT) testing process, we did find the hard way a few times that there were things we did not think of. We had to go back, reconfigure stuff, redesign it, and test it again. – P26, Lead of Digitalisation*

Many decision-makers preferred gradual implementation when it came to implementing the MRS. Some called the initial process ‘testing’. This stage appears to be one of the most intense, involving real-world challenges, equipment alterations, failures, and pressure.

> *We have had projects that took some time to succeed, including this one. There are always real-world challenges when you come to implementing these things. – P26, Lead of Digitalisation*

P31 mentioned equipment alterations they had to make during the gradual implementation stage. Sometimes, decision-makers understand that certain types of racks or materials that interact with mobile robots can get damaged in time and, therefore, need to be replaced or repaired.

> *We put the load carriers into tracks on the floor. And the steel (holding load carriers) was way too thin to handle our load carriers. They bent, and we needed to do something there. Also, gravity racks had to be adjusted. And there are always some software changes. – P31, Technical Manager*

Some minor issues, such as dust on barcode labels that have pallet addresses, can also interrupt the whole operation.

> *If there is a piece of dust in the printer that prints out the labels, the barcode will not be good enough for the AGV to scan it. – P34, Project Manager*

As the process advances, these minor issues may result in minor failures in the implementation process. Due to that, the upper management and/or the employees can feel pressure and become desperate.

> *We were about 6 to 8 weeks into our testing phase, and it was discovered that something was wrong with the system. I do not know the intricacies of it, but the decision was that we had to go back to the start. So, that was a little bit frustrating at the time because people had put a lot of work into doing that*

> *testing. (…) At that point, I thought: Are we ever going to be able to do this? – P28, Operational Lead*

There also are failures that could have more catastrophic results as mobile robots sometimes lift or place heavy material handling units such as pallets. The example below also states the noticeable difference (in terms of health & safety) between an MRS adoption and IT-based innovation adoption.

> *It was quite scary when a big pallet of apple juice came down from 7 metres. (…) You would have to go smooth, and the layout has to work on a millimetre basis. – P37, Warehouse Logistics Coordinator*

In some cases, it was not all about the MRS integration. Managers had to integrate this automation solution into other automation solutions, such as conveyors. That also requires input from both suppliers.

> *It was not just the AGVs that were part of the solution. What we had to do as well was to integrate them with automatic conveyors. That was a separate company (supplier). They then had to communicate. – P27, Project Manager*

Full implementation of MRS can take months. Both in case 3 and case 4, it took at least a couple of months to routinise the MRS.

> *We gradually increased it over about six or seven weeks. We went from those two to ten aisles about six or seven weeks later. So, phase by phase, just doing a bit more each week. – P26, Lead of Digitalisation*

Some of the challenges faced during gradual implementation, such as mobile robot deadlocks, take longer than anticipated and lasts even in full implementation.

> *It took maybe three or four months before we solved all these deadlocks. – P29, Warehouse Manager*

> *There are minor things. We are still finding new sources of errors but gradually getting them down. – P34, Project Manager*

Therefore, the solution needs continuous monitoring and supervision along with worker training. Supervision sometimes requires operational experience with the MRS.

> *It (MRS) needs our ops managers to spend time on the shop floor doing the picks, seeing it, walking around with colleagues, and just understanding it for*

> *themselves so that they can train and coach colleagues to do things faster. – P26, Lead of Digitalisation*

4.4.2.4 Assimilation and Learning

Rogers (2003) and many other previous works of literature discuss that routinisation of the implementation is the last step of innovation diffusion. However, MRS implementation can occur in more than one warehouse operation and/or in other warehouses in various scenarios resulting in different experiences. We cannot conclude that successful implementations mean the innovation is routinised and learned completely to be re-implemented. For example, Case 4 had three (buy type of TAD) successful MRS implementations in different warehouses, but after over a year of testing the fourth implementation, an 'ally' type of TAD, they are getting hopeless.

> *I must be honest with you; I am not quite as optimistic today as I was at the start. – P28, Warehouse Logistics Coordinator*

Therefore, the assimilation and learning phase is indispensable while looking into the diffusion of MRS innovation. This phase affects each previous phase through the decision focus areas and the factors affecting the MRS process. For instance, P37 talked about the 'warehouse and warehouse operation selection' decision in the Initiation phase and mentioned the importance of keeping it simple in the first implementations.

> *The lesson learned is I would have bought (mobile robots) less than actually needed, made it work, and put more in after, just to ensure the investment. – P37, Warehouse Logistics Coordinator*

There are other comments aligned with P37. P28 also mentioned that they are already looking for different implementations for loading and unloading operations.

> *I think we should have taken small steps. Because that lack of knowledge and experience was painful for those involved, but there is a good learning curve. In hindsight, we should have stuck to a simpler solution and got it in quicker. (…) You know we'll start with that (this MRS), but it will obviously expand to loading and unloading trailers. – P28, Operational Lead*

In terms of the ‘robot type and their coordination’ decision, AGVs were chosen as AMRs were recent several years ago. However, we see decision-makers unhappy with AGVs and looking for AMR solutions for future implementations.

> *There were no good solutions for that in 2015 and 16 when we started investigating this. Now you can have this camera technology to see obstacles, and they can choose among different paths. They know all about the flooring in the space and see personnel moving around. If I had done this project today, I would have selected that autonomous with the camera technology instead of a laser. – P29, Warehouse Manager*

When it comes to the effect of assimilation & learning on the ‘decision to adopt’ phase of ‘buy’ and ‘ally’ organisations, we see managers’ intention to stick to a successful supplier. They tend to plan multiple implementations and observe how they get along with the supplier in different scenarios and implementation cycles.

> *We have three truck types: reach trucks, counterbalance, and cage movers. The challenge for us is that if I went down to a different supplier, they would have a different three. Then suddenly, that makes it difficult to transfer them (AGVs) between sites (warehouses). So that is where the partnership comes in, really. We had to choose early on who our partner was and at least for the foreseeable future, we will keep deploying those. But we will have to go through repeated procurement cycles to make sure we are still getting good value from them. – P26, Lead of Digitalisation*

In another case, the organisation of P21 decided to change their suppliers due to dissatisfaction with responsiveness and MRS investments.

> *We basically chose them (the supplier) because they could deliver at that moment. Later on, we see that they are not big enough. They did not fulfil the projects as we wanted them to. They were slow to return to things we wondered about and when we needed things fixed. It took weeks before they came back to us. For instance, another supplier has been putting a lot of effort into being good at AGVs and is leaning forward to investing in AGVs. So, we have made a general deal with them this year. – P21, Group Logistics Manager*

For ‘make’ organisations, there are MRS development-related take-aways based on learning. P2 mentions how they approached MRS development following a management-related failure.

> *We started to re-design the already existing product from scratch. (...) But it seems to me that there was a lack of product-management there (past ‘make’*

> *experience of the organisation). In other words, there were issues such as the business owner not being challenged enough, and the requirements not being detailed from different angles. In fact, after doing these things, we got closer to success. – P2, Operational Excellence Lead (Ex-Robotics Lead)*

Learning for the implementation phase is generally about a particular decision, such as ‘human-robot interaction management’.

> *If I did this again, I would pay much more attention to training the people working in the area. (…) You also need to have separate walkways for personal traffic, mark them and separate them as much as possible. Do that up front. – P29, Warehouse Manager*

Another takeaway is about spare parts under the decision ‘maintenance and failure handling’ mentioned by P28.

> *One of the biggest lessons learned is to get the right spare parts. Proper communication sessions with our engineers to say, what's what? What is likely to go wrong the most and making sure we have got those parts on hand. – P28, Operational Lead*

As learning at the macro-level, P26 expressed their intention to create a standard model (including the decision focus areas discussed in this paper) to simplify the MRS adoption process and told it takes multiple implementations before reaching that aspiration.

> *What we aspire to do is to create a standard model, a template that we can apply to any environment. We are quite early in the process still. So, in terms of automated forklifts, we will hopefully have that standard template when we have done five projects. – P26, Lead of Digitalisation*

P21 supported these ideas adding that they want to be able to orchestrate multiple MRS on a higher level for simplified management purposes.

> *You do not buy it, get it delivered, and just push the button, but we want to push it in that direction. (…) Having a layer there controls all these things. That has been considered. We have been thinking about how we can orchestrate this on a bit higher level in the coming years. – P21, Group Logistics Manager*

P16 also agrees with the intention to standardise, especially for an organisation with multiple warehouses, and added that they are looking for technologies that can be adopted in various warehouses simultaneously.

> *We do not want a solution that is only good for one location. We are trying to standardise as much as possible. It makes it much easier for the companies like ours. – P16, Global Logistics Manager*

Combining all phases creates the resulting figure below (Figure 4-5).

4.4.3 Factors Affecting MRS Adoption Process

Factors affecting MRS adoption can be grouped into technological (MRS-related), organisational, and environmental. Some prior factors were found to be irrelevant according to the data collected. Further, new factors were deduced from the study (Figure 4-6).

4.4.3.1 Technological

Technology Maturity. The scarcity of desired MRS technology may inhibit adoption or affect TAD. P15 mentioned the difficulty they had in finding a quality solution for their scenario. Note that the organisation of P15 changed their mind from buying the MRS off-the-shelf to building an alliance for a tailored MRS.

> *I think we are entering into something that works in some cases, but it is not really mature yet. We had hard times finding (MRS solutions that work with) operations like ours within the conditions we work with, the temperature and all that is. – P15, Country Logistics Manager*

Relative Advantage. Experts think MRS brings many advantages to the warehouse compared to manual solutions. Key benefits include standardising capacity and increasing service level, worker productivity, warehouse safety, and warehouse space efficiency. As an example, having undertaken a successful implementation, P29 summarised the relative advantages of MRS.

> *We pick more than twice the speed over the manual warehouse. We are doing it more efficiently; we save space in the regional warehouses. We have one main warehouse where we pick fast, so we have fewer goods in stock and a higher turnover for the warehouse. We can sell more, and we do not have goods going out of date. – P29, Warehouse Lead*

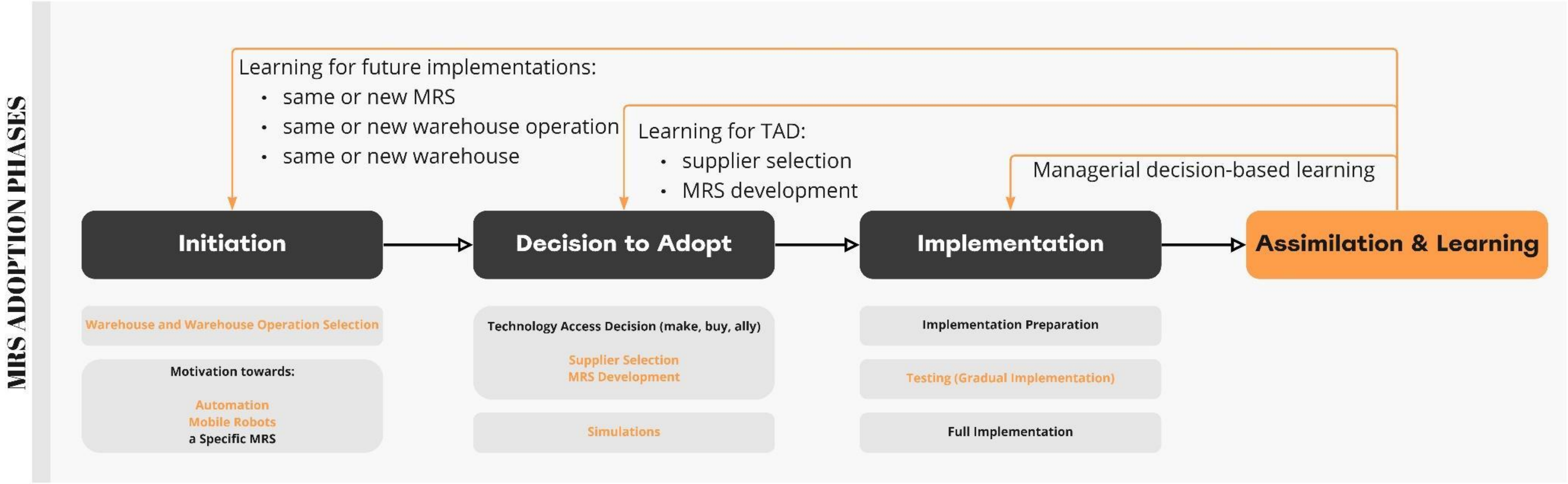


Figure 4-5 MRS adoption phases with yellows being new additions

Figure 4-6 Factors affecting MRS adoption with oranges being new additions

Complexity. One of the most critical factors in the integration of MRS is its complexity. System complexity has multiple angles and can affect many decisions at different levels, such as human-robot interaction management, software & hardware development of robots, or mobile robot task allocation plan. An example is the effect of software complexity of MRS as P31 from said.

> *There were always some software changes during the installation. Then after the implementation, you always have to do a correction. We needed maybe three months of operation before we fixed all the software issues. – P31, Technical Manager*

Compatibility. Mobile robots are generally adopted in existing warehouses with prior processes, layouts, and equipment. Therefore, MRS should be compatible with these existing elements in use, as P15 discussed.

> *I would say as a challenge; we were trying to find something that actually fits within our current environment. We are not making a Greenfield; creating it from scratch. We are trying to find solutions that can fit in our buildings, with some modifications. – P15, Country Logistics Manager*

Cost. Experts believe the cost is a critical factor towards MRS adoption. In their opinion, achieving lower operational costs through MRS adoption would help decrease prices and make them more competitive. P30 from talked about the effects of cost reduction in their operations.

> *One motivation is to be more efficient to lower the price in the stores. If we can reduce our costs while picking the products, we will be a better competitor in the market. – P30, Project Manager*

Trialability. Experimenting with the MRS is a factor that can affect the decisions taking place in the 'decision to adopt' (supplier selection stage) and 'implementation' (testing stage) phases. For example, P16 explained that the organisation was leaning towards a 'buy' decision and had seen a proof of concept of a solution. Then, they thought the product needed some adjustments and allied with the supplier to co-develop a more tailored version of the existing MRS.

> *We actually did a small proof of concept two years ago. Technology was not there 100%, so they went back home and developed a solution. (…) I think that will be beneficial for everyone because when you have some kind of timeline in front of you, you can also allow yourself to invest. So, I am definitely willing also to invest in the development of future solutions together with our supplier. – P16, Global Logistics Manager*

Replaceability. Mobile robots are flexible in terms of infrastructure. They can easily be installed at the beginning or replaced in an emergency. P33 states that these characteristics make them advantageous against solely human-dependant warehouses and other automation solutions.

> *Risks are low because we always have a possibility to replace the solution with people. We are still able to maintain the operation compared to other warehouses that depend on the system being up. – P33, Project Lead*

4.4.3.2 Organisational

Worker Profile. For many MRS, blue-collar workers will be collaborating with robots. Therefore, their involvement in know-how rather than physical capability can be significant for decision-makers. P30 emphasises worker involvement in MRS adoption.

> *Keep personnel from the department that is supposed to handle these mobile robots in the meetings. Because they are the expert in the area, they know how the transport should be handled. They need to be in the meetings with the supplier to ask both dumb questions and technical questions. – P30, Project Manager*

Further, when it comes to distributing roles and responsibilities for the solution. P26 mentioned how discussions involving blue-collar workers became decisive in human task decisions.

> *Some colleagues are very negative about it just because it is change. There are undoubtedly some people who think this will take my job. And then you get hugely positive people who just see the changes happening, and they understand it. They understand the reasons we are doing it. They accept and support. P28 (ex-blue-collar worker) is an operations manager (of the MRS) on the site during the implementation and is absolutely fully supportive. He gets the opportunity for his career development: what if I get on the train early, then I will be in a good place going forward. – P26, Lead of Digitalisation*

Innovativeness of Organisation. The organisation's perspective towards technology and innovation highly affects MRS adoption. According to P1, technology will disrupt conventional companies with logistics functions.

> *The logistics sector is pretty conventional, there are no alternatives that can solve the problems with technology, or if there are, the number of these alternatives is few. Here, we see the opportunity. The world will be shaped as logistics means technology, and we believe in this. The mission is to disrupt all companies that do not believe in technology. Our faith is framed with technology. – P1, CEO*

The innovativeness of an organisation should not only be understood from management-level perspectives. Operational workers' approach towards innovation is also a critical factor in shaping the organisation's innovativeness, as mentioned by P25.

> *Absolutely I would (supervise the robot system). I think that is very exciting. I am very fascinated by technology. I drive a Tesla. I know it (technology) is the future, and I know it is good to show interest in the field as I am also thinking about my future. – P25, Blue-collar worker*

Organisation Size. If the organisation has multiple warehouses with similar operations, efforts to create a standard implementation model start from the decision to adopt phase. Organisations should consider all these layouts and different circumstances before implementing the MRS, as P16 recalled.

> *We were doing the trial in a specific location in Denmark, but for that trial, we had five other managers from three sites in Denmark and two sites in Sweden participating in the trial. We should make sure that the solution we approve is*

> *a solution which works at least in the sites where we see +80% similarity. – P16, Global Logistics Manager*

Top Management Support. Especially support from C-level managers affects the MRS adoption decision-making process and increases worker motivation. P9 explained how the approach of their CEO facilitated the project as a whole.

> *Actually, it all started with our CEO. He loves to look for new opportunities. As far as I remember, he also discussed this solution with several Professors who study such solutions in the USA. Our CEO is the architect of this project, who researched everything about it and gave us the support we needed. – P9, Warehouse Manager*

Warehouse Infrastructure. In some cases, the infrastructure of the warehouse can become an obstacle to MRS adoption. It can complicate the layout planning, which then reflects on the operations. P37 and P36 mentioned their warehouse infrastructure and the challenges it caused to MRS.

> *We had a lot of challenges, but that was in the layouts, basically. Because of the many places they (mobile robots) have to go and different heights and widths. (…) We have the hardest place to do this because it is an old warehouse. Many corners. – P37, Warehouse Logistics Coordinator*
>
> *We are an old company; this building was built in 1968 and since then we are expanding the building mass to cope with the volumes that have been put on. So, the warehouse building is not optimal. – P36, Warehouse Manager*

4.4.3.3 Environmental

Technology Development Ecosystem. Especially for the ‘make’ type of organisations, the ecosystem they reside in can create extra challenges regarding the specific products or sub-systems they want to outsource. P3 summarised the difficulties they faced with the sub-systems they wanted to purchase:

> *Mobile robots are new to Turkey. It was left unattended in here. Therefore, even though the companies that we demand some sub-systems or products work in that sub-system sector, they may require extra thinking, effort, and resources to cater for our needs. They get into a kind of R&D process together with us. – P3, Robotics Lead*

Accessibility of Technology. Even if there is a supplier and the product is available globally, or in the organisation, it might not be accessible to the country where the warehouse resides. P26 recalled they could not use an MRS due to its absence in the UK:

> *It was our advert; a bit of PR in the United States. Colleagues here saw it. And they were like: can I have this to do my container unloading? And the reality is that they will not be in the UK for another 18 months. So great that our organisation is doing it in the States and developing these solutions. But then it gets advertised and then there is this expectation that suddenly we can do the same. – P26, Lead of Digitalisation*

Supply Chain Disruptions. Supply chain experts state that supply chain disruptions (covid-19, war) cause considerable delays in MRS adoption. P30 complained about the delays these disruptions caused.

> *The supply of some materials is affected. We are starting up a new project in the receiving area now. But the delay... The delivery time is 32 weeks, so the suppliers are struggling. We are, in fact, affected in many ways. Both with the pandemic that we have and also now the war. – P30, Project Manager*

Product Type/Shape Changes. Some mobile robot solutions can only lift certain materials or material handling units such as pallets. In case of a product shape alteration (by the customer, manufacturer, or organisation), the robot may require extra maintenance, and some decisions might have to be reconsidered. P26 theorised about this:

> *I mentioned all these different types of products that we are taking over to the production line. Every time there is a change, then suddenly we need to change our system. (…) So, we have to maintain the system. And sometimes, that maintenance of the system means a change to the AGVs. We might have to configure it for a different type of stillage, for instance. – P26, Lead of Digitalisation*

Competitive Pressure. One of the drivers of MRS adoption is competition. As MRS adoption is strongly associated with efficient warehouse operations with higher throughput values, decision-makers adopt MRS to maintain their service in this era with higher customer expectations. P26 said:

> *Our competitors are also doing this. We have to make sure we are providing the best service for our customers. Otherwise, our customers will not stay with us. So, they want to know that we are providing a leading-edge service, using the latest technology, and delivering value for them, keeping their costs low, providing more accurate and dependable service. – P26, Lead of Digitalisation*

Government Legislation. Legislations sometimes become the driving factor for organisations to adopt MRS. Especially in warehousing, governments emphasise workers' health and safety and restrict how much weight a person can lift in a day. P22 talked about that:

> *Yes, we are waiting for it (about the weightlifting restriction). I have heard that Denmark has done that. Countries around us do that. We will follow them shortly. If that happens, we have to find solutions to pick heavy goods, which is why we are trying this robot. – P22, Warehouse Manager*

Supply Chain's MRS Perspective. It is not only competitors who are adopting MRS. The presence of MRS in the upstream or downstream of the supply chain the organisation belongs to can trigger an intention to adopt and enlighten the organisation about managerial decisions. P31 mentioned the upstream example, while P26 mentioned the downstream example.

> *A company that stores the load carriers that are being used by us. They have had this supplier for some years. They are very familiar with those load carriers and moving them around. That meant that they could easily implement this system at our warehouse. – P31, Technical Manager*
>
> *Our customer works with this supplier on their sites as well. That gave us some actual data about AGVs that the supplier provides. They could do the job. – P26, Lead of Digitalisation*

4.4.4 Compilation of MRS adoption phases, managerial decisions, and factors

It is salient that the decisions discussed in the managerial decision framework are embedded within the process of MRS adoption. Therefore, these decisions were considered indispensable to the MRS implementation. Further, technological, organisational, and environmental factors influence MRS adoption and implementation by affecting the managerial decision framework. Drawing from IDT, TOE, and the managerial decision framework discussed previously, an elaborated MRS adoption framework is now introduced in Figure 4-7.

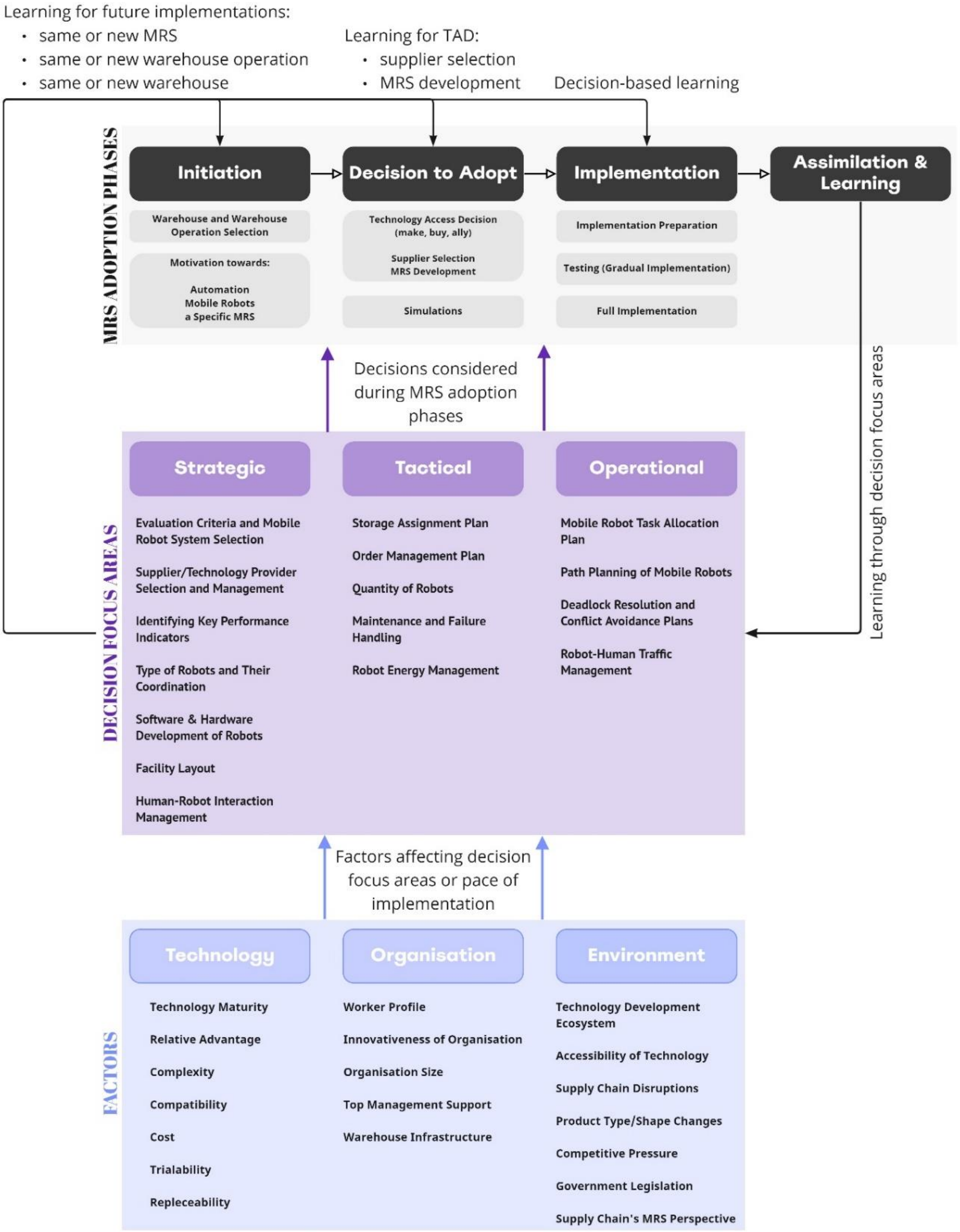


Figure 4-7 MRS adoption framework

4.5 Discussion

4.5.1 A case illustration

An example process (a sub-case from case 3) will be explained in the discussion to show how TOE factors affect the managerial decision framework and influence the MRS adoption process. This sub-case is a warehouse for a production site next to it and aims to carry materials in material handling units to the production area. The warehouse employs laser-guided vehicles in put-away and replenishment operations of pallets and stillages.

At the initiation phase, decision-makers were not satisfied with the scarcity and cost (compared to laser-guided robots, human workers were more expensive) of human labour and considered automating their warehouse operations. They also believed that automation is more advantageous than the existing manual solution to increase and standardise the warehouse throughput. The decision-makers visited another customer warehouse and saw the laser-guided robots carrying pallets. That visit was what motivated them towards laser-guided vehicles. Observing the solution ensured that this MRS would satisfy their operational requirements. As a result, they decided to buy laser-guided robots for their warehouse. We see ‘cost’, ‘relative advantage’, and ‘supply chain’s MRS perspective’ factors affecting the ‘evaluation criteria and MRS selection’ decision.

They started looking for suppliers during the decision to adopt phase, as it was a ‘buy’ TAD. However, due to supplier scarcity (an environmental factor), their supplier selection decision was only a choice among three or four suppliers that could do what they asked for (lift pallets up to 11 metres high).

In the preparation stage of the implementation phase, as the technology was compatible (technological factor) with physical installation, there were no extra problems with the facility layout planning decision. During the gradual implementation stage, they got away with fewer complications in worker training. Their worker profile was already quite interested in learning to control and work with the MRS. However, during the full implementation stage, due to covid-19 (supply chain disruptions), a chip shortage decreased their customer’s demand.

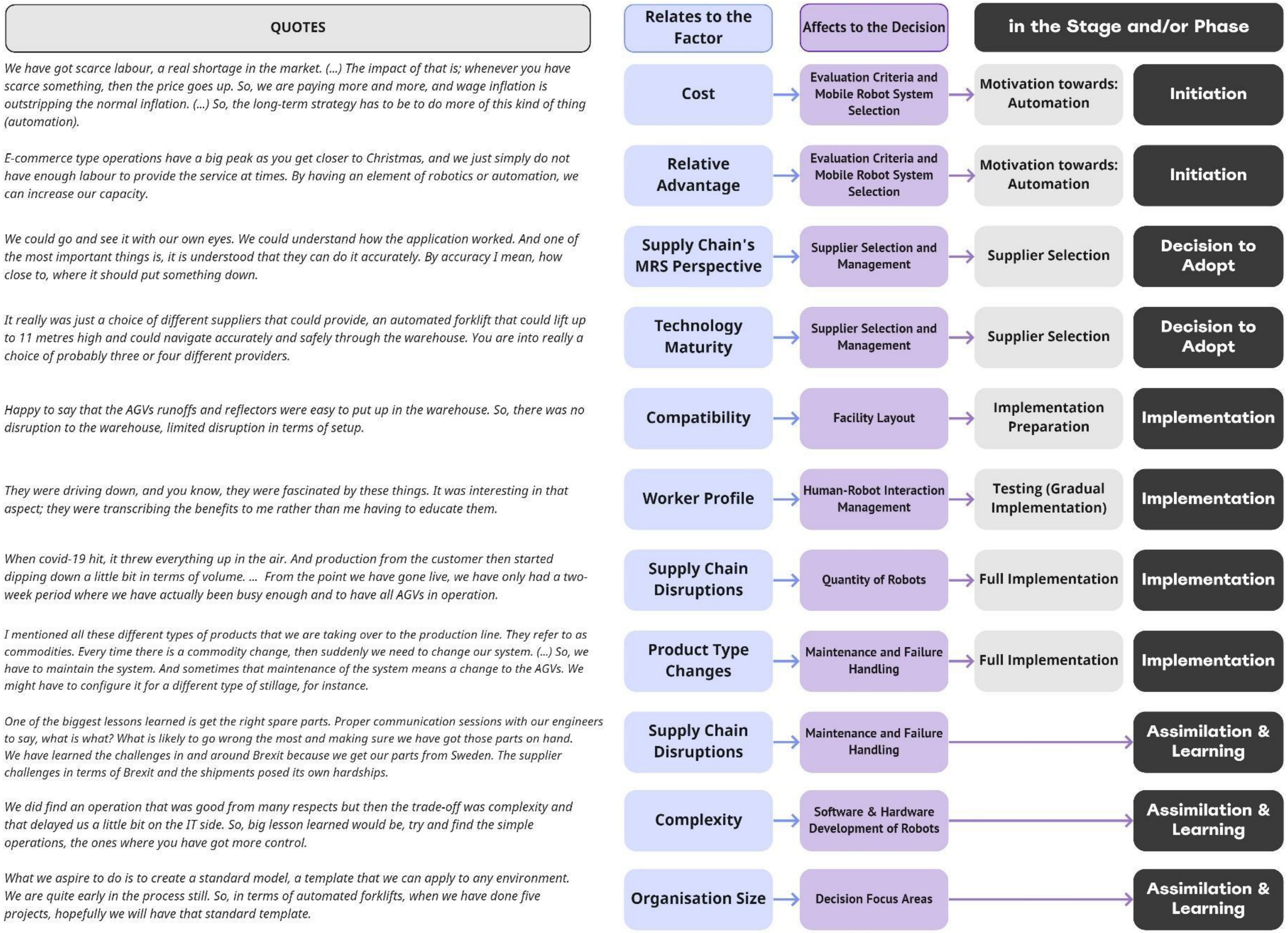
They had to recalculate how many active mobile robots they needed every week. Indeed, they could only use the full fleet for two weeks. This is how environmental factors affected their ‘quantity of robots’ decision. Further, in the same stage, their customer changed the product type they work with, which caused extra maintenance on mobile robots.

They have learned that they should carefully manage spare parts inventory because they have faced delays bringing in stocked-out spare parts due to Brexit. Further, they discovered that complex solutions could delay the implementation due to IT integration issues, and therefore, they will be looking out for simpler MRS. Most importantly, they know they will have multiple implementations due to the organisation's size. Consequently, they aspire to create a template model similar to the MRS adoption framework this paper offers. It involves not only one decision point but the decision focus areas as a whole.

Many other decision points and factors affected the organisation’s MRS adoption journey. Still, this section aimed briefly to explain how the proposed MRS adoption framework, containing decision focus areas and factors, functions in different phases, which is a key contribution of this paper (Figure 6).

4.5.2 Significance of Learning in MRS Adoption

MRS is a type of innovation that has a fast-paced development environment. As P29 (Warehouse Manager) stated, there were very few AMR-type MRS back in the 2016s, but now you see many in the market. Thus, it cannot be concluded that other implementations will be the same as the first one and succeed. Those implementations will be different, and a new solution is a potential for failure. This characteristic keeps MRS as an innovation even if the organisation is in their fourth implementation (case 4).



QUOTES	Relates to the Factor	Affects to the Decision	in the Stage and/or Phase	
We have got scarce labour, a real shortage in the market. (...) The impact of that is; whenever you have scarce something, then the price goes up. So, we are paying more and more, and wage inflation is outstripping the normal inflation. (...) So, the long-term strategy has to be to do more of this kind of thing (automation).	Cost	Evaluation Criteria and Mobile Robot System Selection	Motivation towards: Automation	Initiation
E-commerce type operations have a big peak as you get closer to Christmas, and we just simply do not have enough labour to provide the service at times. By having an element of robotics or automation, we can increase our capacity.	Relative Advantage	Evaluation Criteria and Mobile Robot System Selection	Motivation towards: Automation	Initiation
We could go and see it with our own eyes. We could understand how the application worked. And one of the most important things is, it is understood that they can do it accurately. By accuracy I mean, how close to, where it should put something down.	Supply Chain's MRS Perspective	Supplier Selection and Management	Supplier Selection	Decision to Adopt
It really was just a choice of different suppliers that could provide, an automated forklift that could lift up to 11 metres high and could navigate accurately and safely through the warehouse. You are into really a choice of probably three or four different providers.	Technology Maturity	Supplier Selection and Management	Supplier Selection	Decision to Adopt
Happy to say that the AGVs runoffs and reflectors were easy to put up in the warehouse. So, there was no disruption to the warehouse, limited disruption in terms of setup.	Compatibility	Facility Layout	Implementation Preparation	Implementation
They were driving down, and you know, they were fascinated by these things. It was interesting in that aspect; they were transcribing the benefits to me rather than me having to educate them.	Worker Profile	Human-Robot Interaction Management	Testing (Gradual Implementation)	Implementation
When covid-19 hit, it threw everything up in the air. And production from the customer then started dipping down a little bit in terms of volume. ... From the point we have gone live, we have only had a two-week period where we have actually been busy enough and to have all AGVs in operation.	Supply Chain Disruptions	Quantity of Robots	Full Implementation	Implementation
I mentioned all these different types of products that we are taking over to the production line. They refer to as commodities. Every time there is a commodity change, then suddenly we need to change our system. (...) So, we have to maintain the system. And sometimes that maintenance of the system means a change to the AGVs. We might have to configure it for a different type of stillage, for instance.	Product Type Changes	Maintenance and Failure Handling	Full Implementation	Implementation
One of the biggest lessons learned is get the right spare parts. Proper communication sessions with our engineers to say, what is what? What is likely to go wrong the most and making sure we have got those parts on hand. We have learned the challenges in and around Brexit because we get our parts from Sweden. The supplier challenges in terms of Brexit and the shipments posed its own hardships.	Supply Chain Disruptions	Maintenance and Failure Handling		Assimilation & Learning
We did find an operation that was good from many respects but then the trade-off was complexity and that delayed us a little bit on the IT side. So, big lesson learned would be, try and find the simple operations, the ones where you have got more control.	Complexity	Software & Hardware Development of Robots		Assimilation & Learning
What we aspire to do is to create a standard model, a template that we can apply to any environment. We are quite early in the process still. So, in terms of automated forklifts, when we have done five projects, hopefully we will have that standard template.	Organisation Size	Decision Focus Areas		Assimilation & Learning

Figure 4-8 Case illustration

Further, MRS does not only mainly involve software integration such as IS technologies mentioned in the theoretical background. MRS has a massive physical integration aspect which involves human workers. Therefore, the human safety side of these implementations is highly mentioned in the literature (Inam et al., 2018; Petković et al., 2019; Raineri et al., 2019) and in cases. The researcher listened to incidents in different cases, such as pallets falling from a rack or manual forklifts colliding with mobile robots.

Moreover, human workers fear losing their jobs (Bechtsis et al., 2017) which also challenges decision-makers. Therefore, to efficiently manage the adoption of MRS and similar technologies, this paper suggests that the 'assimilation & learning' phase is an indispensable part of this journey. Some papers adopting IDT as their theory address learning partially as 'assimilation' (Hazen et al., 2012; Zhu et al., 2006) and some others relate learning to absorptive capacity (Knoppen et al., 2015) theory developed by Cohen and Levinthal (1990). However, academia, and especially SCM, requires more study on the learning part of technology/innovation adoption.

From a more theoretical point of view, the findings overlap with single, double, and triple-loop learning (Argyris and Schön, 1997; Tosey et al., 2012). Single-loop learning reflects changes in the organisation's knowledge without adjusting processes (Snell and Chak, 1998) and considers the question: are we doing things right (Flood and Romm, 1996)? These ideas are relevant to the learning through the decision focus areas for existing implementation, such as adjusting a path planning algorithm while keeping the process the same. Double loop learning brings extra discussion by asking: are we doing the right things (Flood and Romm, 1996)? This question relates to the learning happening for future implementations. Decision-makers re-consider their motivation, including other MRS and TAD. Finally, triple-loop learning is on a deeper level that links together the chain of events about the diversity of issues, challenges faced, and decisions are taken to form a new structure or strategy (Georges L. Romme and van Witteloostuijn, 1999; Tosey et al., 2012). That reflects the template or model decision-makers aspire to create after multiple MRS implementations. The MRS adoption framework offered in Section 4.4.4 could act as a starting point for pilot MRS implementation in smart warehouses. Then, with the help of single, double, and triple-loop learning cycles, it can be upgraded to its full use while the organisation scales with more mobile robots or new MRS. Eventually, the adoption framework, upgraded with the assimilation and learning, would support organisations to maintain and efficiently control mobile robot adoption to its full performance.

Other than mobile robot technology, innovations that can be (re-)implemented (in a different process or using a new version of a similar technology) within the organisation can also use the insights this paper offers. Organisations can consciously add learning for their existing and future implementations as an extra phase to their innovation adoption journey. Further, the stages this study identifies within different phases could enlighten the adoption journey of similar technological innovations that comprise successive implementations.

This paper also studied the technological, organisational, and environmental factors and how they can affect the process of innovation adoption through managerial decisions and lead to actions. These actions cause learning at different levels and loops and make factors enablers or barriers through the journey, as studied in Mathauer and Hofmann, (2019), Wei et al., (2015), X. Wu and Subramaniam, (2011).

4.6 Conclusion

4.6.1 Theoretical Contribution

IDT (Rogers, 2003) and other articles using IDT (Mathauer and Hofmann, 2019; Sternberg et al., 2021; Vu et al., 2022; Zhu et al., 2006) consider innovation as a linear process generally formed of three phases (initiation, decision to adopt, implementation) and focus on gaining the anticipated benefit out of it at once. However, MRS adoption is a cyclical process, and assimilation & learning of that particular innovation is the most significant step towards creating a template (as high-level managers P16, P21, and P26 emphasize) or a model for similar future implementations.

Taking a step out of the MRS context, the structure of the ‘assimilation & learning’ phase in the framework can be related to the triple-loop learning model where: 1) single-loop learning is relevant to corrections through decision focus areas for existing implementations, 2) double-loop learning is relevant to the ‘assimilation and learning’ for future similar implementations, and 3) triple-loop learning is relevant to the learning informed by a chain of events and challenges to form a mobile robot adoption framework/model. This relevance might be generalised and become helpful in the adoption of similar innovations.

IDT offers generalised stages/steps of an innovation adoption journey. Papers are adopting these stages and elaborating them to fit the particular innovation studied, such as Blockchain (Vu et al., 2022). This study uses the same logic to explain the MRS adoption journey, including phases and stages combining IDT and the data derived from the case study. It elaborates on pre-defined stages and identifies new stages in adopting MRS. This will help future research focusing on the challenges encountered in pre-defined stages and/or phases in not only MRS adoptions but also similar warehouse technology adoptions especially involving physical implementations.

Moreover, IDT and studies using IDT do not focus on TAD other than Mathauer and Hofmann, (2019). Mathauer and Hofmann (2019) focus on the results of TAD while this paper provides a thick description, including motivations and rationale for a selected TAD for the entire decision to adopt phase in MRS adoption. This way, it aims to offer more generalisable results.

Finally, technological, organisational, and environmental factors affecting MRS adoption were synthesised. Determining the significance of these factors might be a future research area for academia. More importantly, these factors helped form the elaborated MRS adoption framework using an integrative theoretical approach. From the theoretical perspective, this framework is expected to enlighten the question of how MRS innovation is adopted in warehouses.

4.6.2 Managerial Implications

As the practical use of mobile robot systems increases, decision-makers are confronted with many decisions. This study aims to explain the MRS implementation journey by defining the steps and stages they will most likely encounter. It considers carefully synthesised decision focus areas, thereby supporting managers in avoiding costly mistakes such as implementing unsuitable mobile robot systems or overlooking key decision factors. Further, it points out technological, organisational, and environmental factors that managers have to consider, as these factors might become an enabler or a barrier according to the specific scenario.

The mobile robot sector is rapidly evolving, and new technologies are constantly being developed. Therefore, decision-makers need to create a model or a template to assimilate the whole journey. For that reason, warehouse decision-makers will benefit from the MRS adoption framework this study offers when they face the (inevitable) requirement to automate their warehouse processes. These findings will serve not only big logistics players but also help small and medium - sized companies to adapt to the logistics market’s automation-based and competitive nature.

Finally, it is observed that many organisations are leaning towards a ‘buy’ decision as making mobile robot solutions from scratch is not their core business. Considering this fact, a set of supplier selection criteria was discussed to help decision-makers in the supplier selection decision.

4.6.3 Research Limitations

In every research, there are limitations. The main limitation of this research was covid-19. Due to travel restrictions, researchers could not travel to do site observation in some cases. Further, they could not conduct face-to-face interviews and had to perform almost all the interviews online. Finally, another limitation was not having a fully implemented ‘make’ type of case which would potentially limit the external validity of this study for ‘make’ type of cases.

4.6.4 Further Research

The adoption framework (Figure 4-7) offered by this paper could be generalisable for the innovation adoption of logistics functions, especially when the innovation involves both IT and physical aspects. Moreover, it is evident in this study that the ‘assimilation & learning’ phase affects every step of innovation adoption. Therefore, the feasibility of this framework and, more importantly, the effect of ‘assimilation & learning’ in adopting other technologies can be investigated in future studies.

4.7 References to Chapter 4

Argyris, Ch. and Schön, D.A. (1997), “Organizational Learning: A Theory of Action Perspective”, Reis, No. 77/78, p. 345, doi: 10.2307/40183951.

Ahmed, A. L., and Kassem, M. (2018). A unified BIM adoption taxonomy: Conceptual development, empirical validation and application. Automation in Construction, 96, 103–127. https://doi.org/10.1016/j.autcon.2018.08.017

Baker, J. (2012). The Technology–Organization–Environment Framework. In Y. K. Dwivedi, M. R. Wade, and S. L. Schneberger (Eds.), Information Systems Theory (Vol. 28, pp. 231–245). Springer New York. https://doi.org/10.1007/978-1-4419-6108-2_12

Baker, P., and Halim, Z. (2007). An exploration of warehouse automation implementations: Cost, service and flexibility issues. Supply Chain Management: An International Journal, 12(2), 129–138. https://doi.org/10.1108/13598540710737316

Bechtsis, D., Tsolakis, N., Vlachos, D., and Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Benzidia, S., Ageron, B., Bentahar, O., and Husson, J. (2019). Investigating automation and AGV in healthcare logistics: A case study based approach.

International Journal of Logistics Research and Applications, 22(3), 273–293. https://doi.org/10.1080/13675567.2018.1518414

Borah, A., and Tellis, G. J. (2013). Make, Buy, or Ally? Choice of and Payoff to Alternate Strategies for Innovations. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2321468

Boysen, N., de Koster, R., and Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. European Journal of Operational Research, 277(2), 396–411. https://doi.org/10.1016/j.ejor.2018.08.023

Capron, L., and Mitchell, W. (2010). Finding the Right Path. Harvard Business Review.

Cohen, W. M., and Levinthal, D. A. (1990). Absorptive Capacity: A New Perspective on Learning and Innovation. Administrative Science Quarterly, 35(1), 128. https://doi.org/10.2307/2393553

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. MIS Quarterly, 13(3), 319–340. JSTOR. https://doi.org/10.2307/249008

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. The Academy of Management Review, 14(4), 532–550. https://doi.org/10.2307/258557

Evangelista, P., McKinnon, A., and Sweeney, E. (2013). Technology adoption in small and medium-sized logistics providers. Industrial Management & Data Systems, 113(7), 967–989. https://doi.org/10.1108/IMDS-10-2012-0374

Fazlollahtabar, H., and Saidi-Mehrabad, M. (2015). Methodologies to Optimize Automated Guided Vehicle Scheduling and Routing Problems: A Review Study. Journal of Intelligent & Robotic Systems, 77(3–4), 525–545. https://doi.org/10.1007/s10846-013-0003-8

Flood, R. L., and Romm, N. R. A. (1996). Contours of diversity management and triple loop learning. Kybernetes, 25(7/8), 154–163. https://doi.org/10.1108/03684929610149747

Fragapane, G., de Koster, R., Sgarbossa, F., and Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. European Journal of Operational Research, 294(2), 405–426. https://doi.org/10.1016/j.ejor.2021.01.019

Georges L. Romme, A., and van Witteloostuijn, A. (1999). Circular organizing and triple loop learning. Journal of Organizational Change Management, 12(5), 439–454. https://doi.org/10.1108/09534819910289110

Gerring, J. (2006). Case Study Research: Principles and Practices.

Given, L. M. (2008). The sage encyclopedia of qualitative research methods. Thousand Oaks, CA: Sage.

Gnekpe, C., and Coeurderoy, R. (2017). The impact of internal and external technology sourcing on innovation performance: A review and research agenda. International Journal of Technology Management, 73(1/2/3), 21. https://doi.org/10.1504/IJTM.2017.082355

Hartley, J. L., Sawaya, W., and Dobrzykowski, D. (2022). Exploring blockchain adoption intentions in the supply chain: Perspectives from innovation diffusion and institutional theory. International Journal of Physical Distribution & Logistics Management, 52(2), 190–211. https://doi.org/10.1108/IJPDLM-05-2020-0163

Hazen, B. T., Overstreet, R. E., and Cegielski, C. G. (2012). Supply chain innovation diffusion: Going beyond adoption. The International Journal of Logistics Management, 23(1), 119–134. https://doi.org/10.1108/09574091211226957

Inam, R., Raizer, K., Hata, A., Souza, R., Forsman, E., Cao, E., and Wang, S. (2018). Risk Assessment for Human-Robot Collaboration in an automated warehouse scenario. 2018 IEEE 23rd International Conference on Emerging

Technologies and Factory Automation (ETFA), 743–751. https://doi.org/10.1109/ETFA.2018.8502466

Jaghbeer, Y., Hanson, R., and Johansson, M. I. (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

Ketokivi, M., and Choi, T. (2014). Renaissance of case research as a scientific method. Journal of Operations Management, 32(5), 232–240. https://doi.org/10.1016/j.jom.2014.03.004

Knoppen, D., Johnston, D., and Sáenz, M. J. (2015). Supply chain relationships as a context for learning leading to innovation. The International Journal of Logistics Management, 26(3), 543–567. https://doi.org/10.1108/IJLM-09-2012-0089

Lai, Y., Sun, H., and Ren, J. (2018). Understanding the determinants of big data analytics (BDA) adoption in logistics and supply chain management: An empirical investigation. The International Journal of Logistics Management, 29(2), 676–703. https://doi.org/10.1108/IJLM-06-2017-0153

Lamballais, T., Roy, D., and De Koster, M. B. M. (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

Le-Anh, T., and De Koster, M. B. M. (2006). A review of design and control of automated guided vehicle systems. European Journal of Operational Research, 171(1), 1–23. https://doi.org/10.1016/j.ejor.2005.01.036

Low, C., Chen, Y., and Wu, M. (2011). Understanding the determinants of cloud computing adoption. Industrial Management & Data Systems, 111(7), 1006–1023. https://doi.org/10.1108/02635571111161262

Mathauer, M., and Hofmann, E. (2019). Technology adoption by logistics service providers. International Journal of Physical Distribution & Logistics Management, 49(4), 416–434. https://doi.org/10.1108/IJPDLM-02-2019-0064

Merschformann, M., Lamballais, T., de Koster, M. B. M., and Suhl, L. (2019). Decision rules for robotic mobile fulfillment systems. Operations Research Perspectives, 6, 100128. https://doi.org/10.1016/j.orp.2019.100128

Mudambi, S. M., and Tallman, S. (2010). Make, Buy or Ally? Theoretical Perspectives on Knowledge Process Outsourcing through Alliances: Knowledge Process Outsourcing through Alliances. Journal of Management Studies, 47(8), 1434–1456. https://doi.org/10.1111/j.1467-6486.2010.00944.x

Petković, T., Puljiz, D., Marković, I., and Hein, B. (2019). Human intention estimation based on hidden Markov model motion validation for safe flexible robotized warehouses. Robotics and Computer-Integrated Manufacturing, 57, 182–196. https://doi.org/10.1016/j.rcim.2018.11.004

Raineri, M., Perri, S., and Guarino Lo Bianco, C. (2019). Safety and efficiency management in LGV operated warehouses. Robotics and Computer-Integrated Manufacturing, 57, 73–85. https://doi.org/10.1016/j.rcim.2018.11.003

Ridder, H.-G. (2017). The theory contribution of case study research designs. Business Research, 10(2), 281–305. https://doi.org/10.1007/s40685-017-0045-z

Rogers, E. M. (2003). Diffusion of Innovations (5th ed). Free Press.

Roy, D., Nigam, S., de Koster, R., Adan, I., and Resing, J. (2019). Robot-storage zone assignment strategies in mobile fulfillment systems. Transportation Research Part E: Logistics and Transportation Review, 122, 119–142. https://doi.org/10.1016/j.tre.2018.11.005

Saunders, M., Lewis, P. and Thornhill, A. (2012) Research Methods for Business Students. Pearson Education Ltd., Harlow.

Shamout, M., Ben-Abdallah, R., Alshurideh, M., Alzoubi, H., Kurdi, B. A., and Hamadneh, S. (2022). A conceptual model for the adoption of autonomous robots in supply chain and logistics industry. Uncertain Supply Chain Management, 10(2), 577–592. https://doi.org/10.5267/j.uscm.2021.11.006

Snell, R., and Chak, A. M.-K. (1998). The Learning Organization: Learning and Empowerment for Whom? Management Learning, 29(3), 337–364. https://doi.org/10.1177/1350507698293005

Sternberg, H. S., Hofmann, E., and Roeck, D. (2021). The Struggle is Real: Insights from a Supply Chain Blockchain Case. Journal of Business Logistics, 42(1), 71–87. https://doi.org/10.1111/jbl.12240

Tornatzky, L. G., and Fleischer, M. (1990). The Processes of Technological Innovation. Lexington, Mass. : Lexington Books.

Tosey, P., Visser, M. and Saunders, M.N. (2012), “The origins and conceptualizations of ‘triple-loop’ learning: A critical review”, Management Learning, Vol. 43 No. 3, pp. 291–307, doi: 10.1177/1350507611426239.

Venkatesh, V., Morris, M. G., Davis, G. B., and Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. MIS Quarterly, 425–478.

Vivaldini, K. C. T., Rocha, L. F., Becker, M., and Moreira, A. P. (2015). Comprehensive Review of the Dispatching, Scheduling and Routing of AGVs. In A. P. Moreira, A. Matos, and G. Veiga (Eds.), CONTROLO’2014 – Proceedings of the 11th Portuguese Conference on Automatic Control (Vol. 321, pp. 505–514). Springer International Publishing. https://doi.org/10.1007/978-3-319-10380-8_48

Vu, N., Ghadge, A., and Bourlakis, M. (2022). Evidence-driven model for implementing Blockchain in food supply chains. International Journal of Logistics Research and Applications, 1–21. https://doi.org/10.1080/13675567.2022.2115987

Wei, J., Lowry, P. B., and Seedorf, S. (2015). The assimilation of RFID technology by Chinese companies: A technology diffusion perspective. Information & Management, 52(6), 628–642. https://doi.org/10.1016/j.im.2015.05.001

White, S. (2000). Competition, Capabilities, and the Make, Buy, or Ally Decisions of Chinese State-Owned Firms. Academy of Management Journal, 43(3), 324–341. https://doi.org/10.2307/1556398

Wong, L.-W., Leong, L.-Y., Hew, J.-J., Tan, G. W.-H., and Ooi, K.-B. (2020). Time to seize the digital evolution: Adoption of Blockchain in operations and supply chain management among Malaysian SMEs. International Journal of Information Management, 52, 101997. https://doi.org/10.1016/j.ijinfomgt.2019.08.005

Wu, I.-L., and Chuang, C.-H. (2009). Analyzing contextual antecedents for the stage-based diffusion of electronic supply chain management. Electronic Commerce Research and Applications, 8(6), 302–314. https://doi.org/10.1016/j.elerap.2009.04.013

Wu, I.-L., and Chuang, C.-H. (2010). Examining the diffusion of electronic supply chain management with external antecedents and firm performance: A multi-stage analysis. Decision Support Systems, 50(1), 103–115. https://doi.org/10.1016/j.dss.2010.07.006

Wu, X., and Subramaniam, C. (2011). Understanding and Predicting Radio Frequency Identification (RFID) Adoption in Supply Chains. Journal of Organizational Computing and Electronic Commerce, 21(4), 348–367. https://doi.org/10.1080/10919392.2011.614203

Wu, Y., Cegielski, C. G., Hazen, B. T., and Hall, D. J. (2013). Cloud Computing in Support of Supply Chain Information System Infrastructure: Understanding When to go to the Cloud. Journal of Supply Chain Management, 49(3), 25–41. https://doi.org/10.1111/j.1745-493x.2012.03287.x

Yin, R. K. (2018). Case study research and applications: Design and methods (Sixth edition). SAGE.

Zhu, K., Kraemer, K. L., and Xu, S. (2006). The Process of Innovation Assimilation by Firms in Different Countries: A Technology Diffusion Perspective on E-Business. Management Science, 52(10), 1557–1576. https://doi.org/10.1287/mnsc.1050.0487

5 Conclusions

5.1 Matching Research Objectives with Findings

This section shows how the initial overall research objectives are fulfilled through chapters 2, 3, and 4. This thesis aimed to shed light on the entire MRS adoption journey in warehouses. It included the motivation of warehouse managers to adopt such systems and also examined the implementation journey of these automation solutions. There were three research objectives at the beginning:

1) To systematically review and categorise the managerial decisions that warehouse managers need to consider from the extant literature.
2) To identify, categorise, and evaluate MRS from the extant literature and investigate potential system selection approaches.
3) To empirically investigate the MRS adoption journey and elaborate on the literature about the managerial decisions and factors affecting the MRS adoption journey.

Table 5-1 expresses how initial research objectives are addressed and fulfilled in the thesis also mentioning relevant chapters. Even though it seems like there is a one-to-one relationship between research objectives and chapters, it is evident that chapter 2 acts as a foundational basis for other chapters. Also, chapter 4 elaborates on and completes the conceptual managerial decision framework that was first developed in chapter 2.

5.1.1 Mobile Robot Adoption Journey

This section builds on Figure 1-2 to expand on the MRS adoption journey by explaining the artefacts of each chapter and how these artefacts can shape the journey (Figure 5-1).

Phase 1: Initiation

After spotting an unproductive or inefficient (i.e., no or less added value) warehouse operation, decision-makers will be seeking potential solutions to their pain points. At this point, they should be knowledgeable about the benefits of MRS to consider MRS as a potential technology to adopt so they can improve their operations. Chapter 3 collects evidence from the literature and supply chain experts to list the potential benefits MRS could bring (3.5.3). Further, it creates an initiation point by developing a set of evaluation criteria out of these foreseen benefits which would then support the motivation to adopt such solutions (see Table 3-2).

Phase 2: Decision to Adopt

The next phase in a generic MRS adoption journey is the decision to adopt. In this phase, managers need to select a suitable MRS and also decide how to access the system (technology access decision). Chapter 3 develops an MRS rating table (Table 3-3) including ten systems ranked through five evaluation criteria. It also offers MCDMs involving decision trees (Figure 3-2) and/or mathematical models (Equation (3-5) which provide the flexibility of altering the weights of each criterion. Finally, once the MRS to be implemented is determined, Chapter 4 points out alternatives to technology access options (Figure 4-1).

Phase 3: Implementation

Generally, most of the managerial decision focus areas are evaluated and finalised at this phase. Chapter 2 presents a managerial decision framework artefact that is formed through the systematic literature review (Figure 2-2). Further, there are contextual factors that affect these managerial decisions and the pace of MRS adoption. Chapter 4 sets out more than ten contextual factors categorised as technological, organisational, and environmental (Figure 4-6).

Phase 4: Assimilation & Learning

This phase aims to create a template for the MRS adoption journey that consists of the phases, mobile robot systems, managerial decisions, and contextual factors. Chapter 4 combines all the outputs of Chapters 2, 3, and 4 in a single MRS adoption framework (Figure 4.7). This aggregated framework can act as an initial implementation template for the managers for their pilot implementations. In time, through learning cycles, it can be updated and tailored to better suit the specific needs of organisations and support successive implementation efforts.

Table 5-1 Matching research objectives with findings

Research Objectives	Findings	Chapters
To systematically review and categorise the managerial decisions that warehouse managers need to consider from the extant literature.	Thirteen decisions are devised and analysed in detail using insights from 107 papers	Chapter 2
	Thirteen decisions were categorised through their characteristics and with a system implementation logic as 1) Strategic, 2) Tactical, and 3) Operational	Chapter 2
	Three new decisions and three new focus areas were included to make the managerial decision framework more comprehensive	Chapter 4
To identify, categorise, and evaluate MRS from the extant literature and investigate potential system selection approaches.	Ten mobile robot systems are identified through the literature	Chapter 2
	Ten mobile robot systems were divided with regard to their way of navigation in the warehouses as 1) Linear Route Robots, 2) Guided Robots, 3) Freeway Robots, and 4) Hybrid Systems	Chapter 3
	A ranking system was developed using the ideas from the extant literature and each system was evaluated through their characteristics	Chapter 3
	The ‘Equal Weight’ approach was offered as a system selection approach and demonstrated through a scenario and a decision tree. According to that scenario, linear route robots appear to be the best system with the highest grade	Chapter 3
	The second approach offered is the ‘Full Consistency Method’ that used the insights of five supply chain experts. According to this system selection approach, the best system is linear route robots for a generic warehouse.	Chapter 3
To empirically investigate the MRS adoption journey and elaborate on the literature about the managerial decisions and factors affecting the MRS adoption journey.	A conceptual managerial decision framework was formed from the literature	Chapter 2
	Also including the conceptual managerial decision framework, a theoretical framework was developed with potential innovation adoption phases and contextual factors (technological, organisational, and environmental)	Chapter 4
	A multiple case studies showed that: 1) the MRS adoption journey is cyclical with a continuous ‘Assimilation and Learning’ phase and further implementation instances, 2) 19 contextual factors affect managerial decisions and the overall pace of MRS adoption, 3) 16 managerial decision focus areas should be addressed in MRS adoption and they affect each adoption phase differently, and 4) there are three different levels of learning in MRS adoption that can be explained by triple-loop learning theory	Chapter 4

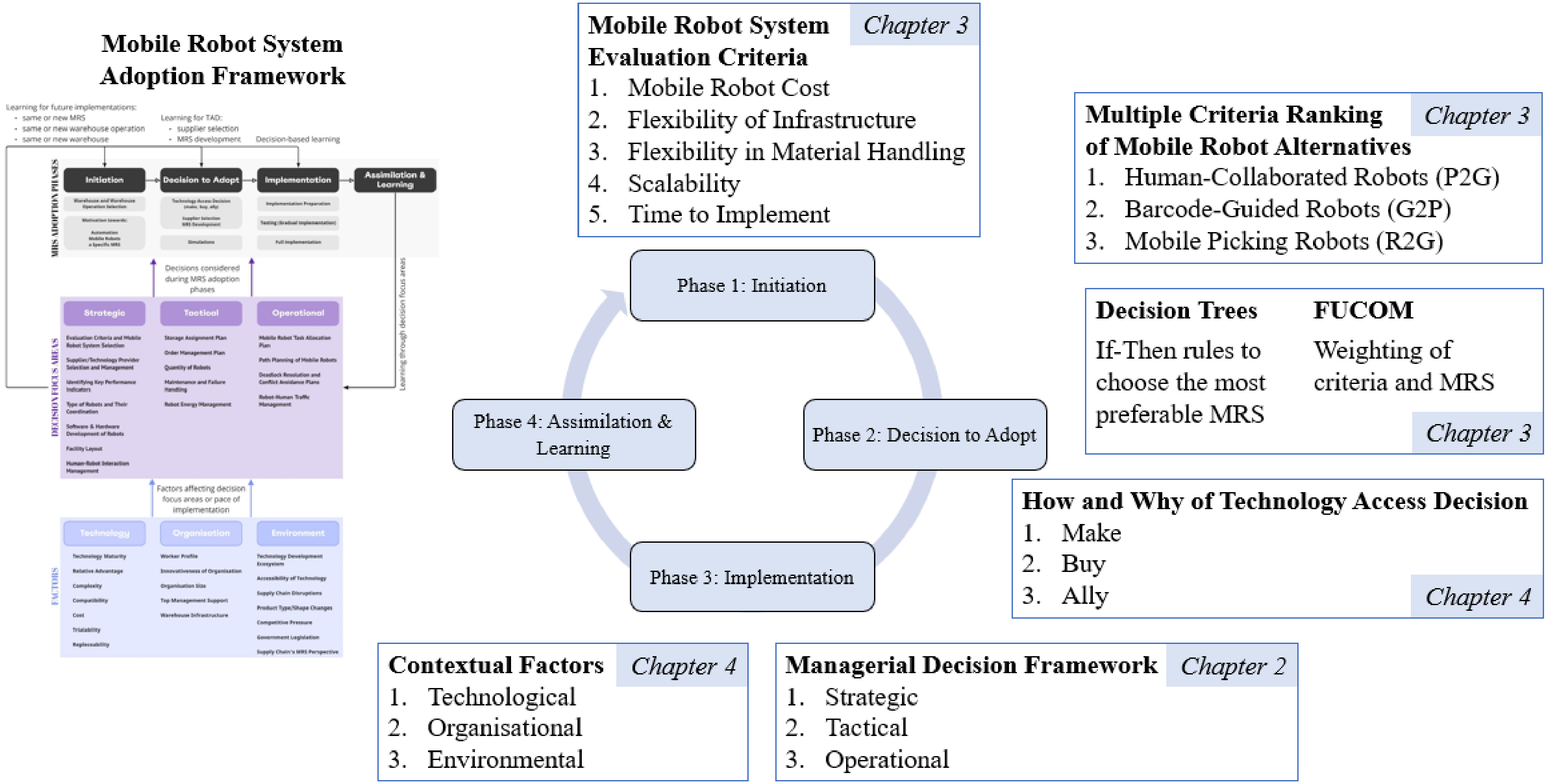


Figure 5-1 Shaping the MRS adoption journey

)

5.2 Contributions of the Thesis

This section is divided into three for each type of contribution: 1) theoretical contribution, 2) methodological contribution, and 3) practical contribution.

5.2.1 Theoretical Contribution

As the aim of this thesis is to explain the MRS adoption journey, it makes theoretical contributions to various parts of this journey (Table 5-2).

There are recent literature reviews and explanatory papers on warehousing and automation solutions (Azadeh et al., 2019; Bechtsis et al., 2017; Boysen et al., 2019; Custodio and Machado, 2020; Fragapane et al., 2021; Jaghbeer et al., 2020; Wior et al., 2018). Yet, there is very little focus on mobile robots and papers offering research avenues are outdated (Le-Ahn et al., 2006; Vis, 2006). This thesis addresses this gap with an up-to-date research agenda in Chapter 2 that is further extended in 5.4. Moreover, the previous studies (Fragapane et al., 2021; Le-Ahn et al., 2006; Vis, 2006) that attempted to form a decision framework on MRS adoption is rather fragmented and have a technology focus. This thesis forms an integrated managerial decision framework that categorises a comprehensive list of managerial decisions for MRS selection and implementation. Moreover, this study concentrates on reviewing MRS alternatives and explains them one by one. It develops a ranking system consisting of significant (according to supply chain experts) MRS evaluation criteria and assesses MRS alternatives through these criteria.

To respond to the call (Boysen et al., 2019) for empirical work regarding the automation system selection approach in warehouses, this thesis adopts FUCOM and explains how this novel multiple-criteria decision-making method could become a system selection approach. It also discusses the outcomes based on the importance of evaluation criteria with similar studies such as Fazlollahtabar et al., (2019) and Zavadskas et al., (2018). Building on the list of criteria used in the ranking system, this study explains what motivates decision-makers to adopt MRS in warehouses by listing the significant criteria that affect the MRS adoption decisions of supply chain managers.

Mostly supported by chapter 4, this thesis explains the entire journey of adopting MRS in warehouses through the theoretical lens of IDT (Rogers, 2003). It also elaborates on the IDT in the context of MRS. The development of IDT takes place from multiple angles.

Firstly, it compiles an extensive MRS adoption framework consisting of phases of MRS adoption, managerial decisions to consider, and TOE factors affecting these decisions. Previous works adopting IDT (Mathauer and Hofmann, 2019; Sternberg et al., 2021; Vu et al., 2022; Zhu et al., 2006) consider innovation as a linear process generally formed of three phases (initiation, decision to adopt, and implementation). Yet, this study sets out a fourth phase as ‘Assimilation and Learning’ which is a continuous phase, making the MRS adoption a cyclical process. The ‘Assimilation and Learning’ phase is particularly important because, in a generic warehouse, multiple MRS implementations are expected rather than a single MRS implementation. This phase not only means learning from mistakes but also involves assimilating the technology to exploit its benefits. The phase is, therefore, helpful when it comes to creating an implementation template similar to the MRS adoption framework (Figure 4-7).

Other than including the fourth phase, this thesis elaborates on pre-defined (Rogers, 2003) stages and identifies new stages in the context of MRS adoption. For instance, there is an extensive focus on the ‘Decision to Adopt’ phase building on the work of Mathauer and Hofmann, (2019) with the inclusion of ‘TAD’ and ‘Simulations’ stages. Contributions to these phases and stages will help future research focusing on the challenges encountered in pre-defined stages and/or phases in not only MRS adoptions but also similar warehouse technology adoptions especially involving physical implementations.

By integrating IDT and TOE framework, this study puts emphasis on the TOE factors and their effect on managerial decisions and the MRS adoption process. These factors can sometimes become enablers or barriers in different scenarios. Therefore, this study identifies 19 TOE factors in the context of MRS implementation and directs future research on defining the significance and type of these factors.

Table 5-2 Overview of the contribution of the thesis

Paper Title	Theoretical Contribution	Practical Contribution	Methodological Contribution
Systematic Review of Mobile Robots in Warehouses: Decision Framework and Research Agenda (Chapter 2)	• Forming a conceptual and integrated managerial decision framework that categorises decisions for MRS selection and implementation. • Devising a research agenda that identifies and structures future research avenues.	• Helping decision-makers to implement an MRS in a logical order and without overlooking a managerial decision.	-
Mobile Robots in Warehouses: Evaluation Criteria for System Selection (Chapter 3)	• Defines a ranking system to support the selection of potential MRS. • Evaluates and assesses MRS alternatives through a decision tree and a novel multiple-criteria decision-making approach (the full consistency method). • Explains what motivates decision-makers to adopt MRS in warehouses. • Develops a typology of mobile robots and associated systems.	• Shows decision-makers a way to evaluate and select MRS. • Supports the practicality of evaluation criteria through demonstrations and a novel method. • Discusses additional criteria that can be useful for different scenarios (insights of SC experts).	• Being one of the very few papers to perform the novel ‘Full Consistency Method’ in the context of warehousing and mobile robots. Also, the methodological approach this study develops is not only valid for mobile robot automation but could potentially become a way of assessing other types of warehouse equipment and automation alternatives.

Mobile Robot System Implementation in Warehouses: an Adoption Framework (Chapter 4)	• Including ‘Assimilation & Learning’ as a phase in IDT and analysing other phases in detail for the MRS context. • Defining MRS adoption as a cyclical process and anticipating more than one implementation rather than focusing only on the implementation at hand. • Relating MRS adoption with single, double, and triple -loop learning to make the findings more generalisable for a wider context of similar innovations. • Compiling an extensive managerial decision framework to consider in MRS adoption, and presenting technological, organisational, and environmental factors affecting these decisions. • Extending the ‘Decision to Adopt’ phase with TAD and linking both TAD and ‘Decision to Adopt’ phase to managerial decisions (many managerial decisions are first considered at this phase rather than the ‘Implementation’ phase).	• Explaining the MRS implementation journey by defining phases and stages that decision-makers will most likely be encountering. • Considering decision focus areas, thereby supports managers in avoiding costly mistakes. • Devising technological, organisational, and environmental factors that managers have to consider. • Offering an MRS adoption framework for MRS integration and implementation which can act as an initial template for future MRS implementations. • Discussing a set of supplier selection criteria to help decision-makers in the supplier selection decision.	• The case study conducted in this paper is one of the very few for MRS in warehouses. It shows how differentiation in cases might be achieved which leads to analytical generalisation.

Finally, keeping the intention of achieving generalisable theoretical outcomes, the continuous learning cycles in the MRS adoption can be related to the single, double, and triple loop learning model (Argyris and Schön, 1997; Tosey et al., 2012). This thesis relates its outcomes to these models through managerial decisions, the 'Assimilation and Learning' phase, and the MRS adoption framework (from specific to general concepts).

5.2.2 Methodological Contribution

This thesis has two key methodological contributions: 1) the case study and 2) the FUCOM method. Firstly, the case study conducted in this paper is one of the very few involving MRS in warehouses. Other studies are Hmidach et al. (2020), Škerlič et al. (2017), and Zhang et al. (2021). In this study, cases were selected according to three underlying considerations: 1) TAD (make, buy, ally), 2) Company country (Turkey, UK, Denmark, Norway), and 3) Company type (grocery retailers, 3PLs). This case selection strategy shows how external validity in cases might be achieved which, then, leads to analytical generalisation (Ridder, 2017; Yin, 2018).

Secondly, being one of the very few papers to perform the novel 'Full Consistency Method' in the context of warehousing and mobile robots, the application presented in this paper is a demonstration and the proof of concept of a mobile robot system selection strategy. It extends the scope of previous FUCOM studies (Fazlollahtabar et al., 2019; Zavadskas et al., 2018) in terms of included system types, and therefore, is richer in terms of findings of the applied method. Considering deviation consistency values being '0' or a negligible positive value, the results are reliable with high validity in terms of methodology (Pamučar et al., 2018). Hence, FUCOM is applicable to demonstrate an evaluation of mobile robot systems regarding the predefined set of evaluation criteria. Further, the methodological approach this study develops is not only valid for mobile robot automation but could potentially become a way of assessing other types of warehouse equipment and automation alternatives.

FUCOM is also used in group decision-making processes in the supply chain to form a consensus among decision-makers (Fazlollahtabar et al., 2019). Nevertheless, there is a threat of manipulation (opinion leaders influencing others) in that approach which led the researcher of this thesis to implement individual evaluation processes.

Finally, as FUCOM can be further customised with additional criteria and/or sensitivity analyses, this study offers the necessary methodological guidance for both academia and practice.

5.2.3 Practical Contribution

The researcher believes that mobile robot automation is at an early stage. The sooner the firms consider implementing these solutions, the more benefit they will get by gathering experience. This thesis aims to provide insights for managers considering deploying mobile robots in their warehouses. It explains the MRS implementation journey by defining the steps and stages they will most likely encounter.

When we think of MRS and similar innovation adoption journeys from a macro perspective, the first step would be the motivation for the solution which also includes the pain points of the current approach (Rogers, 2003). This thesis offers a range of significant potential motivations (some of which could also be named as evaluation criteria) deduced from the literature and the supply chain experts.

Once the company is keen to adopt an MRS, they will be seeking out MRS types and assess them according to their operations and evaluation criteria. This thesis first lists the available MRS and then evaluates them through a set of criteria and a ranking system. To support the practicality of the evaluation criteria, this work demonstrates system selection approaches adopting multi-criteria decision-making methods. Overall, it shows decision-makers a way to evaluate and select MRS. This step is typically followed by a TAD which is deeply investigated in this study through the ‘buy’, ‘make’, and ‘ally’ type of decisions including supplier characteristics and relationships.

As the practical use of mobile robot systems increases, decision-makers are confronted with many decisions in the implementation journey including MRS selection decisions and TAD. According to Llopis-Albert et al. (2019), managers pay more attention to management and financial issues rather than technical issues. In contrast, academic papers mainly focus on technical decisions rather than management decisions. This study provides a comprehensive managerial decision framework to have a balanced approach among management and financial (primarily strategic and tactical decisions), and technical (primarily operational decisions) issues. It, therefore, helps managers to avoid overlooking any decisions in the implementation which could become costly mistakes such as implementing unsuitable mobile robot systems or overlooking key decision factors.

Together with the steps that managers will most likely encounter and decisions that require their attention, there are contextual factors that affect the entire journey, sometimes dramatically. These factors are identified and categorised as technical, organisational, and environmental, using the output of four countries' MRS context.

Finally, as mobile robot sector is rapidly evolving, and new technologies are constantly being developed supply chain managers need to create a model or a template to assimilate the whole journey. For that reason, warehouse decision-makers will benefit from the final MRS adoption framework this study offers when they face the inevitable requirement to automate their warehouse processes. This research places learning at the heart of the adoption framework as it anticipates multiple MRS implementations for each warehouse. Learning affects every step of the journey and highly increases the efficiency of ongoing and future implementations.

All in all, these findings will serve not only big logistics players but also help small and medium -sized companies to adapt to the logistics market's automation-based and competitive nature.

5.3 Research Limitations

As with any study, this thesis also has several limitations. First and foremost, covid-19 was a significant limitation as it inhibited the researcher to travel to the warehouses. It also prevented face-to-face interviews. Because of that, the researcher could not communicate with some of the blue-collar personnel.

Secondly, the case study itself has a couple of limitations due to the nature of the methodology. As the companies of the subject were multi-national and large companies, it was quite difficult, or sometimes not possible, to gather some of the documents that contain sensitive information about the companies. Further, even though the researcher aimed to achieve generalisable results by increasing the variety of company type, country, and technology access decisions; external validity might still be limited. The reason is that this study does not include companies from every country (there are not many candidate companies owing to the recency of the subject), and it was undertaken with a few types of mobile robot systems.

Relevant to the recency of the subject, it was also tough to find supply chain experts who are also knowledgeable about mobile robots for Paper 2. It would be a more generalisable result to have a hundred experts filling the survey for FUCOM but given the time limitations and covid-19 restrictions, the researcher could only be able to collect data from five experts.

Finally, with regard to MRS types covered in the systematic literature review, the list might not be exhaustive. There are many innovative MRS perspectives developed by the tens of start-ups in the market and it is almost impossible for academia to keep up with that pace.

Other limitations are mentioned in the ‘Conclusion’ sections of each paper/chapter see (2.5, 3.6, and 4.6.3).

5.4 Future Research Directions

As a general approach, any study that addresses the limitations of empirical papers of this thesis would put forward further insights. Other than that, this study creates several research avenues. Firstly, continuing with the mixed method logic, the importance of the contextual (technological, organisational, and environmental) factors can be determined through a quantitative method involving practitioners.

Secondly, there can be a longitudinal study focusing on an organisation from the initiation/motivation phase until they fully implement a mobile robot system. In that case, we can capture further insights in relevant timelines to elaborate on the MRS adoption framework offered in this study.

Thirdly, a study can focus on the enablers and barriers of adopting MRS in different countries and/or company types. The researcher believes that the contextual (TOE) factors offered in this study would be helpful for that type of research.

This thesis contains laser-guided robots (carrying pallets), barcode-guided robots (carrying shelves), and human-collaborated robots (carrying small products). A different study can concentrate on other MRS alternatives. Comparing the outcome of this thesis and this study would result in increased analytical generalisation.

This thesis focused on logistics service providers and grocery retailers. Other types of companies might be taken into consideration in future research such as manufacturing (automotive, electronic, apparel) or non-grocery retailing companies.

Finally, as this thesis relates its outcomes to single, double, and triple loop learning models, further research can be conducted to highlight these details and how they match in different innovation contexts.

Research agenda (2.4) in Paper 1 can also be helpful for MRS decision-specific research directions.

5.5 References to Chapter 5

Argyris, Ch., and Schön, D. A. (1997). Organizational Learning: A Theory of Action Perspective. Reis, 77/78, 345. https://doi.org/10.2307/40183951

Azadeh, K., De Koster, R. B. M., and Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. In Transportation Science (Vol. 53, Issue 4). https://doi.org/10.1287/trsc.2018.0873

Bechtsis, D., Tsolakis, N., Vlachos, D., and Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Boysen, N., De Koster, R. B. M., and Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. In European Journal of Operational Research (Vol. 277, Issue 2, pp. 396–411). Elsevier B.V. https://doi.org/10.1016/j.ejor.2018.08.023

Custodio, L., and Machado, R. (2020). Flexible automated warehouse: a literature review and an innovative framework. International Journal of Advanced Manufacturing Technology, 106(1–2), 533–558. https://doi.org/10.1007/s00170-019-04588-z

Fazlollahtabar, H., Smailbašić, A., and Stević, Ž. (2019). FUCOM method in group decision-making: Selection of forklift in a warehouse. Decision Making: Applications in Management and Engineering, 2(1), 49–65. https://doi.org/10.31181/dmame1901065f

Fragapane, G., de Koster, R., Sgarbossa, F., and Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. European Journal of Operational Research, 294(2), 405–426. https://doi.org/10.1016/j.ejor.2021.01.019

Hmidach, S., El Kihel, Y., Amegouz, D., El Kihel, B., and Regad, Y. (2020). Optimizing warehouse logistics flows by integrating new technologies: Case study of an agri-food industry. 2020 IEEE 2nd International Conference on

Electronics, Control, Optimization and Computer Science (ICECOCS), 1–5. https://doi.org/10.1109/ICECOCS50124.2020.9314501

Jaghbeer, Y., Hanson, R., and Johansson, M. I. (2020). Automated order picking systems and the links between design and performance: a systematic literature review. International Journal of Production Research, 0(0), 4489–4505. https://doi.org/10.1080/00207543.2020.1788734

Le-Anh, T., and De Koster, R. B. M. (2006). A review of design and control of automated guided vehicle systems. European Journal of Operational Research, 171(1), 1–23. https://doi.org/10.1016/j.ejor.2005.01.036

Llopis-Albert, C., Rubio, F., and Valero, F. (2019). Fuzzy-set qualitative comparative analysis applied to the design of a network flow of automated guided vehicles for improving business productivity. Journal of Business Research, 101, 737–742. https://doi.org/10.1016/j.jbusres.2018.12.076

Mathauer, M., and Hofmann, E. (2019). Technology adoption by logistics service providers. International Journal of Physical Distribution & Logistics Management, 49(4), 416–434. https://doi.org/10.1108/IJPDLM-02-2019-0064

Pamučar, D., Stević, Ž., and Sremac, S. (2018). A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). Symmetry, 10(9), 393. https://doi.org/10.3390/sym10090393

Ridder, H.-G. (2017). The theory contribution of case study research designs. Business Research, 10(2), 281–305. https://doi.org/10.1007/s40685-017-0045-z

Rogers, E. M. (2003). Diffusion of Innovations (5th ed). Free Press.

Škerlič, S., Muha, R., and Sokolovskij, E. (2017). Application of modern warehouse technology in the Slovenian automotive industry. Transport, 32(4), 415–425. https://doi.org/10.3846/16484142.2017.1354315

Sternberg, H. S., Hofmann, E., and Roeck, D. (2021). The Struggle is Real: Insights from a Supply Chain Blockchain Case. Journal of Business Logistics, 42(1), 71–87. https://doi.org/10.1111/jbl.12240

Tosey, P., Visser, M., and Saunders, M. N. (2012). The origins and conceptualizations of ‘triple-loop’ learning: A critical review. Management Learning, 43(3), 291–307. https://doi.org/10.1177/1350507611426239

Vis, I. F. A. (2006). Survey of research in the design and control of automated guided vehicle systems. European Journal of Operational Research, 170(3), 677–709. https://doi.org/10.1016/j.ejor.2004.09.020

Vu, N., Ghadge, A., and Bourlakis, M. (2022). Evidence-driven model for implementing Blockchain in food supply chains. International Journal of Logistics Research and Applications, 1–21. https://doi.org/10.1080/13675567.2022.2115987

Wior, I., Jerenz, S., and Fay, A. (2018). Automated transportation systems subject to interruptions in production and intralogistics - a survey and evaluation. International Journal of Logistics Systems and Management, 30(4), 421. https://doi.org/10.1504/IJLSM.2018.093581

Yin, R. K. (2018). Case study research and applications: Design and methods (Sixth edition). SAGE.

Zavadskas, E. K., Nunić, Z., Stjepanović, Ž., and Prentkovskis, O. (2018). Novel Rough Range of Value Method (R-ROV) for selecting automatically guided vehicles (AGVs). Studies in Informatics and Control, 27(4), 385–394. https://doi.org/10.24846/v27i4y201802

Zhang, D., Pee, L. G., and Cui, L. (2021). Artificial intelligence in E-commerce fulfillment: A case study of resource orchestration at Alibaba’s Smart Warehouse. International Journal of Information Management, 57, 102304. https://doi.org/10.1016/j.ijinfomgt.2020.102304

Zhu, K., Kraemer, K. L., and Xu, S. (2006). The Process of Innovation Assimilation by Firms in Different Countries: A Technology Diffusion Perspective on E-Business. Management Science, 52(10), 1557–1576. https://doi.org/10.1287/mnsc.1050.0487

APPENDICES

Appendix A Systematic Literature Review

A.1 SLR Methodology Details

Table A-1 Selection Criteria of SLR

SELECTION CRITERIA	INCLUSION	EXPLANATION
LANGUAGE	Papers should be in English	It is the language of this paper
ACCESSIBILITY	Full text of papers should be accessible	Papers should be fully evaluated
REVIEW	Peer-reviewed papers	Quality and validity of the papers should be ensured
TYPE OF PUBLICATION	Academic journals and conference papers/proceedings are included	To keep the quality high and the number of papers manageable
YEAR OF PUBLICATION	Academic journals published later than 2000 or conference papers/proceedings published later than 2015	Mobile robot systems in warehousing drastically developed after the year 2000 so papers before 2000 would miss breakthroughs. Quality conference papers older than 5 years are assumed to have become academic journals, thus they are excluded
SCOPE AND CONTEXT	Mobile robot systems in warehouses will be considered.	Other contexts, such as manufacturing, are not in the scope of this research. Systems that do not involve mobile robots are not in the scope of this research

Table A-2 Quality Criteria of SLR

QUALITY CRITERIA	THEORY ROBUSTNESS	CONTRIBUTION TO KNOWLEDGE	METHODOLOGY AND ARGUMENTS	IMPLICATION FOR PRACTICE
1	The literature review is weak or does not exist. Even though a theory exists, it is not supported effectively	The contribution is either not advanced or clear	The logic behind data is not supported or methodology is not strong	The concepts and ideas presented are ambiguous or somewhat irrelevant, thus they are very difficult to implement
2	The theory is somewhat validated. A basic level of literature review supports the topic-theory match	Contribution builds upon the existing ideas or studies	The logic behind data is supported but it is limited, or methodology/research design could be improved	There is a potential for implementing the proposed ideas with minor revisions or adjustments
3	The theory is nicely explained and supported by the presence of a relevant literature review. The theory fits the topic	Expands the issue with an innovative approach and well-explained solution	Data is well supported by ideas; the research design is robust and analysis is rigorous	A significant benefit may be obtained if the ideas being discussed are put into practice
N/A	This criterion is not applicable	This criterion is not applicable	This criterion is not applicable	This criterion is not applicable

A.2 Analysis of Papers Reviewed in SLR

Table A-3 Analysis of papers reviewed in the SLR

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Abbas et al., 2018	Empirical	AS/RS, Conveyor, Mobile Robots	Sorting	Not mentioned	Robot utilisation / idleness	AGV	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Not mentioned	Shortest path algorithms such as Dijkstra's	Not mentioned
Azadeh et al., 2019	Review	Review barcode-guided, human-collaborated mobile robots	Picking, Replenishment	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness, task delay / response time	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mention strategies	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mention strategies	Not mentioned	Not mentioned
Bauters et al., 2016	Empirical	Barcode-Guided Mobile Robots	Picking	Cost, service quality, material handling flexiblity, infrastructure flexiblity, and scalability	Robot utilisation / idleness, workstation utilisation, throughput	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching but how?	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Bechtsis et al., 2017	Review	Not mentioned	Not mentioned	Not mentioned	Emission metrics, utilisation of robots, resource efficiency metrics	Mention electric and diesel robots next to battery robots	Defines coordination types	Not mentioned	Review human-robot interaction management sub-sections	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mention online allocation strategies	Not mentioned	Not mentioned
Bogue, 2016	Review	Review barcode-guided, human-collaborated, and mobile picking robots	Picking	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Boysen et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Studies the effect of SKU diversity on shelves	Offline/Static, batching with simulated annealing	Through SKU diversity in shelfs	Not mentioned	Not mentioned	Simulated annealing	Not mentioned	Not mentioned
Boysen et al., 2019	Review	Review barcode-guided, human-collaborated mobile robots	Picking, Replenishment, Sorting	Define criteria for e-commerce setting	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Review different policies	Review static and dynamic strategies	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Chen et al., 2018	Empirical	Freeway Mobile Robots	Sorting	Not mentioned	Not mentioned	AMR	Mixed. Task Alloc. Centralised, Path Planning Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Imrpoved Artificial Potential Function	Imrpoved Artificial Potential Function
Claes et al., 2017	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Monte carlo tree search with iterative greedy heuristic	Monte carlo tree search with iterative greedy heuristic	Not mentioned
Confessore et al., 2013	Empirical	Not mentioned	Not mentioned	Not mentioned	Avg. task completion time	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Optimised number of robots as a conclusion	Migration of task in case of failure	Charges when battery is low with deterministic time	Network flow based vehicle initiated dispatching	Not mentioned	Limits number of vehicles in zones and increases expected time for congested zones
De Koster, 2018	Review	Reviews barcode-guided and human-collaborated mobile robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
De Koster et al., 2004	Empirical	Not mentioned	Not mentioned	Not mentioned	Robot utilisation, task delay /response time	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Not mentioned	Compare rules	Not mentioned	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
D'Emidio & Khan, 2019	Empirical	Grid-based system	Not mentioned	Not mentioned	Robot travel distance, Avg task completion time	AMR	Mixed	Compares different number of aisles and lengths	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Auction	Safe Interval Path Planning	Prioritisation
Digani et al., 2015	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AMR	Mixed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes and statistically proves the validity	Not mentioned	Not mentioned	Not mentioned	D* with model predictive control to be assigned to the zones, A* in the zones	Negotiation (according to priority and zone change requests) with resource allocation strategy. Zoning with Voronoi decomposition
Digani et al., 2016	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Computation / negotiation time	AMR	Mixed. Macro-management is Centralised, inside of sectors are Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Not mentioned	A*	Prioritisation. Zones to efficiently control the area
Digani et al., 2019	Empirical	Self-Picking Mobile Robots	Picking	Not mentioned	Robot travel time, avg task completion time	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Waiting time minimisation through negotiation	Quadratic optimisation with A*	Prioritisation. Zones to efficiently control the area
Dou et al., 2015	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot utilisation / idleness, robot travel time	AMR	Mixed. Task Alloc. Centralised, Path Planning Distributed	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching but how?	Not mentioned	Not mentioned	Not mentioned	Genetic algorithm	Q-learning	Learning reward and prioritisation
Draganjac et al., 2016	Empirical	Autonomous Forklifts	Shipping	Not mentioned	Not mentioned	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Migration of task in case of failure	Not mentioned	One out of N algorithm	State lattice construction and A*	Prioritisation and private zone - waiting or re-route
Draganjac et al., 2020	Empirical	Autonomous Forklifts	Shipping	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness, computation / negotiation time, number of deadlock / conflicts / routing failures	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	One out of N algorithm	Shortest path algorithms such as Dijkstra's	Prioritisation and re-routing
Enright & Wurman, 2011	Opinion	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Fan et al., 2018	Empirical	Barcode-Guided Mobile Robots	Sorting	Not mentioned	Throughput (time-based, order line-based), number of deadlocks / conflicts / routing failures, number of active robots	AGV	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Minimises number of mobile robots required	Not mentioned	Not mentioned	Not mentioned	Link weight increment heuristic with time window	Forward time window searching, waiting
Farinelli et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Avg task completion time, computation / negotiation time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Greedy local heuristic solving distributed constraint optimisation problem	Shortest path algorithms such as Dijkstra's	Prioritisation
Fazlollahbaitar et al., 2013	Review	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Reviews exact approaches, meta-heuristics, and AI solutions	Reviews exact approaches, meta-heuristics, and AI solutions	Reviews exact approaches, meta-heuristics, and AI solutions
Feng et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot travel distance	AMR	Not mentioned	Compares Flying-V and Traditional layouts with different number of aisles and aisle lenghts	Not mentioned	Random storage assignment policy	Not mentioned	Not mentioned	Not mentioned	Not mentioned	0-1 integer programming	Shortest path algorithms such as Dijkstra's	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Ferrara et al., 2014	Empirical	Laser-Guided Mobile Robots and Pallet Shuttles Mixed System	Put-away, Picking	Not mentioned	Robot utilisation / idleness	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching but how?	Optimisation through queueing network	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Fussler et al., 2019	Empirical	Rail Using Mobile Robots	Picking	Not mentioned	Not mentioned	AGV	Not mentioned	Not mentioned	Not mentioned	SKU storage optimisation through Mixed Integer Programming adjusted via Simulated Annealing	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Priority-rule-based approach, order swapping	Not mentioned	Not mentioned
Ghassemi & Chowdhury, 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot utilisation / idleness, computation / negotiation time	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Bipartite graph matching with fuzzy task clustering	Shortest path algorithms such as Dijkstra's	Not mentioned
H. Wang et al., 2019	Empirical	Human-collaborated mobile robots	Picking	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness, robot travel time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching but how?	Compares different fleet sizes	Not mentioned	Not mentioned	Genetic algorithm	A*	Zones to efficiently control the area
Halming et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot travel distance, travel time, number of deadlocks / conflicts / failures	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Shortest response time	A*	Reservation of routes through time windows
Hamann et al., 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Minimises the charging locations in the operational area through online connected dominating set algorithm	Not mentioned	Not mentioned	Not mentioned
Hanson et al., 2018	Case Study	Barcode-Guided Mobile Robots	Picking	Cost, material handling flexibility	Hit rate, number of deadlocks / conflicts / routing failures	AMR	Not mentioned	Not mentioned	Mention advantages of ergonomics	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
He et al., 2018	Empirical	Not mentioned	Picking	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Storage according to product service levels	Online/Dynamic	Impact of different fleet sizes considered	Not mentioned	Not mentioned	Deadline minimisation through Differentiated Probabilistic Queueing solved by simulated annealing and order swapping	Not mentioned	Not mentioned
Hornakova et al., 2019	Empirical	Laser-Guided and Autonomous Forklifts	Not mentioned	Mobile robot cost, infrastructure flexibility	Not mentioned	Define AGV, AMR, and seven criteria to select among alternatives. Use AHP method	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Huang et al., 2015	Review	Review barcode-guided and mobile picking robots	Not mentioned	Cost, material handling flexibility, scalability	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Inam & Raizer, 2018	Empirical	Human-collaborated mobile robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Risk assessment in human-robot collaboration scenarios	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
K. Wang et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Six scenarios with different number of aisles and layers. Single vs double-deep shelf layouts	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Kattepur et al., 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Migration of task in case of failure	Dual-decomposition to minimise battery consumption	Contract net protocol (negotiation)	Not mentioned	Not mentioned
Kimura et al., 2015	Empirical	Pick & Transport Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Krnjak et al., 2015	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Robot travel distance, number of deadlocks / conflicts / routing failures	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	A* with state lattice	Checks for collision before each step
Lamballais et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness,	AMR	Not mentioned	Shelf, and workstation layout studies through queueing theory	Not mentioned	ABC storage policy vs random storage policy	Online/Dynamic	Performance estimations through the number of mobile robots	Not mentioned	Not mentioned	Not mentioned	Dijkstra's	Zones to efficiently control the area.
Lamballais et al., 2020	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness,	AMR	Not mentioned	Studies on proportion of picking and replenishment workstations	Not mentioned	Optimises number of shelves per SKU and shelf replenishment level through queueing theory.	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Shortest path algorithms such as Dijkstra's	Uni-directional aisles
Lau et al., 2007	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Migration of task in case of failure	Not mentioned	Artificial immune system based exploration	Not mentioned	Not mentioned
Le-Ahn & De Koster, 2006	Review	Not mentioned	Not mentioned	Not mentioned	Robot travel time, travel distance, utilisation, number of deadlocks / conflicts/ routing failures, task delay /response time	Not mentioned	Defines coordination types	Reviews flowpath of robots and strategies for idle robot positioning	Not mentioned	Not mentioned	Not mentioned	Reviews fleet sizing methods	Not mentioned	Reviews battery management	Reviews online / fixed task allocation	Not mentioned	Reviews zoning strategies, conflict management, and system workload balancing
Le-Ahn et al., 2010	Empirical	Not mentioned	Not mentioned	Not mentioned	Robot utilisation / idleness, task delay /response time	Not mentioned	Not mentioned	Studies U and I layouts	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compare heuristics and rules	Shortest path algorithms such as Dijkstra's	Not mentioned
Lee & Murray, 2019	Empirical	Pick & Transport Robots	Picking	Not mentioned	Robot travel distance, computation / negotiation time	AMR	Not mentioned	Compares two types of layouts with different number of workstations and storages	Not mentioned	Uniform storage policy	Offline/Static, batching but how?	Compares different fleet sizes	Not mentioned	Charges when battery is nearly 0%	Linear programming	Linear programming	Not mentioned
Lee et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking, Replenishment	Not mentioned	Not mentioned	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Charge when energy level is below 40%	Not mentioned	Improved A* using manhattan distance and reserving all possible routes and including turning times	Time window to calculate, waiting before starting, re-route to another optimal route and go-away to prevent
Li et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching through three-stage hybrid heuristic algorithm	Not mentioned	Not mentioned	Not mentioned	Mixed heuristic algorithm	Not mentioned	Not mentioned
Li et al., 2020	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Avg task completion time, computation / negotiation time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Particle swarm optimisation	Shortest path algorithms such as Dijkstra's	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Lienert et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based)	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Re-route if a robot fails	Not mentioned	Not mentioned	A*	Reservation of routes through time windows
Liu, 2018	Empirical	AS/RS, Conveyor, Mobile Robots	Put-away, Picking	Not mentioned	Robot travel time	AGV	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Genetic algorithm	Shortest path algorithms such as Dijkstra's	Not mentioned
Llopis-Albert et al., 2019	Empirical	Not mentioned	Not mentioned	Mobile robot cost, implementation time, scalability	Robot utilisation / idleness, robot travel time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Ly., 2019	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	ABC zoning storage policy and closest open location storage within the zones	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Shortest distance	k-shortest path planning	Waiting, re-routing through time windows-based conflict detection
Ma & Koenig, 2016	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Conflict-based min-cost-flow algorithm	Conflict-based min-cost-flow algorithm	Conflict-based min-cost-flow algorithm
Ma et al., 2014	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Studies double-warehouse	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	PSO variants (Con-Per-PSO and SA-PSO)	PSO variants (Con-Per-PSO and SA-PSO)
Ma et al., 2017	Empirical	Barcode-Guided Mobile Robots	Not mentioned	Not mentioned	Not mentioned	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Not mentioned	Once assigned, tasks could be swapped	Token passing with task swaps	Token passing with task swaps
Merschformann et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking, Replenishment	Not mentioned	Robot travel distance, robot utilisation / idleness, workstation utilisation	AMR	Not mentioned	Not mentioned	Not mentioned	Study five different rules for storage assignment	Offline/Static, batches replenishment orders via random or shelf-based batching	Compares different fleet sizes per workstation	Not mentioned	Not mentioned	Not mentioned	Windowed Hierarchical Cooperative A*	Windowed Hierarchical Cooperative A*
Moeller et al., 2016	Case Study	Not mentioned	Picking	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Change Management	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Ng et al., 2020	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AD* (adaptive dynamic path finding)	Gaussian mixture-based background segmentation algorithm for detection, re-route
Pagani et al., 2017	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Throughput (time-based, order line-based)	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Not mentioned	Neural networks trained with genetic algorithm	Not mentioned	Not mentioned
Panda et al., 2018	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Robot travel distance, travel time	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Oppositional-based learning + invasive weed optimisation	Oppositional-based learning + invasive weed optimisation

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Papcun et al., 2019	Empirical	Freeway Mobile Robots	Picking	Not mentioned	Not mentioned	Not mentioned	Centralised	Not mentioned	Human workers follow mobile robot path through augmented reality glasses	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Shortest path algorithms such as Dijkstra's	Not mentioned
Petkovic et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Human intention estimation through hidden markov model and bayesian theory of mind approach	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Voronoi diagram based path planning	Not mentioned
Polten & Emde, 2020	Empirical	Autonomous Forklifts	Picking, Put-away	Not mentioned	Not mentioned	AMR	Not mentioned	Optimised layout studies for narrow aisle warehouses	Not mentioned	Not mentioned	Not mentioned	Number of forklifts are advised to be lower than number of aisles when aisles are narrow	Not mentioned	Not mentioned	Large neighbourhood search and lateness minimisation	Not mentioned	Re-route if the aisle is occupied by another forklift or prioritisation
Qi et al., 2018	Empirical	Linear Route Mobile Robots	Not mentioned	Not mentioned	Robot travel distance, robot utilisation / idleness, robot travel time, number of deadlocks / conflicts / routing failures, task density	AGV	Centralised	Comparisons under eight warehouse layouts	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Shortest distance	Shortest path algorithms such as Dijkstra's	First come first served, check each time before deadlock, re-route. Zones to efficiently control the area
R. Tai et al., 2018	Empirical	Not mentioned	Not mentioned	Not mentioned	Throughput (time-based, order line-based)	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Shortest distance	k-shortest path planning	Time window with delays
R. Yan et al., 2017	Empirical	Laser-Guided Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Identifies mission reliability of mobile robots via fault tree analysis and petri net approach	Not mentioned	Not mentioned	Not mentioned	Not mentioned
R. Yan et al., 2018	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Preventive and corrective maintenance through petri nets and genetic algorithm	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Raineri et al., 2019	Empirical	Laser-Guided Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Safety through velocity planner	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Roy et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Cost, material handling flexibility, scalability	Throughput (time-based, order line-based)	AMR	Not mentioned	Not mentioned	Not mentioned	Random open location shelf storage policy	Not mentioned	Only compares dedicated vs pooled fleets in zones	Not mentioned	Not mentioned	First come first served with a multi-class closed queueing model	Not mentioned	Estimates system performance with and without zones
Sabattini et al., 2017	Empirical	Autonomous Forklifts	Not mentioned	Not mentioned	Not mentioned	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Integer linear programming	Shortest path algorithms such as Dijkstra's	Conflict graph and linear programming
Santos et al., 2016	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Robot travel distance	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Time Enhanced A*	Time Enhanced A*
Sarkar & Agarwal, 2019	Empirical	Self-Picking Mobile Robots	Picking	Not mentioned	Deadline misses	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Offline/Static, waves of orders	Not mentioned	Not mentioned	Not mentioned	Minimum penalty scheduling	Not mentioned	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Sarkar et al., 2018	Empirical	Self-Picking Mobile Robots	Picking	Not mentioned	Computation / negotiation time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, waves of orders	Optimisation through Nearest-neighbor based clustering and routing	Not mentioned	Not mentioned	Nearest-neighbor based clustering and routing	Nearest-neighbor based clustering and routing	Not mentioned
Sartoretti et al., 2019	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Not mentioned	AMR	Mixed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Migration of task in case of failure	Not mentioned	Not mentioned	Reinforcement Learning combined with imitation learning (OD-recursive M*)	Cost incurred if collision occurs
Schmidt & Schulze, 2009	Review	Not mentioned	Not mentioned	Cost, service quality, material handling flexibility, infrastructure flexibility, and scalability	Not mentioned	Not mentioned	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Semwal et al., 2018	Empirical	Self-Picking Mobile Robots	Picking	Not mentioned	Avg. task completion time	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Charges when battery is nearly 0%	A mechanism to sequentially execute interdependent tasks	Not mentioned	Not mentioned
Singhal et al., 2018	Empirical	Not mentioned	Not mentioned	Not mentioned	Avg task completion time	AMR	Mixed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Auction	Not mentioned	Congestion tracker and re-route
Smolic-Rocak et al., 2010	Empirical	Laser-Guided Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Time windows based dynamic routing	Shortest path algorithms such as Dijkstra's	Time windows based dynamic routing
Stern, 2019	Review	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Groups algorithms under four titles and reviews them	Defines conflict types
Tai et al., 2019	Empirical	Barcode-Guided Mobile Robots	Not mentioned	Not mentioned	Throughput (time-based, order line-based), computation / negotiation time	Not mentioned	Centralised	Compares two types of layouts with different number of workstations and storages	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Shortest makespan	k-shortest path planning	Time windows - Waiting before moving to the next grid if it is occupied and prioritisation
Thanos et al., 2019	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Static last in first out	Insert Route algorithm with solution improvement via late acceptance hill climbing	Insert Route algorithm with solution improvement via late acceptance hill climbing
Tsang et al., 2018	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AMR	Mixed. Task Alloc. Centralised, Path Planning Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Genetic algorithm with learning heuristic	Recursive excitation/relaxation artificial potential field	Recursive excitation/relaxation artificial potential field
Vis, 2006	Review	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Reviews flowpath of robots and rules for idle robot positioning	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Reviews battery management	Reviews rules	Reviews dynamic and static algorithms	Reviews conflict avoidance through flow-path of robots
Vivaldini et al., 2015	Review	Autonomous Forklifts	Not mentioned	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Reviews online / offline allocation	Reviews dynamic and static algorithms	Reviews dynamic and static algorithms

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Vivaldini et al., 2016	Empirical	Autonomous Forklifts	Shipping	Not mentioned	Robot travel distance, Avg task completion time, task density	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Optimum number of robots through a mathematical model	Not mentioned	Not mentioned	Both tabu search with nearest neighbour and shortest job first	Enhanced Dijkstra's including turning times	Reservation of routes through time windows
Wang et al., 2020	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based), robot travel distance	AMR	Not mentioned	Through a design framework with queueing, three different layouts	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Wei & Ni, 2018	Empirical	Grid-based system	Not mentioned	Not mentioned	Robot travel distance	AMR	Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Tabu temporal difference learning consisting of adaptive action selection rule and tabu action elimination strategy	Tabu temporal difference learning consisting of adaptive action selection rule and tabu action elimination strategy
Weidinger et al., 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot travel distance, computation / negotiation time	AMR	Not mentioned	Two aisles and aisle lengths with different number of workstations	Not mentioned	Compares five storage assignment policies.	Not mentioned	Optimum number of robots through a mathematical model	Not mentioned	Not mentioned	Adaptive large neighbourhood search	Adaptive large neighbourhood search	Not mentioned
Wior et al., 2018	Review	Categorise and review systems based on their navigation	Not mentioned	Cost, material handling flexibility	Robot utilisation / idleness, workstation utilisation, throughput, avg task completion time, task delay / response time, number of deadlocks / conflicts / routing failures	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Review the effect of failure on systems	Not mentioned	Not mentioned	Not mentioned	Review preventive and corrective ability of systems
Witczak et al., 2020	Empirical	Autonomous Forklifts	Shipping	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Fault-tolerant control algorithm in case of failure	Not mentioned	Fault-tolerant control algorithm	Not mentioned	Not mentioned
Wurman et al., 2008	Opinion	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Online/Dynamic	Compares different fleet sizes	Not mentioned	Not mentioned	Not mentioned	A*	Not mentioned
X. Li et al., 2019	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Shortest response time (idles vs closest to finish)	k-shortest path planning	Waiting, re-routing with deadlock detection algorithm. Zones to efficiently control the area
Z. Liu et al., 2018	Review	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Review vision, sensor, and radio frequency - based human activity recognition	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mention online allocation strategies	Not mentioned	Not mentioned
Xu et al., 2019	Empirical	Not mentioned	Not mentioned	Not mentioned	Not mentioned	AMR	Mixed. Charging Distributed, Task Alloc. Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Task sequencing with bipartite graph matching and time windows	Heuristic distributed task allocation	Not mentioned	Not mentioned
Xue & Dong, 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Avg task completion time	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, waves of orders	Not mentioned	Not mentioned	Not mentioned	Improved ant colony optimisation	Not mentioned	Not mentioned
Y. Liu et al., 2019	Empirical	Freeway Mobile Robots	Sorting	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Minimises number of mobile robots required	Not mentioned	Creates a charging task according to power consumed by active time and speed	Multi-adaptive genetic algorithm	Not mentioned	Not mentioned

Reference	Type of Study	System Type	Warehouse Operation	Evaluation Criteria	Identifying KPIs	Robot Type	Robot Coordination	Layout	Human-Robot Interaction	Storage Assignment	Order Management	Fleet Sizing	Maintenance and Failure Handling	Energy Management	Task Allocation	Path Planning	Deadlock Resolution and Conflict Avoidance
Y. Liu et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Not mentioned	AGV	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Re-calculate task and path planning	Not mentioned	Not mentioned	Improved Cooperative A*	Dynamic Weight Guidance
Yan et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot travel distance, travel time, avg task completion time, task delay / response time, number of deadlocks / conflicts / routing failures	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Compares different fleet sizes	Not mentioned	Not mentioned	Not mentioned	Dijkstra's	Rule-based
Yoshitake et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Workstation utilisation	AMR	Mixed. Task Alloc. Centralised, Path Planning Distributed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Recharge if it falls below 50%	Real-time holonic scheduling	Real-time holonic scheduling	Not mentioned
Yuan & Gong, 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based), robot utilisation / idleness, workstation utilisation, robot-human ratio	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Optimum number of robots through a mathematical model, dedicated vs pooled robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Yuan et al., 2019	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Robot travel distance	AMR	Not mentioned	Not mentioned	Not mentioned	Studies how many products on which shelf and shelf location via simulated annealing	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Two-stage Mixed algorithm: Greedy algorithm and simulated annealing	Not mentioned
Z. Liu et al., 2019	Empirical	Freeway Mobile Robots	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mixed	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Re-calculate task and path planning	Not mentioned	Auction	Incidental delivery	Not mentioned
Z. Zhang et al., 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Avg. task completion time	AMR	Centralised	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Charge when energy level is below 20%	Prioritisation	Improved Dijkstra's	Selecting other route, waiting before starting, route modification, re-dispatching
Zavadskas et al., 2018	Empirical	Laser-Guided and Autonomous Forklifts	Not mentioned	Not mentioned	Not mentioned	Define seven criteria and apply R-Rov method to select among alternatives	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Zou et al., 2017	Empirical	Barcode-Guided Mobile Robots	Picking	Not mentioned	Throughput (time-based, order line-based), workstation utilisation	AMR	Not mentioned	Compares different number of aisles and lengths	Not mentioned	Not mentioned	Online/Dynamic	Not mentioned	Not mentioned	Not mentioned	Near optimal assignment rule	Shortest path algorithms such as Dijkstra's	Uni-directional aisles
Zou et al., 2018	Empirical	Barcode-Guided Mobile Robots	Picking	Cost, material handling flexbility, scalability	Throughput (time-based, order line-based), workstation utilisation	AMR	Not mentioned	Considers placing charging locations in operational area	Not mentioned	Not mentioned	Not mentioned	Finds required number of robots for instances	Not mentioned	Semi-open queueing network considering throughput performance	Not mentioned	Shortest rectangular path	Uni-directional aisles
Zou et al., 2019	Empirical	Human-collaborated mobile robots	Picking	Not mentioned	Not mentioned	AMR	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Offline/Static, batching with seed algorithm.	Not mentioned	Not mentioned	Not mentioned	Two stage heuristic algorithm	Two-stage heuristic algorithm refined by neighbourhood search heuristic	Zones to efficiently control the area

Appendix B Multi-Criteria Decision-Making

B.1 The Questionnaire for the FUCOM

(Ethics Approval Review Reference: CURES/14622/2021)

Mobile Robot Automation in Warehouses

Informed Consent

You are invited to participate in a research study about mobile robot systems in warehouses. The goal of this research study is to understand the opinions of supply chain experts on a set of evaluation criteria to choose a mobile robot system over others.

Participation in this study is voluntary. If you agree to participate in this study, please fill the form below. You may skip any questions you do not want to answer.

The information you will share with us will be kept completely confidential to the full extent of the law and ethics policies, and the results will only be presented in aggregate form with full anonymity of companies and participants.

General Questions

Q1. How many years of supply chain experience do you have in total?

Q2. What is the name of the organisation that you work for?

Q3. What is the headcount of your organisation?

Q4. What is your job title?

Q5. Could you briefly describe your role in the organisation?

Evaluation Criteria Questions

Flexibility in infrastructure: The adaptability of the system to process and/or layout changes

Flexibility in material handling: The capability of the system to handle products in different size and shape

Mobile robot cost: Costs that are directly connected to onboard intelligence and gripping arms

Scalability: The ability of mobile robot systems to cope with the demand fluctuations

Time to implement: Required time for system implementation in a warehouse

Q6. From your point of view, please list aforementioned criteria from the most important to the least important.

The most important criterion:

Second most important criterion:

Third most important criterion:

Fourth most important criterion:

Fifth most important criterion:

Q7. From your point of view, please fill in the blanks below by inserting values between ‘1’ to ‘9’ as importance coefficients. Values can also be decimal numbers such as ‘2.5’.

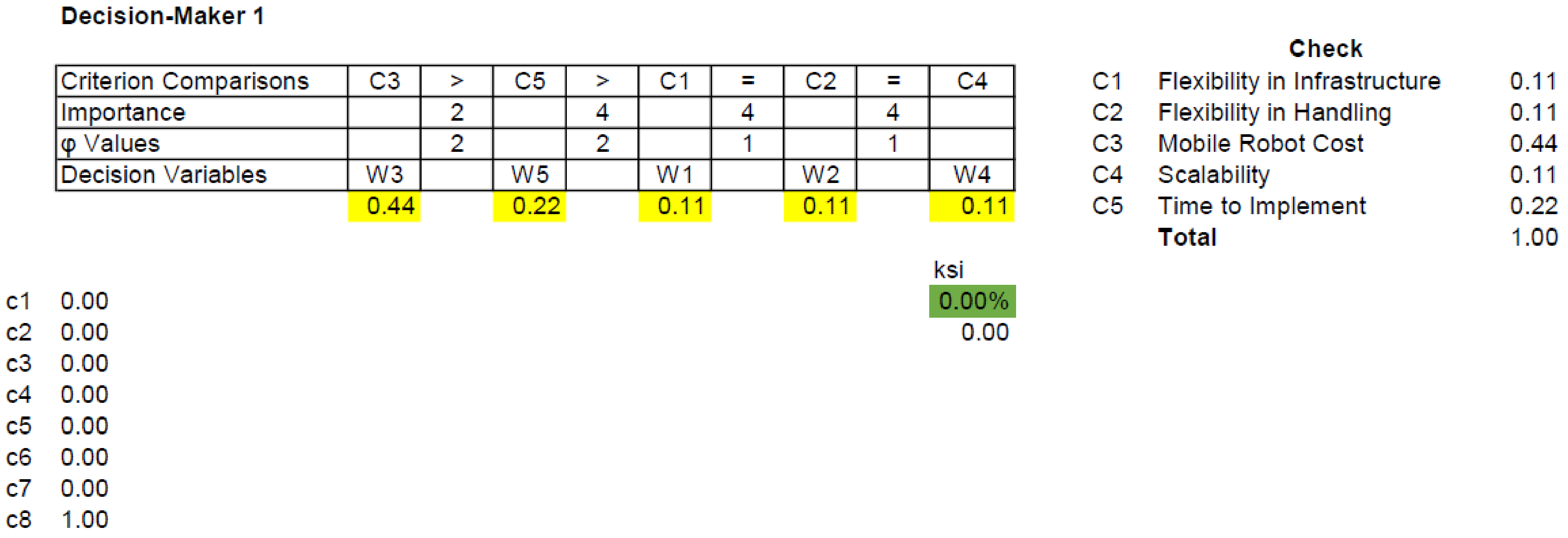
- The **most** important criterion is ____ times as important as the **second** most important criterion.
- The **most** important criterion is _____ times as important as the **third** most important criterion.
- The **most** important criterion is _____ times as important as the **fourth** most important criterion.
- The **most** important criterion is _____ times as important as the **fifth** most important criterion.

Q8. Are there any other criteria you would include for mobile robot system selection? Please describe.

Q9. Please write below if you have any further comments and suggestions.

B.2 The FUCOM

B.2.1 Decision-Maker 1



Decision-Maker 1

Criterion Comparisons	C3	>	C5	>	C1	=	C2	=	C4
Importance		2		4		4		4	
φ Values		2		2		1		1	
Decision Variables	W3		W5		W1		W2		W4
	0.44		0.22		0.11		0.11		0.11

ksi

0.00%

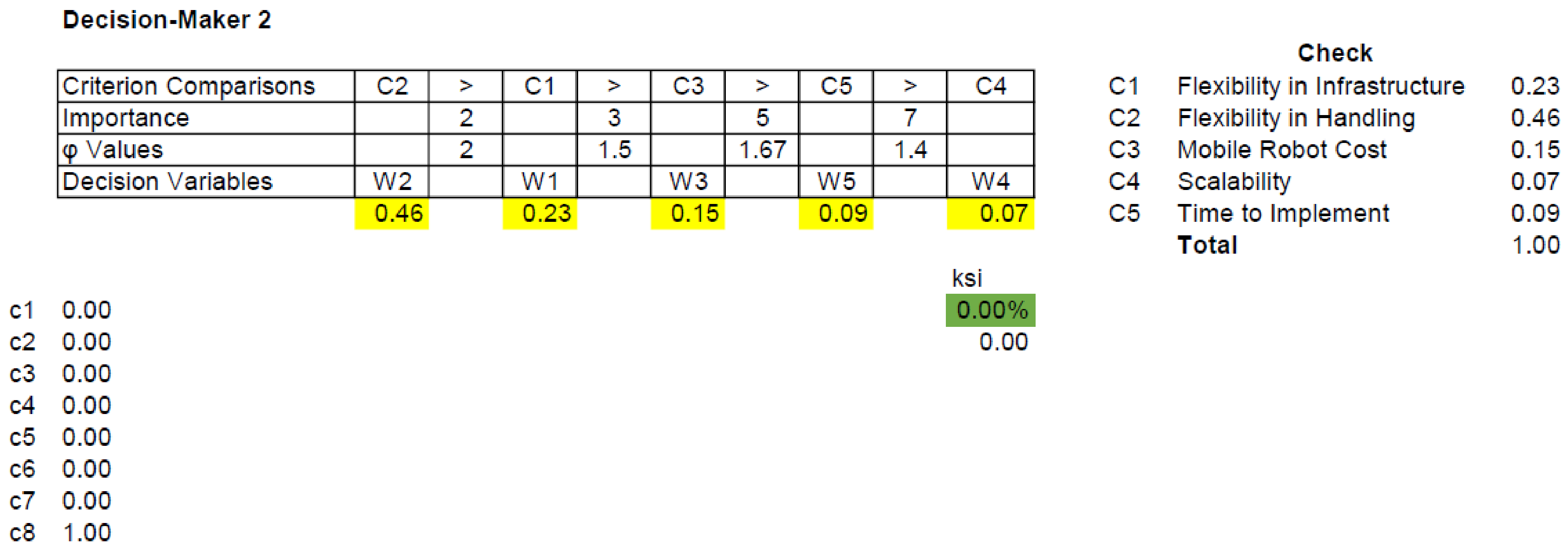
0.00

	Check	
C1	Flexibility in Infrastructure	0.11
C2	Flexibility in Handling	0.11
C3	Mobile Robot Cost	0.44
C4	Scalability	0.11
C5	Time to Implement	0.22
	Total	1.00

c1	0.00
c2	0.00
c3	0.00
c4	0.00
c5	0.00
c6	0.00
c7	0.00
c8	1.00

Figure B-1 Details of decision-maker 1

B.2.2 Decision-Maker 2



Decision-Maker 2

Criterion Comparisons	C2	>	C1	>	C3	>	C5	>	C4
Importance		2		3		5		7	
φ Values		2		1.5		1.67		1.4	
Decision Variables	W2		W1		W3		W5		W4
	0.46		0.23		0.15		0.09		0.07

Check

C1	Flexibility in Infrastructure	0.23
C2	Flexibility in Handling	0.46
C3	Mobile Robot Cost	0.15
C4	Scalability	0.07
C5	Time to Implement	0.09
	Total	1.00

ksi

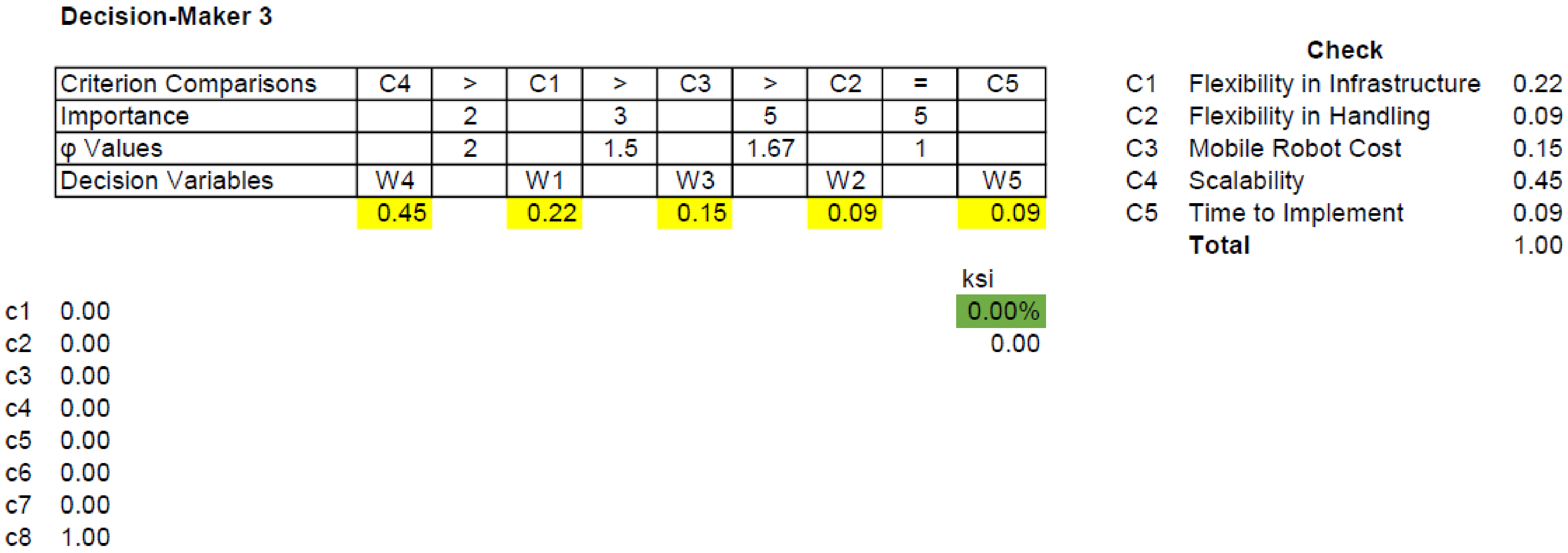
0.00%

0.00

c1	0.00
c2	0.00
c3	0.00
c4	0.00
c5	0.00
c6	0.00
c7	0.00
c8	1.00

Figure B-2 Details of decision-maker 2

B.2.3 Decision-Maker 3



Decision-Maker 3

Criterion Comparisons	C4	>	C1	>	C3	>	C2	=	C5
Importance		2		3		5		5	
φ Values		2		1.5		1.67		1	
Decision Variables	W4		W1		W3		W2		W5
	0.45		0.22		0.15		0.09		0.09

	Check	
C1	Flexibility in Infrastructure	0.22
C2	Flexibility in Handling	0.09
C3	Mobile Robot Cost	0.15
C4	Scalability	0.45
C5	Time to Implement	0.09
	Total	1.00

ksi

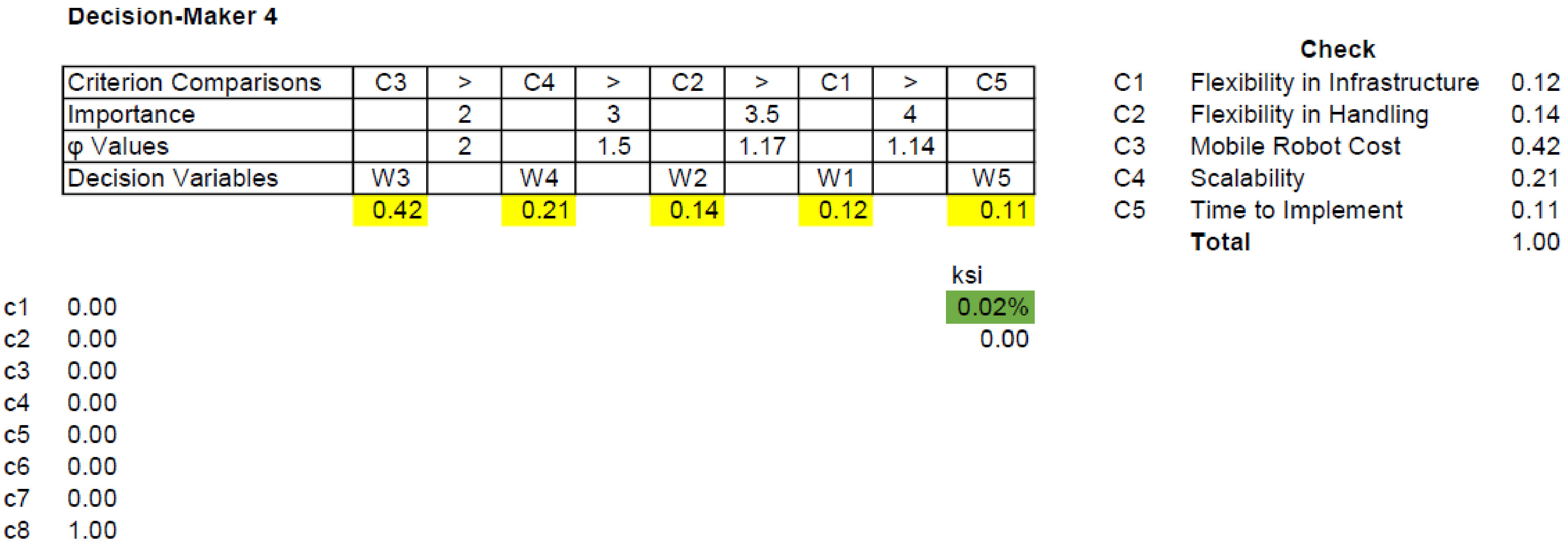
0.00%

0.00

c1	0.00
c2	0.00
c3	0.00
c4	0.00
c5	0.00
c6	0.00
c7	0.00
c8	1.00

Figure B-3 Details of decision-maker 3

B.2.4 Decision-Maker 4



Decision-Maker 4

Criterion Comparisons	C3	>	C4	>	C2	>	C1	>	C5
Importance		2		3		3.5		4	
φ Values		2		1.5		1.17		1.14	
Decision Variables	W3		W4		W2		W1		W5
	0.42		0.21		0.14		0.12		0.11

Check

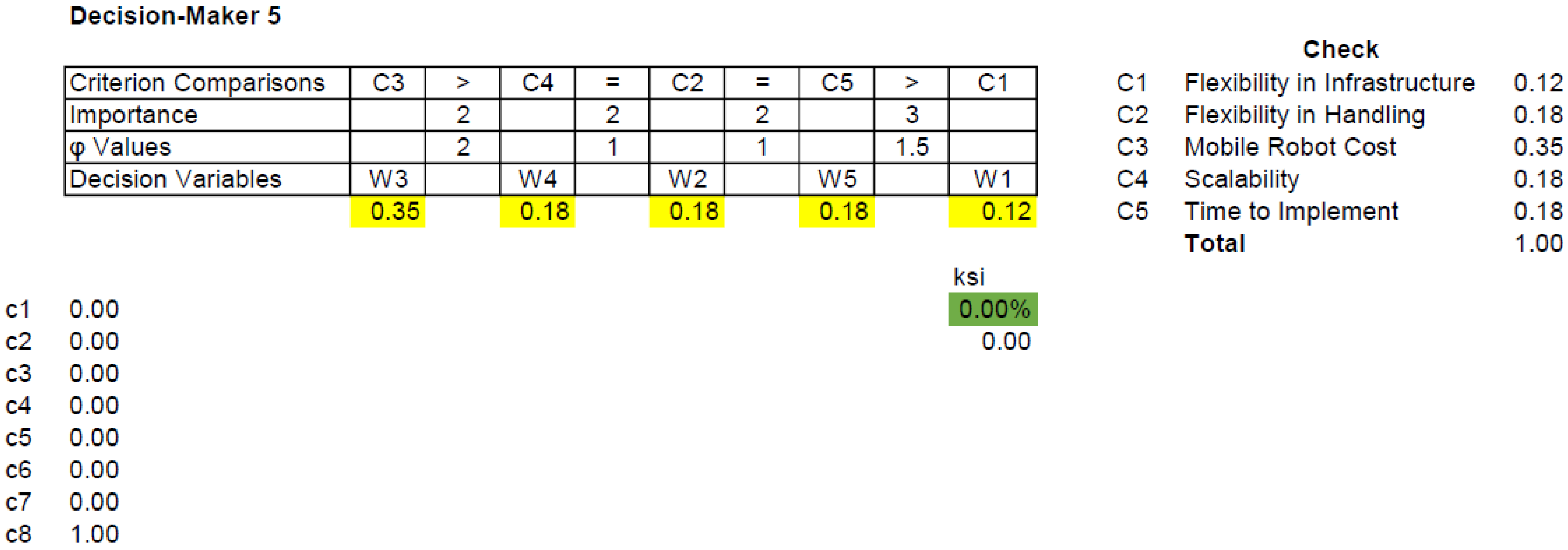
C1	Flexibility in Infrastructure	0.12
C2	Flexibility in Handling	0.14
C3	Mobile Robot Cost	0.42
C4	Scalability	0.21
C5	Time to Implement	0.11
	Total	1.00

ksi
0.02%
0.00

c1	0.00
c2	0.00
c3	0.00
c4	0.00
c5	0.00
c6	0.00
c7	0.00
c8	1.00

Figure B-4 Details of decision-maker 4

B.2.5 Decision-Maker 5



Decision-Maker 5

Criterion Comparisons	C3	>	C4	=	C2	=	C5	>	C1
Importance		2		2		2		3	
φ Values		2		1		1		1.5	
Decision Variables	W3		W4		W2		W5		W1
	0.35		0.18		0.18		0.18		0.12

	Check	
C1	Flexibility in Infrastructure	0.12
C2	Flexibility in Handling	0.18
C3	Mobile Robot Cost	0.35
C4	Scalability	0.18
C5	Time to Implement	0.18
	Total	1.00

ksi

0.00%

0.00

c1	0.00
c2	0.00
c3	0.00
c4	0.00
c5	0.00
c6	0.00
c7	0.00
c8	1.00

Figure B-5 Details of decision-maker 5

B.2.6 Total Rating Calculations for Each MRS

Table B-1 Accumulation of criteria weights

	DM1	DM2	DM3	DM4	DM5	Weighted Average
C1	0.11	0.23	0.22	0.12	0.12	**0.16**
C2	0.11	0.46	0.09	0.14	0.18	**0.20**
C3	0.44	0.15	0.15	0.42	0.35	**0.30**
C4	0.11	0.07	0.45	0.21	0.18	**0.20**
C5	0.22	0.09	0.09	0.11	0.18	**0.14**
					Totals	**1**

Table B-2 Calculation of total ratings for systems

Mobile Robot Systems	**Flexibility of Infrastructure (C1)**	**Flexibility in Handling (C2)**	**Mobile Robot Cost (C3)**	**Scalability (C4)**	**Time to Implement (C5)**	**Rating * Weight C1**	**Rating * Weight C2**	**Rating * Weight C3**	**Rating * Weight C4**	**Rating * Weight C5**	**Total Rating of the System**
Rail or Wire Using Robots	1	3	3	2	2	0.16	0.59	0.91	0.40	0.27	**2.34**
Barcode Guided Robots	2	3	2	2	2	0.32	0.59	0.61	0.40	0.27	**2.20**
Laser Guided Robots	2	1	2	2	2	0.32	0.20	0.61	0.40	0.27	**1.80**
Autonomous Forklifts	3	1	1	3	3	0.48	0.20	0.30	0.61	0.41	**2.00**
Human Collaborated Robots	3	2	2	2	3	0.48	0.39	0.61	0.40	0.41	**2.30**
Mobile Picking Robots	3	1	1	3	3	0.48	0.20	0.30	0.61	0.41	**2.00**
AS/RS, Conveyors, Linear Route Robots	1	1	3	1	1	0.16	0.20	0.91	0.20	0.14	**1.61**
Picker & Transport Robots	3	1	1	3	3	0.48	0.20	0.30	0.61	0.41	**2.00**
Laser Guided Robots & Pallet Shuttles	1	1	3	1	1	0.16	0.20	0.91	0.20	0.14	**1.61**

Appendix C The Case Study

(Ethics Approval Review Reference: CURES/14622/2021)

C.1 Case Study Logic

Case study was chosen as the methodology to investigate the phenomenon of mobile robot automation in warehouses because it provides opportunity to the researcher for novel theoretical development (Eisenhardt, 1989). Further, it provides an in-depth and detailed understanding of context (Yin, 2018).

It seems making different technology access decision could bring contrasting outcomes. Therefore, selecting organisations with different technology access decisions would look like the researcher is seeking theoretical replication. However, the phases and stages encountered, the managerial decisions considered, and the learning process encountered is quite close to one another For instance, both ‘buy’ case and ‘make’ case considers ‘supplier selection and management’ decision but one buys MRS from it, the other one has multiple suppliers for raw material purchasing. The only main difference is the implementation time variations. Hence, this multiple-case study is built on a literal replication logic that predicts similar outcomes with minor alterations in each case (Yin, 2018).

C.2 Protocol Questions

Protocol questions are prepared before the data collection content. Protocol questions are asked to the researcher to clarify which data to be collected (Yin, 2018). These questions directed the researcher while preparing interview questions, documents that the researcher seeks, and what type of data to collect in observations.

Table C-1 Protocol questions

Data Type	***Data Details***
Interviewee Profile	What is the experience of the interviewee in logistics and in this company? What is the responsibility of the interviewee in the company and in the warehouse?
Warehouse Profile	Which mobile robot systems are preferred for various type of products and warehouse operations?
Motivation	What motivated them for warehouse automation?
	What motivated them for the solution they selected? What have they considered as decision parameters? How did they compare their solution to other automation solutions?
	Who are the decision-makers in the process and how was the decision taken? What was the reaction of the workers in the warehouse operations? How did they manage the operational alteration process?
Technology Access Decision	Did they make, buy, or ally? Why? If they bought, did they ask for customisation? What are they?
Implementation	How did they plan the implementation? Did they get help from a technology provider or an integrator? Did the plan work? Have they formed a team/department for this solution? Who are the members of this team and what do they do? How did they manage the project?
	What are their decision/focus areas at strategic, tactical, and operational levels and how do they handle them? If they took help from a third party, how did it impact on the number/importance of resulting managerial decisions?

	What has changed with the mobile robot system? How are their motivations matched with the outcomes? Are they met? How do they measure that? How did they benefit from the solution and how do they measure success?
	What are the challenges they faced in the installation/integration stage and what are their current problems? How do they cope with their problems?

C.3 Data Collection Details

Table C-2 Generic interview questions

Focus Areas	Questions	No of Data Objective
Details of the Interviewee	How many years of experience do you have in logistics companies in total?	1
	How many years of experience do you have in this company?	1
	What are your responsibilities in the company?	1
	What are your responsibilities in the warehouse operations?	1
Products and Warehouse Operation	What type of products do you store in your warehouse and how do you pick them (individual, carton, pallet)?	2
	How many SKUs do you have in the warehouse? What is your pick rate? (Do you have documents, dashboards for me that might be of use?)	2
	What type of products and warehouse operation/s are you implementing your mobile robot solution for?	2
	Before this solution, were you picking your products completely manually or did you have another automation solution in the process?	2
System Details and Motivation	Why did you want to automate your warehouse? (Use motivations as probes such as: 'Does it have something to do with labour productivity? Why?')	3
	Is this your first implementation attempt for a mobile robot system? Please describe your experience if any.	4
	Please describe the mobile robot automation solution that is being implemented in the warehouse.	4
	How many warehouses of yours use the same system? Are these implementations different in any ways?	4
	Why did you choose this solution for your warehouse?	4

	Did you compare your solution to other automation solutions? How?	4
	Who played role in the system selection decision? Please describe the decision process. (executive directors, a department, a team)	5
	How have you communicated your decision to workers?	5
	How were the reactions of the workers to the automation solution? How did their day-to-day tasks get effected?	5
Buy, Make, Ally	Have you bought the solution from a technology provider or built the entire system by yourself?	6
	Why did you choose to outsource the solution? / Why did you choose to build the solution in-house? What do you think about vendor/supplier availability?	6
If **Buy or Ally**	Would you name it as 'a solution purchasing from a technology provider' or 'a strategic alliance with the technology provider'? Why?	6
	Have you asked for customisations from the technology provider on the original solution? Were they accepted? Are these customisations specifically addressed to your needs? What was the role of the technology provider in the integration and in further decisions?	6
	Were you involved in the installation/integration process or was the solution a type of plug & play solution? (If you were involved in the installation/integration process, how?)	6
Implementation	How did the integration/installation process work?	7
	Was there a third party as an integrator or a consultant for the implementation process? If yes, what was their role? If no, why did the company choose not to work with a third party?	7
	How did you plan the implementation? (Follow-up questions such as: 'Were there meetings?', 'Who attended those?', 'Was there a team for implementation?', 'What were their roles?', 'Was there a pilot implementation?')	7
	What did you consider as managerial decisions in the implementation of mobile robots? (According to the title of the interviewee, ask for other decision areas in our	8

	framework such as: 'What about energy management of the robots? How do you manage that?')	
	Was there a guiding framework/document for the entire project including these managerial decisions? If yes, can you share the document? If no, would that have helped in the implementation?	8
	Did the technology provider or the integrator help in forming these managerial decisions?	8
	How often do you review and update those decisions? For instance, do you reconsider these decisions daily, monthly, or yearly? Why?	8
	What has changed with the mobile robot system? Please describe.	9
	How did the solution improve the warehouse operations?	9
	How do you measure these improvements?	9
	Do you think your initial motivations are met with the outcomes? Please describe how they are met or not.	9
	What was hard at the beginning of the implementation process? How did you overcome those difficulties?	10
	Are you still facing any challenges in the implementation of the system considering the decision we discussed? What are those challenges?	10
	How do you deal with these challenges?	10
	Do you think there is room for improvement about the system in use? Why?	10
	What are your insights on mobile robot system selection as a user?	10
	What are your insights on lessons learned from the implementation? What do warehouses need to avoid?	10

Table C-3 Documents the researcher seeks

Document	Explanation
A company profile	No of people working for the company and warehouse/s. A brief financial to determine the size of the company. A customer profile.
A warehouse profile	A list of product categories, No and size of SKUs in each category and their order profiles. A dashboard with operational metrics, if possible, such as the productivity of workers, utility of robots.
A warehouse sketch	Warehouse layout with operational areas and flows
Mobile robot system	A document from the technology provider about the system details.
Planning document/s	Documents with timelines about the implementation plan either it is prepared by the technology provider or in-house.
A document of considered decisions	List of focus areas to be covered or important decisions to be made (could be in a framework format)
A system performance document	A performance analysis document or dashboard for the system in use

Table C-4 Overview of documents collected

Case	TAD	Document Types	Subject	Total no of Documents
Case 1	Make	Presentation Excel file Web page Photo	System introduction and specs Gantt chart Layout	6
Case 2	Ally	Presentation Photo Image	System analysis and specs Flowchart Layout	8
Case 3	Buy, Ally	Article Web page Brochure Presentation Excel file Photo Video Press briefings	System introduction and specs System analysis System footage Layout Gantt chart	12
Case 4	Buy, Ally	Presentation Video Web page	System introduction and specs Brief system analysis Layout System footage	4

Table C-5 Overview of observations

Case	TAD	Observation Activity	Date
Case 1	Make	A three-hour visit to the hardware development and testing facility with full access	13/08/21
Case 1	Make	A two-hour meeting observation on mobile robot implementation planning	23/08/21
Case 1	Make	A four-hour visit to the warehouse that is planned to be partially automated by the shelf-carrying mobile robot system	15/12/21
Case 3 **(Warehouse 1)**	Buy	A two-hour visit to the warehouse that is partially automated by the pallet-carrying laser-guided mobile robots with a full tour	21/03/22

C.4 Data Analysis Details

C.4.1 Within Case Analysis, Cross Case Analysis

For each case company, the first step was to write a comprehensive within case study report for the MRS adoption journey of that warehouse, which integrates the information from the analysis of all primary and secondary data sources relevant to subject of the study.

For data analysis, template analysis was employed which is a strong thematic analysis technique used in qualitative analysis (King and Brooks, 2017). It can be initiated via a priori (i.e., a template) coding structure as of shown in Table C-6 to guide the researcher at early stages of coding. It also allows emerging codes and relevant alterations in the coding structure. Further to template analysis, pattern matching was used to consolidate the output of different data sources and compare it with the theoretical framework (Yin, 2018).

The cross-case analysis seeks differences and similarities between the cases (Eisenhardt, 1989). This part of the analysis also benefits from pattern matching and elaborates on the coding structure to finalise the coding process.

Table C-6 Initial coding structure

Theme	Category	Code
Phases	Initiation	Need for innovation
		Motivation towards a specific MRS
	Decision to Adopt	Technology access decision
	Implementation	Implementation preparation
		Clarifying
		Full implementation
Decision Focus Areas	Strategic	Evaluation criteria and MRS selection
		Identifying KPIs
		Type of robots and their coordination
		Facility layout
		Human-robot interaction management
	Tactical	Storage assignment plan
		Order management plan
		Quantity of robots
		Maintenance and failure handling
		Robot energy management
	Operational	Task allocation
		Path planning
		Deadlocks and conflict avoidance
Factors	Technological	Technology maturity
		Relative advantage
		Observability
		Complexity

	Compatibility
	Cost
	Trialability
Organisational	Worker profile
	Technological compatibility
	Innovativeness of organisation
	Organisation size
	Financial support
	Top management support
	IT infrastructure
	Managerial capability
Environmental	Supplier support
	Competitive pressure
	Government legislation
	Environmental uncertainty
	Supply chain’s MRS perspective

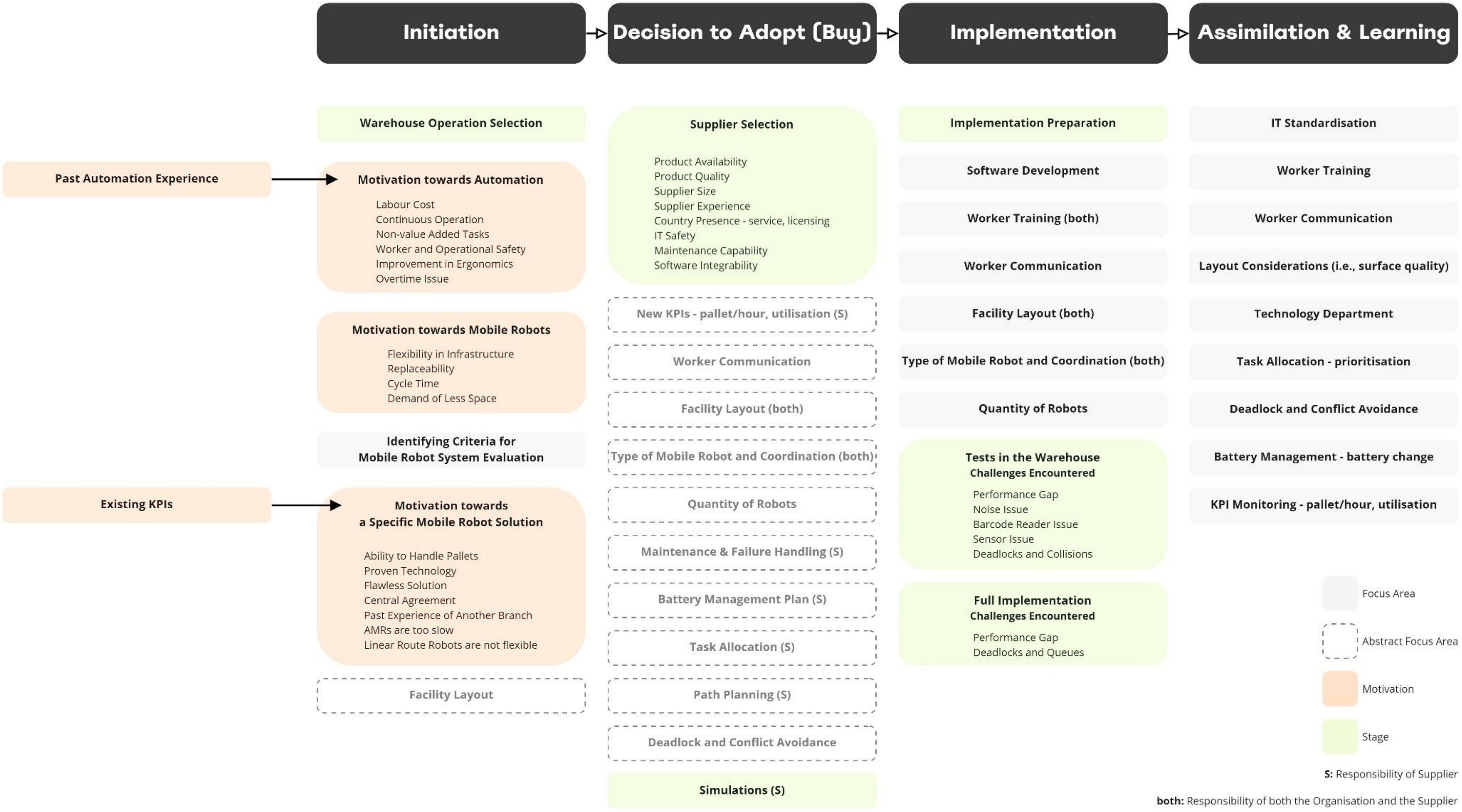


Figure C-1 Process and decisions for case 4, warehouse 1

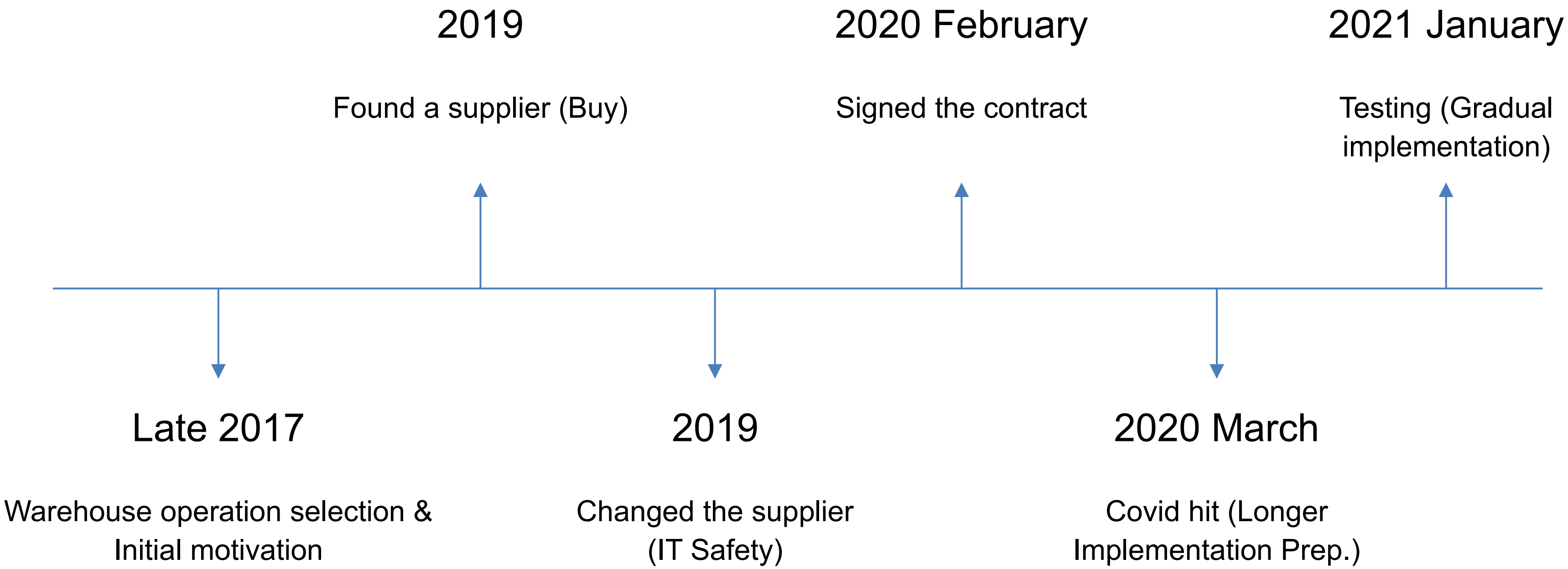


Figure C-2 Timeline for case 4, warehouse 1

C.4.2 A Section of Within Case Analysis

MRS adoption journey by steps (Case 3 – Warehouse 1)

TAD: Buy

MRS type: Pallet-carrying laser guided mobile robots

Warehouse and Operation Selection

Integrate with the existing automation solutions

Ergonomic issues of the operation

Motivation Towards Automation

Remove the worry of labour scarcity (by automating repetitive tasks) as they have difficulty finding workers especially in demand peaks.

Health and safety

Motivation Towards Mobile Robots

Learning

Re-deployability

Motivation Towards a Specific MRS

Remove physical burden

Safety around racking area

Technology Access Decision

Not their core business to make

Supplier alliance aspirations

Simulations (feasibility and fleet size estimation)

Implementation Preparation (~2 months)

Setup caused no disruptions to ongoing ops

Testing (~4 months)

Started with one lane and increased up to ten - gradual implementation

Lots of frustrations due to software issues

Difficulties to control the testing together with ongoing ops

Caused overtimes and pressure on implementation team

Performance gap and real-world challenges

Full Implementation

Adjustments to increase the efficiency by up to 25%

There still are deadlocks but being reduced dramatically

Assimilation & Learning

Jump into MRS but keep it simple in the first implementation (do not get caught to what you see in the videos)

Go see the solution and ask what happens when things go wrong

Get experience and do your learning before the technology gets advanced

Workers will take their time to adapt to the solution

Need smooth floor

Better spare part management

Looking for new warehouse operations to automate

Need a template for future MRS

Learning is important to retrofit the solution

Less worries with the human workforce now (in case they quit their jobs)

C.5 References to Appendix C

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. The Academy of Management Review, 14(4), 532–550. https://doi.org/10.2307/258557

King, Nigel and Brooks, Joanna (2017) Template Analysis for Business and Management Students. Mastering Business Research Methods . Sage, London, UK. ISBN 9781473911574

Yin, R. K. (2018). Case study research and applications: Design and methods (Sixth edition). SAGE.