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Supporting the design of automated guided vehicle systems in internal logistics

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Abstract

Applications of automated guided vehicle (AGV) systems are becoming increasingly widespread in internal logistics for performing transports automatically. Recent technological advancements in navigation and intelligence have improved the functionality of vehicles and together with attention to Industry 4.0 have created further interest in AGV systems in industry and academia. Research on AGV systems has mainly focused on technical aspects, but to support AGV system design and, thereby, be able to achieve the full potential from use of AGV systems in internal logistics, more knowledge is needed that takes further into consideration aspects related to humans and the organisation, alongside the technical aspects.

The purpose of this thesis is to develop knowledge to support the design of AGV systems and three research questions are formulated. The thesis is based on three papers, two of which are based on multiple case studies and one study based on simulation modelling. The thesis results provide input to the design process for AGV systems in three main ways. First, in developing an understanding for which requirements influence an AGV systems and how the requirements can be met in the AGV system configuration. Second, regarding how the load capacity of AGVs impact the performance of the AGV system, and third by identifying challenges with respect to the work organisation and related to human factors when AGV systems are introduced in internal logistics settings.

Keywords: Automated guided vehicle system, AGV system, load capacity, internal logistics, internal transport, human factors, industry 4.0, design requirements

List of appended papers

Paper I: Thylén, N., Hanson, R., Johansson, M. I. (2020). ”Requirements Affecting the Design of Automated Guided Vehicle Systems”.

Working paper, to be submitted to an academic journal.

An earlier version of this paper was published in the proceedings of the conference “*PLANs forsknings- och tillämpningskonferens*”, (digital) October 2020.

Contribution: Planning of the study and data collection were performed jointly by the authors. The first author did most of the writing of the paper, and drafts of the paper were then discussed and improved together with the two co-authors. The analysis was performed mainly by the first author, and was discussed with the two co-authors, resulting in a final analysis and conclusion.

Paper II: Thylén, N., Fager, P., Hanson, R., Frantzén, M. (2022). “Load capacity and performance in Automated Guided Vehicle systems in in-plant materials supply for mixed-model assembly”.

Working paper, to be submitted to an academic journal

Contribution: Planning of the study was mainly conducted by the first author with advice from the other authors. Data collection and analysis were performed jointly by the first and second authors of the paper. The simulation model was developed by the first author with support from the fourth author. The paper was written by the first author, where drafts of the paper were discussed with and altered jointly by all authors. Analysis of the simulation results was mainly performed by the first author and then discussed together with all four authors.

Paper III: Thylén, N., Wänström, C., Hanson, R. (2021). ”Human- and Organisation-related Challenges in the Introduction of Automated Guided Vehicles in Production”.

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Contribution: Planning of the study was performed jointly by the three authors of the paper. Data collection was performed by the first and third author together. The paper was mainly written by the first author, where the theoretical framework was jointly developed by the first and second author. Drafts of the paper were discussed with all authors and revisions of the text performed. The analysis was mainly conducted by the first author and discussed with the other authors.

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Nils Thylén

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1. Introduction

This thesis deals with developing support for the process of designing automated guided vehicle (AGV) systems in internal logistics and seeks to contribute by providing input to the design process. Beginning the thesis, this chapter introduces the area in which research for the thesis was conducted and outlines the research problem. Next, it presents the purpose of the thesis and its scope, followed by three research questions formulated to focus the research. It concludes with an outline of the reminder of the thesis that briefly presents the content of each chapter of the cover paper.

1.1. Overview of research and trends related to AGV systems

Companies today face mounting demands in many regards, including for faster delivery times, higher quality and more customisable products due to today's increasingly globalised and competitive market (Zheng et al., 2021; Stentoft and Rajkumar, 2020). Such demands force companies to improve their operations and to become more efficient, which drive many companies toward Industry 4.0 (Zheng et al., 2021). Industry 4.0 is a trending topic and has received attention in both academia and industry (Frank et al., 2019). An important part of Industry 4.0 is the automation of manual tasks (Kadir et al., 2019), which can greatly benefit internal logistics (Winkelhaus et al., 2022), a vital part in production. Because internal logistics can constitute a large portion of the production cost of a product (Esmaeilian et al., 2016), inefficient internal logistics can cause significant increases in overall production costs (Marvizadeh and Choobineh, 2014). Although internal logistics currently involve a high degree of manual operations, for example, in internal transport (Winkelhaus et al., 2022), automation is becoming increasingly widespread. In that context, AGV systems have been shown to be able to improve internal logistics by automating internal transport (Yan et al., 2022; Bechtsis et al., 2017).

Similar to Industry 4.0, AGV systems have received attention in both academic research (e.g. Fragapane et al., 2021a; Le-Anh and de Koster, 2006; Vis, 2006) and in industry. In parallel, the market for AGVs is growing rapidly (De Ryck et al., 2020), and the number of companies that are adopting AGV systems is on the rise (Hu et al., 2020). In general, AGVs are driverless vehicles used to transport material automatically between locations and thereby automate internal transport (De Ryck et al., 2021). The first AGVs were introduced in the 1950s (Kumbhar et al., 2018), and early AGVs were guided by physical guidepaths that provided little flexibility and entailed high installation costs (Schulze and Wullner, 2006). In recent years, pushed by developments in Industry 4.0 and industrial artificial intelligence (Hu et al., 2020) and by the improved functionality of AGVs in terms of intelligence, sensors and autonomous guidance (Zhan and Yu, 2018), interest in AGVs amongst academics and industrial players has increased. AGV systems are seen as one part of facilitating the creation of cyber-physical systems, which themselves are integral to the concept of Industry 4.0 (Ivanov et al., 2021). Amongst other things, AGV systems have been shown to be able to provide benefits to internal logistics by reducing labour costs and improving productivity (Bechtsis et al., 2017). Additionally, forklifts can cause pain in the necks, shoulders and backs of drivers (Karltun et al., 2017), but by introducing an AGV system, such pain can be eliminated, and operators can be assigned to more stimulating tasks than driving a forklift or another transport vehicle.

Despite the increased adoption of AGV systems in industry and though such systems continue to receive attention in research, some issues concerning AGV systems remain unresolved. Work procedures often change when a process is automated (Kadir and Broberg, 2021), and considering how, for example, introducing an AGV system can affect operators and the work procedures related to the system is important. Beyond that, a host of requirements can influence how the AGV system is configured, and understanding those requirements can facilitate the process of designing the system. These issues are expanded upon in the following section.

1.2. AGV systems

This section presents how AGV systems are conceived in the cover paper, followed by a presentation of the topic of human- and organisation-related considerations in such systems and Industry 4.0. Thereafter, a subsection describing a general design process and requirements that can influence AGV systems.

1.2.1. Components of AGV systems

In this thesis, based on literature reviews addressing issues within the design of AGV systems (Fragapane et al., 2021a; Le-Anh and de Koster, 2006; Vis, 2006), an AGV system is conceived as including a number of components. Each component is conceived as consisting of a technical dimension and a work organisation dimension in relation to the work required for the operation of the system. The components can vary in terms of their dimensions; some may have a stronger technical dimension than work organisation dimension, whereas the opposite is true for other components. In particular, the dimension of work organisation, refers to the work procedures, routines, processes and organisational structures needed for the operation of the AGV system. The components and their technical and organisational dimensions are explained in greater detail in section 2.1. Throughout the cover paper, an AGV system's configuration refers to the artefact of a finished design process, while design is the term used to describe the process in which the components are decided.

According to the literature reviews of Le-Anh and de Koster (2006) and Vis (2006), an AGV system consists of numerous components that need to be addressed in the process of designing the system. These components have been addressed in the literature, including guidepath design (Rezapour et al., 2011), fleet sizing (Ferrara et al., 2014; Choobineh et al., 2012), control (Dang et al., 2021; Ho et al., 2012), idle vehicle positioning (Ventura et al., 2015), battery management (Kabir and Suzuki, 2019; Kabir and Suzuki, 2018) and failure management (Yan et al., 2018). Although many components of AGV systems have received ample research, there are parts which have not received as much attention like AGV systems where each vehicle is capable of carrying multiple loads at the same time (Yan et al., 2022; Dang et al., 2021).

The mixed environments in which AGV systems can be used contain many dynamic objects, humans, forklifts and tugger-trains, to name a few, that interact with each other, and humans may be needed in order to ensure that the systems operate at the desired level. Monitoring an AGV system and intervening in the case of failure may be required (Fragapane et al., 2021a). For those reasons, work procedures and routines need to be developed that consider the work organisation dimension of the AGV system's components. The next section delves into how humans and organisational aspects have been considered in literature on Industry 4.0 and AGV systems.

1.2.2. Human- and organisation-related considerations in Industry 4.0 and AGV systems

According to Vijayakumar et al. (2021), there is a risk of designing production or logistics systems that do not offer the expected performance if humans are not considered in the design. Not considering humans adequately can lower system performance and cause problems for employees, including musculoskeletal disorders due to repetitive tasks and poor worker well-being (Neumann et al., 2021). On that topic, Sgarbossa et al. (2020) have discussed "phantom profits" in reference to situations in which expected profits are not realised due to the negative consequences, such as (e.g. sick leave, increased errors and reduced quality) of not taking humans into account in the design process.

Research related to Industry 4.0 has largely adopted a technical focus and been technologically driven (Nayernia et al., 2021; Neumann et al., 2021). As a result, humans and their changing roles in Industry 4.0 have often gone unaddressed (Winkelhaus et al., 2022; Kadir and Broberg, 2021; Neumann et al., 2021). Likewise, research on AGV systems has also largely had a technical focus (Fragapane et al., 2021a; Benzidia et al., 2019). However, AGV systems are often used in mixed environments in which they interact with humans and manually operated vehicles, which stresses the need to consider humans and their work in relation to the systems. Along those lines, Industry 5.0 is an emerging concept that has a human-centric focus instead of the technological focus of Industry 4.0 (European Commission, 2021).

An organisation-focused perspective on implementing Industry 4.0 has also been lacking in research (Nayernia et al., 2021). Reiman et al. (2021) have stated that focusing exclusively on human aspects at the individual level may be too narrow and that some relevant aspects of human-based work might be excluded. It is therefore important to consider aspects at the organisational level as well (Reiman et al., 2021). Kadir and Broberg (2021) have pointed out, changes in the work should be addressed when Industry 4.0 technologies are introduced. In several cases that they studied, such technologies were introduced without having any formal process for considering the redesign of work procedures, which resulted in a suboptimal division of work between humans and the technologies and a need for training could not be fully understood.

1.2.3. Design process relating to AGV systems

When designing a product or system, including an AGV system, it is important to understand the requirements that need to be met by the outcome of the design process (Tompkins et al., 2010; Johansson, 2007; Chakrabarti et al., 2004). In models of design processes, listing requirements is often the first step. In a design process for materials handling systems proposed by Tompkins et al. (2010), the first and second steps of the process respectively entail determining objectives and listing requirements. Johansson (2007) has proposed design process model for materials supply systems, in which the first step is developing an understanding of the requirements that influence the process. The closer that a design process is to being finished, the more costly it becomes to make changes (Slack et al., 2013). Thus, it is important to have a good understanding of the requirements from the beginning of the design process in order to reduce the need to make costly redesigns at later stages in the process.

To guide the decision-making involved in choosing a system's configuration, Johansson (2007) has stated that it is important to follow a design process. Following such a process makes it easier to grasp the details of the system. It also reduces the risk of sub-optimisation and thereby improves the finished configuration of the system. In the context of AGV systems, the system's components interact with each other, because decisions made concerning one component may place constraints on the options available for another component, which makes determining the components complicated (Vis, 2006). Meanwhile, decisions regarding some components are made at the strategic level, whereas decisions for others are made along tactical and operational time horizons (Fragapane et al., 2021a; Le-Anh and de Koster, 2006).

Based on their literature review, Le-Anh and de Koster (2006) have provided suggestions for what input data are required for designing an AGV system, namely the layout of the facility, the number of and localisation of pick-up and delivery locations, types of loads and performance requirements but it not clear how this affects the AGV system components. At the same time, humans are important in the operation of an AGV system and can engage in many interactions with the system. However, the sorts of requirements that humans impose on the configuration of AGV systems has not been addressed in the literature on AGV systems. Because the role of and work demanded by humans change when automation is introduced, Winkelhaus et al. (2022) have highlighted the need for further research on how humans are influenced so that human needs can be taken into account.

1.3. Purpose

As the foregoing sections have shown, AGV systems are experiencing increased use in industry. Although they have long been used in industrial applications, recent technological advancements have resulted in improved the functionality of AGVs and, together with interest in Industry 4.0, have increasingly attracted attention in recent years. Despite all of those upward trends, some issues related to AGV systems, for instance, human factor aspects and the work organisation supporting the systems, would benefit from further research able to generate knowledge to support the design of such systems. Additional support can also help managers and system designers involved in the design process to create efficient AGV systems that can be successfully implemented in industrial contexts. Because internal transport often involves a large amount of manual work, the potential benefits of automating such transport can be significant due to transferring physically straining, time-consuming work tasks to an AGV system (Granlund and Wiktorsson, 2014).

In the process of designing AGV systems, the components are often addressed in ad hoc ways in real-world applications that amount to an error-prone, time-consuming process (Draganjac et al., 2020). Starting a design process with an overview and understanding of the requirements can make the process proceed more smoothly by avoiding costly redesigns later in the process, at which point altering the configuration is difficult. From another perspective, although AGV systems are often used in mixed environments and interact with humans in many ways, research on AGV systems has largely adopted a technical focus (Fragapane et al., 2021a; Benzidia et al., 2019). As a result, knowledge about the ways in which humans in the environment who interact with the AGV system create challenges and impact the system's configuration is limited but needed to support system designers. Developing work procedures and identifying the need for training are important tasks for human-centric design (Kadir and Broberg, 2021) but involve challenges when AGV systems are introduced.

This thesis seeks to contribute to literature on AGV systems, namely by adding knowledge to the gaps identified therein, to contribute to current knowledge on AGV systems, knowledge that can be used as input in a design process in order to create AGV system configurations that tap into the potential for improved system performance (e.g. Bechtsis et al., 2017). Altogether, the knowledge offered by this thesis can be used as input in the process of designing AGV systems.

The purpose of this thesis is thus *to develop knowledge to support the design of AGV systems.*

1.4. Scope

Support is a central term with respect to the purpose of the thesis. From a managerial perspective, support is aimed at managers and system designers in companies that are involved in the design process of AGV systems. From a theoretical perspective, support refers to that the thesis strives to fill the gaps identified in the research on AGV systems and make contributions to the existing knowledge base. Additionally, further research on AGV systems can be supported by the thesis's findings as indicators of what future research should address.

Design process refers to the process in which the components of an AGV system are decided. It is in the design process of an AGV system that the AGV system fulfils the requirements. The AGV system configuration refers to the finished AGV system where all components are specified.

There is a lack of consensus as how an AGV is defined, both in practice and in research. Several different terms are used, including automated guided cart (AGC) (da Costa Barros and Nascimento, 2021), autonomous intelligent vehicle (AIV) (Hellmann et al., 2019), laser-guided vehicle (LGV) (Ferrara et al., 2014) and autonomous mobile robot (AMR) (e.g. Fragapane et al., 2021a; Jun et al., 2021). However, what distinguishes one type of automated vehicle from another is not always clear. In this thesis, AGV is used as a generic term to describe driverless vehicles used to transport material in internal logistics. By extension, an AGV system, or any similar term stated earlier in the paragraph, is used to automate transports in internal logistics and in this thesis is viewed as fulfilling the same function: to move material in internal logistics, which is in line with (Oyekanlu et al., 2020). That is not to say that no differences exist between the terms regarding, for instance, control and navigation. For example, AMRs or AIVs can be regarded as advanced forms of AGVs because they have more advanced functionality than what are commonly referred to as "AGVs" (Jun et al., 2021). Such advanced functionality and how it relates to the components of an AGV system are explained in greater detail in section 2.1.

1.5. Research questions

This subsection presents the three research questions addressed in the thesis. The questions are aligned with the purpose presented in section 1.3 but narrow the purpose to better focus the research.

1.5.1. Research Question 1

For supporting the design process for an AGV system, an important step is understanding the requirements to be addressed in the process. Design process models often start with developing an understanding for and listing all requirements (e.g. Johansson, 2007; Wu, 1994). As redesigns and alterations in an ongoing design process become increasingly expensive and difficult to perform the further along the design process is (Slack et al., 2013), starting from an understanding and an overview requirements from the beginning is important to avoid these costly redesigns later.

Several requirements can influence the configuration of AGV systems. In individual studies, a limited number of requirements important to a particular component in an AGV system's configuration are often investigated. Vis (2006) has identified explains a number of requirements that influence the decision of fleet size, such as the layout of the environment, the number and locations of pick-up and delivery points, traffic congestion and at what points in time transports are needed. More recently, De Ryck et al. (2020), who studied control algorithms and techniques for AGV systems, mean that flexibility, scalability and robustness are requirements for manufacturing in Industry 4.0 and can influence the control of an AGV system, in response to which decentralised control could be a solution. Meanwhile, Lee and Srisawat (2006) have examined dispatching rules for AGV systems and found that the manufacturing environment significantly influences which rules are preferred. In another study, Berman et al. (2009) have pinpointed various performance measures, including throughput, response time, and AGV utilisation which are often used to specify the requirements of an AGV system that have to be met by the system's configuration. A decision-making framework for developing sustainable supply chains with AGV systems has additionally been proposed by Bechtsis et al. (2017) for making decisions that consider environmental, economic and social aspects. Although their framework provides an overview of sustainability-focused decisions for AGV systems, it does not elaborate upon the requirements that can influence decisions made about the components of those systems. There thus appears to be a lack of an overview requirements imposed upon AGV systems in the literature.

AGV systems are often used in environments with other traffic and pedestrians in which human-AGV interaction is common. As stated in section 1.2.2., despite the lack of attention to humans in research on Industry 4.0 and AGV systems, the integration of humans and AGVs can impose important requirements for the configuration of AGV systems. Such requirements have received limited attention in research given such research's typically technical focus (Fragapane et al., 2021a). Neumann et al. (2021) have stated that human factor (HF) aspects, which relate to physical, perceptual, cognitive and psychosocial aspects of the workplace (Sgarbossa et al., 2020), should be incorporated into the design process. Considering aspects of HFs can help to create efficient systems in logistics and manufacturing in which the workers' well-being is paid attention to (Neumann et al., 2021). Requirements related to the people who are required to work together with AGV systems are important and need to be considered together with all other requirements.

The overall configuration of an AGV system can be improved by managing the requirements jointly instead of in isolation, which can be supported by having an overview of requirements from the beginning of the design process. Neumann et al. (2021) have stated, for example, that when HF aspects are dealt with in isolation in the design of, for example, Industry 4.0 technology, there is a greater risk of developing a system that results in poor worker well-being and suboptimal performance. With an overview of requirements, however, it is possible to assess how different requirements relate to each other and the potential interactions between them in meeting the requirements in the AGV system's configuration.

The literature has largely focused on how a small number of requirements influence particular AGV system components, and it is not always clear how the requirements influence the AGV system configuration. However, meeting the requirements in isolation can reduce the overall performance of an AGV system configuration. There is a need for further research that clarifies the requirements that impact AGV system configurations, and a better understanding for, and overview of requirements can support the design of an AGV system. Therefore, the first research question is formulated as:

RQ 1: Which requirements influence AGV systems, and how can they be met in the configuration of the systems?

1.5.2. Research Question 2

The load capacity of a transport vehicle greatly impacts decisions about part feeding (Adenipekun et al., 2022; Nourmohammadi et al., 2021; Battini et al., 2015), wherein the transport vehicle must be chosen, with reference to its load capacity and the number of vehicles, which can impact costs. Load capacity refers to how many loads each vehicle can carry, and AGVs with varying load capacities can be used in part feeding (Battini et al., 2015). However, in many studies on part feeding, the transport vehicles making the deliveries are assumed to be a given according to Adenipekun et al. (2022); Schmid and Limère (2019), and few studies have examined how to determine the most suitable transport vehicle for part feeding in light of load capacity and the number of vehicles needed (Nourmohammadi et al., 2021). Although the load capacity of transport vehicles has been shown to significantly impact costs, that topic has received limited attention in research.

Whereas the technical dimensions of many components of AGV systems have in many ways been thoroughly studied, issues related to the load capacity of AGVs have received limited attention. Single-load AGVs, that is, AGVs with a load capacity of 1, deals with one transport request at a time, while multiload vehicles, as their name implies, can manage several requests at once (Dang et al., 2021) because their load capacity is greater than 1. AGVs with large load capacities create possibilities to increase throughput while also enabling the use of fewer vehicles (Le-Anh and de Koster, 2006). In turn, having fewer vehicles can reduce the risk of traffic congestion and the number of traffic accidents (Bechtsis et al., 2017). However, dispatching AGVs with a load capacity greater than 1 on deliveries becomes more complicated as it involves new decisions on how long to wait, which loads to pick-up and in what order the loads should be delivered (Chen et al., 2015) and potentially if a partially AGV loaded should be rerouted to pick up additional loads (Ho et al., 2012). Moreover, it is easier to create guidepaths for single-load vehicles, and they also provide more flexibility in making changes in the paths than multiload vehicles due to their smaller size (Battini et al., 2015). Yan et al. (2020) have posited that using single-load AGVs can additionally reduce the completion time of transport requests (i.e. the time from starting and finishing a request) compared with multiload alternatives because the requests are completed one by one. Ultimately, the load capacity of AGVs is important as it impacts performance, and different load capacities may be suitable for use in different situations.

Although there seems to be benefits and drawbacks related to the load capacity, the literature does not provide clear guidance for determining in what situations a larger or smaller load capacity is preferable. Additional knowledge related to load capacity can support the design of AGV systems. In many studies, load capacity has not been the chief focus but been included as a variable for studying phenomena such as dispatching (Ho et al., 2012; Ho and Liu, 2009), scheduling (Dang et al., 2021) and maintenance (Yan et al., 2022). Yan et al. (2022), for example, have concluded that an AGV system’s throughput can be improved by utilising multiload AGVs; even so, they do not examine operational performance in detail or situations in which multiload AGVs are preferable. Yan et al. (2020) have compared the performance of one multiload AGV in different dispatching scenarios as its load capacity was increased from 1 to 10 with an AGV system consisting of 1 to 10 single-load AGVs.

The demand for transport (Battini et al., 2015), the strictness of the time windows within which a request needs to be completed (Dang et al., 2021), traffic interferences due to other vehicles and/or humans in the environment (Sabattini et al., 2017; Le-Anh and de Koster, 2006) and the speed of AGVs (Singh et al., 2011) can all influence which load capacity is selected. Because varying the load capacity influences the fleet size, which is the principal driver of investment costs in AGV systems (Vis, 2006), it is important to strike a balance between load capacity and fleet size. An important performance measure is the tardiness of deliveries, meaning the amount of time after the deadline until a delivery is made (Dang et al., 2021). There is a need for further research pinpointing situations in which different AGV load capacities are suitable.

The load capacity chosen in selecting transport vehicles in part feeding can considerably impact costs. Knowledge about which situations favour a large versus small load capacity and how different situations impact the performance of the configuration of an AGV system with varying load capacities can contribute to the literature on AGV systems, wherein load capacity is seldom the chief focus. Thus, the second way in which this thesis seeks to contribute to supporting the design process of AGV systems is to answer RQ 2:

RQ 2: How does load capacity impact the performance of AGV systems?

1.5.3. Research Question 3

When new automation technology is introduced, several changes in the work organisation are needed and these changes can influence the humans working with the new technology. The following two paragraphs address changes in the work organisation, and how humans may be influenced, respectively.

Today, many applications of AGV systems occur in mixed environments, for example in internal logistics (Sabattini et al., 2017), and human work will remain central to internal logistics (Winkelhaus et al., 2022). When automating a manual process including internal transport, challenges related to the work organisation can arise. The tasks assigned to the operators are likely to be affected by an automated process and require changes to be made in the work tasks (Kadir and Broberg, 2021). New employee roles may also be needed when an AGV system is introduced (Benzidia et al., 2019), and new regulations for improving safety for operators within such systems are needed (Bechtsis et al., 2017). Introducing an AGV system also requires changes in the environment in which the system is used and adjustments to the tasks performed (Lagorio et al., 2020). Given the technical focus of previous research on AGV systems, attention needs to be paid to challenges for the work organisation in terms of new as well as changed work procedures, routines and responsibilities that become necessary when an AGV system is introduced. Research regarding which challenges arise connected to the work organisation when AGV systems are introduced is needed.

Another set of challenges relates to the humans who work together with the AGVs that need to perform the new work procedures. HF aspects, physical, cognitive, perceptual and psychosocial aspects, for different employee roles are influenced when new technology is introduced (Neumann et al., 2021). Those aspects can also be influenced by the introduction of an AGV system. Neumann et al. (2006), for example, found that an AGV system can cause a poor ergonomic situation when operators interact with the AGVs and that the system can set the operators' pace of work, influencing physical and psychosocial aspects. Other challenges relate to developing acceptance when a new system is introduced. Operators decide to accept or reject a new technical solution based on their impression of it (Winkelhaus and Grosse, 2020). The acceptance of an AGV system is important but may be challenging to achieve amongst operators. However, considerations for aspects of HFs have seldom been examined in relation to Industry 4.0 (e.g. Neumann et al., 2021; Sgarbossa et al., 2020), and the challenges related to humans in introducing AGV systems needs to be researched.

Current literature on AGV systems is unclear regarding what challenges are related to the organisation of work and the humans who work together with AGV systems. From that perspective, further knowledge is needed concerning human- and organisation-related challenges when AGV systems are introduced. By developing an understanding of the challenges involved at the individual human level, related to the HF aspects, and at the level of the work organisation, possibilities for planning how to manage the challenges can be made. Therefore, RQ 3 focuses on challenges related to the work organisation and the humans working together with an AGV system:

RQ 3: What human- and organisation-related challenges arise in introducing AGV systems?

1.6. Outline of the thesis

This chapter, Chapter 1: Introduction, has given a background to the area in which the research for the thesis was conducted and highlights gaps in past research related to AGV systems. The chapter has presented the purpose and scope of the thesis, followed by the motivation and articulation of the three research questions answered in the thesis. In what follows, Chapter 2: Frame of Reference provides an overview of literature relevant to the purpose and research questions of the thesis; it presents the components of AGV systems, requirements that may influence the configuration of such systems and an overview of models of design processes. Next, Chapter 3: Methodology begins by describing the research process, followed by a presentation of the research design and, in turn, a section explaining the methods used in each of the three papers appended to the thesis. Reflections on research quality conclude the chapter. After that, Chapter 4: Results presents the results from the appended papers in relation to the three research questions, followed by Chapter 5: Discussion, which discusses the findings in the same way. Chapter 5 also elaborates upon how the results contribute to the purpose of the thesis as well as to both theory and practice and ends by discussing the generalisability of the findings and making suggestions for future research. Last, Chapter 6: Conclusions wraps up the thesis by summarising the main findings from the research.

2. Frame of reference

This section presents the frame of reference applied in the thesis, a central theme of which is the design and the configuration of AGV systems. As mentioned in Chapter 1, AGV system is viewed as consisting of several components, each of which has a technical dimension and what this thesis calls a work organisation dimension. Against that general background, section 2.1 first presents the components of an AGV system and identifies decisions to be made regarding those components in designing AGV systems. Next, section 2.2 presents requirements that may influence the configuration of AGV systems derived from the literature. Section2.3 presents design process models.

2.1. Components of AGV systems

The purpose of this thesis is to develop knowledge to support the design of AGV systems. To that purpose, this section provides a review of the literature addressing the components of AGV systems, to determine the decisions that need to be made regarding them in the process of designing such systems. This section's subsections explain each of those components. First, however, this section presents seven components of AGV systems: guidepath design, traffic management and control, fleet sizing, battery management and failure management (Le-Anh and de Koster, 2006; Vis, 2006) and two additional ones: guidance technology and load-carrying mechanism.

The components of an AGV system configuration identified in the reviews of Le-Anh and de Koster (2006) and Vis (2006) are similar to each other but categorised in different ways. In this thesis, the components presented in the cover paper are based on Vis's (2006) categorisation with the exception of that the cover paper merges the component of control related to dispatching, scheduling and routing with the component of traffic management (e.g. avoidance of deadlocks) into a single component called "traffic management and control". According to Vis (2006), control involves ensuring that no conflicts between the AGVs in the system which is also part of traffic management insofar as it refers to the avoidance of deadlocks and collisions. Additionally, Le-Anh and de Koster (2006) state that the localisation of pick-up and delivery positions is input to the AGV system configuration, which is why the location of pick-up and delivery locations is included in the requirements in section 2.2. The review of Fragapane et al. (2021a) for more technically advanced AGVs complements the reviews of Le-Anh and de Koster (2006); Vis (2006) in the cover paper.

Both Le-Anh and de Koster (2006) and Vis (2006) recognise that AGVs have different guidance technologies but do not include it in their frameworks for the AGV system configuration. Although AGVs once moved along mostly physical guidepaths, new guidance technologies have since allowed AGVs to navigate completely without guidepaths (Fragapane et al., 2021a). In turn, such technologies can impact the other components, including guidepath design, for some newer guidance technologies do not require guidepaths in the same ways as before. Because guidance technology can impact the configuration of AGV systems, this thesis includes it as a component in the AGV system configuration, beyond that of Le-Anh and de Koster (2006); Vis (2006).

Another addition concerns load-carrying mechanisms for the AGVs, which today showcase a variety of ways of transporting loads (Ullrich, 2015). Although Le-Anh and de Koster (2006) and Vis (2006) both highlight that single-load and multiload AGVs are available and can influence the AGV system configuration. However, how the choice of load capacity influences the load carrying mechanism is not elaborated upon. For example, if pallets are to be moved by an AGV system, then forklift AGVs could be used for single-load vehicles. However, using a forklift AGV would not be possible for a multiload AGV, and another load-carrying mechanism would be required instead. In that and other cases, the load-carrying mechanism is important to include as a component in the configuration of AGV systems and as such the load-carrying mechanisms are the second addition to that of (Le-Anh and de Koster, 2006; Vis, 2006).

Before proceeding to examine the components in the configuration of AGV systems, two additional points should be made. First, as stated in Chapter 1, this thesis conceives the components of AGV systems as existing in two dimensions, a technical dimension and a work organisation dimension, each of which is discussed in relation to the components in what follows. As mentioned in section 1.2.1, some of the components lean more heavily towards the technical dimension (e.g. guidance technologies and guidepath design), whereas others (e.g. failure management) lean more heavily towards the work organisation dimension. Second, as stated in section 1.4, AGV is used in this thesis as a generic term to cover driverless vehicles in internal logistics. There are differences in the available functionality of AGVs, for example ranging from navigation via physical guidepaths and limited decision-making capabilities to advanced navigation and control (Jun et al., 2021). How such functionality may influence the components of the configuration of AGV systems is also explained in the following sections.

2.1.1. Guidance technologies

The guidance technologies for AGVs have improved considerably in recent decades (De Ryck et al., 2020). Figure 1 gives an overview of technologies, which offer various degrees of flexibility in changing how AGVs move and, as such, constitute an important component in the configuration of AGV systems. Both the investment and installation costs of AGVs are also influenced by the guidance technologies used. As a component of AGV systems, guidance technology is considered to lack a work organisation dimension.

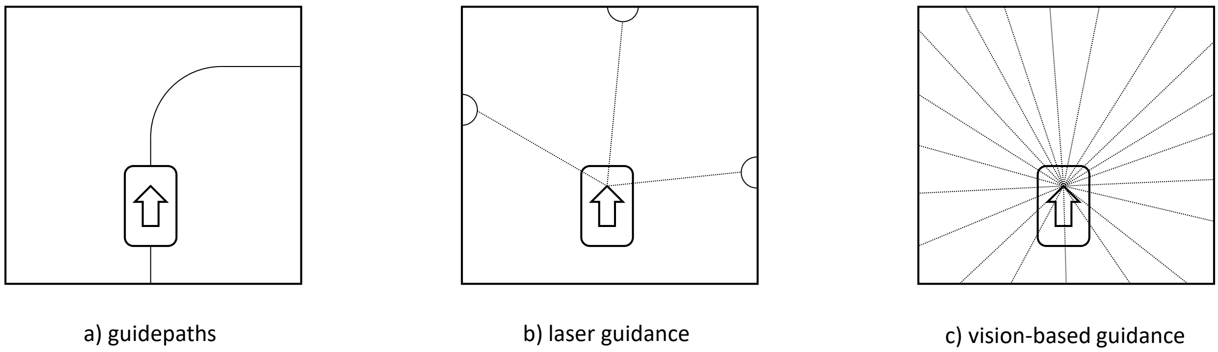


Figure 2.1. *Guidance technologies for AGVs viewed from above (adapted from Fragapane et al., 2021a).*

Figure 2.1a) shows a typical guidepath for AGVs where the guidepath has been physically installed in the environment. There are several ways in which physical guidepaths can be created; tape can be used, either for optical or magnetic navigation, or inductive wires can be embedded in the floor (Le-Anh and de Koster, 2006). Because the guidepaths are indeed physical, altering where AGVs can move can be difficult, and if magnetic or optical tape on the floor is used, then it will be exposed to wear and may have to be reapplied.

By contrast, Figure 2.1b) shows guidepaths using laser and reflector guidance technology. Therein, the AGV is equipped with a laser scanner that detects reflectors in the layout in order to calculate its position. Once several reflectors have been detected by the AGV while navigating the layout, its position can be determined by triangulating the positions from the reflectors, and the AGV can thus navigate through the layout (Fragapane et al., 2021a).

Last, Figure 2.1c) shows vision-based navigation based on simultaneous localisation and mapping (SLAM), a technology for the real-time navigation of vehicles (Bloss, 2008). SLAM involves two activities, creating a map of the environment in which the vehicle moves and calculating the position of where the vehicle is in that environment. Because input from vision sensors is compared with the reference map to determine the location of the vehicle, the set-up allows for free navigation without needing to use any reflectors or physical guidepaths in the layout (Fragapane et al., 2021a). Vision-based navigation can make obstacle avoidance possible. Other or additional sensors can be combined with SLAM such as light detection and ranging (LiDAR) (De Ryck et al., 2020). By using several sensors, navigation becomes more accurate.

Both vision-based navigation and laser and reflector guidance can be combined with fixed guidepaths. Using those navigational technologies, the guidepaths do not have to be physically present in the environment but only in the software for the AGVs. Such guidepaths can be referred to as virtual guidepaths (De Ryck et al., 2020). Having the information about guidepaths in the software makes it easier to adapt the guidepaths if changes occur in the environment.

2.1.2. Guidepath design

AGVs can travel along guidepaths that connect locations within the facility (Vis, 2006). Guidepath design involves determining how to connect different pick-up and drop-off points, charging facilities and idle positions in a way that can minimise the total travel distance (Le-Anh and de Koster, 2006). Guidepath design is influenced by whether having bidirectional traffic in the environment is possible or whether only unidirectional traffic is possible (Nishi et al., 2020). Bidirectional traffic can improve performance but makes controlling the AGV system more complicated. Most often, the localisation of pick-up and delivery positions is fixed in the guidepath design (Le-Anh and de Koster, 2006).

Various guidepath configurations have been developed and evaluated in research (Rezapour et al., 2011). For one, single-loop use a guidepath such that all vehicles travel in a predetermined loop. For another, a tandem guidepath uses a fleet of AGVs assigned to several disjointed guidepath loops, each of which has only one AGV (Asef-Vaziri and Goetschalckx, 2008), while load transfer positions connect the individual loops. A guidepath can also be designed in a network type in which a network of unidirectional and bidirectional paths connect the pick-up and delivery locations (Vis, 2006).

Control and traffic management within AGV systems can be influenced by the decisions made in the guidepath design (De Ryck et al., 2020). For example, if a single-loop configuration is used, then control decisions become easier to manage because situations of deadlock cannot occur. Deadlocks occur only when two or more vehicles lock each other out from performing a certain task and none can continue operation. Using a tandem configuration can simplify the control of the AGV system because each loop uses only one AGV.

From the other direction, the guidance technology used impacts guidepath design. If an AGV can navigate freely without guidepaths, as shown in Figure 1c), then the guidepath design is not as important because, in most cases, the AGVs do not use guidepaths. In that case, areas of the facility where AGVs are allowed to move need to be determined and path planning in those areas must be decided (Fragapane et al., 2021a).

Regarding the work organisation dimension of guidepath design, developing guidepaths is a time-consuming process that has to be performed when an AGV system is introduced (Sabattini et al., 2013). For example, when laser navigation with reflectors is used, the reflectors need to be in places such that AGVs can detect multiple reflectors at each point in the layout to triangulate their positions. To that end, modifications in the placement of reflectors are often needed (Oleari et al., 2014), and the guidepaths and/or areas in which the AGVs may move should be kept up-to-date. If there are changes in the layout, then it may also be necessary to make changes in the guidepaths of the AGV system. Although making changes in guidepaths for AGVs that follow guidepaths is time-consuming especially for physical guidepaths, making adjustments for vehicles with vision-based navigation is often as easy as adding or adjusting a transport zone for the vehicles (Fragapane et al., 2021b).

2.1.3. Traffic management and control

The control of an AGV system, encompassing vehicle routing, scheduling and dispatching (Vis, 2006), typically has the objective of ensuring that transport requests are completed in a timely fashion and that traffic flows smoothly by avoiding conflicts and deadlocks. Traffic management, by extension, which involves preventing deadlocks and collisions, is a problem that has to be addressed in controlling AGVs.

The literature on AGV systems has mostly addressed the control and traffic management of AGVs in areas without human operators. In cases in which the AGVs work in a closed-off area, for example, Amazon's Kiva system (Sabattini et al., 2017), traffic management and control has a limited work organisation dimension. However, in mixed environments, several decisions related to the work organisation need to be made. Depending on where in the layout the guidepaths for the AGVs are located, or where the zones in which the AGVs work if they have more advanced navigational capabilities, different levels of interaction can exist between the AGV system and the operators. In such environments, new routines have to be developed for interacting with AGVs, for example, regarding whether the AGV or the operators have to yield at intersections in the layout. Furthermore, the navigational capabilities of the AGVs have to be taken into account. For instance, AGVs able to temporarily deviate from assigned routes when encountering obstacles are less predictable for the operators in the layout (De Ryck et al., 2020), making it more difficult to determine how the AGVs will behave.

Tasks for the AGV system may be generated and assigned to an available AGV automatically without any manual intervention. In mixed environments, however, there can also be tasks that are assigned by humans (Sabattini et al., 2013), including pressing buttons to summon an AGV. In that case, work procedures have to be developed for task generation as well. The following subsections present aspects of the technical dimension of traffic management and control.

Centralised and decentralised control

Control for an AGV system can be divided into centralised and decentralised control (Le-Anh and de Koster, 2006). Centralised control means that the control of the AGV fleet is maintained by a central controller that makes all decisions about routing, scheduling and dispatching (De

Ryck et al., 2020). Although centralised control seeks to find optimal solutions to problems with controlling AGVs, doing so can be computationally difficult. Moreover, the centralised control's performance may worsen in situations with many vehicles and tasks to assign, and Draganjac et al. (2020) have shown that large fleet sizes can hinder the centralised control of larger systems. By contrast, decentralised control means that each AGV makes decisions based on local information and by communicating with each other AGVs. Although optimal solutions are rarely found with decentralised control, it scales better with the number of vehicles from a computational perspective and is more flexible (De Ryck et al., 2020). More advanced AGVs many times utilise decentralised control such that each vehicle in the fleet can make decisions (Fragapane et al., 2021a).

Dispatching

Dispatching refers to selecting an AGV from a set of available AGVs to perform one transport request from a set of active requests (Miyamoto and Inoue, 2016). Many simple heuristics dispatching rules for assigning transport requests have been investigated such as shortest travel distance, first come first served, earliest due date first, longest waiting time to name a few (Hu et al., 2020). The performance of dispatching can be improved by considering multiple rules simultaneously. The dispatching is a more complicated problem for AGVs having a load capacity larger than one, especially in job shop environments since a partially loaded AGV can be rerouted to pick up additional loads on the way to its destination, at the cost of delaying the currently carried loads (Ho et al., 2012; Ho and Liu, 2009).

Scheduling

Scheduling refers to determining arrival and departure times along the route as well as at pick-up and delivery locations (Vis, 2006). Scheduling can be conducted online or offline. In offline scheduling, the transport requests within a certain time horizon into the future are known, which Dang et al. (2021) state allows optimising the schedule for when the transport requests are completed. In online scheduling, by contrast, due to randomness in the incoming orders and/or a limited time horizon into the future, amongst other factors, the transport orders have to be assigned as they occur, that is, in real time.

Finding that most past studies addressing scheduling focus on the scheduling of vehicles in job shop environments, Chen et al. (2015) developed a scheduling method for deliveries from a single storage point to an assembly line when a multiload carrier is used. For multiload carriers, three decisions have to be made in the dispatching (Chen et al., 2011). The first is when the carrier should be sent on a delivery round, while the second is which load should be taken on a delivery round if the requests available exceed the vehicle's capacity. Last, the order in which the delivery locations will be visited has to be decided when multiple loads are to be delivered in one delivery round.

Routing

Routing refers to determining the path that an AGV should travel when making a delivery (Vis, 2006). In routing decisions with multiple AGVs, it is important to consider that the shortest distance may not result in the shortest travel time due to congestion and/or deadlock. When routing vehicles in AGV systems, the guidepaths are usually used as input in the routing decisions, whereas AGVs utilising vision-based navigation use a map of the environment and seek to find the shortest route to the destination while avoiding conflicts (Fragapane et al., 2021a). With vision-based navigation, an AGV creates a new path every time that it needs to move.

Control zones
Control zones refer to areas used to avoid conflicts where only a limited number of vehicles are allowed to be at a given time (De Ryck et al., 2020). Segments of a guidepath or a certain area of the facility layout can enforce a limit on the number of vehicles there. When a control zone is already occupied, vehicles that want to enter the zone have to replan their routes or wait until the zone becomes available.

Control of idle vehicles
Another aspect of control in AGV systems is handling idle vehicles (Vis, 2006). Because the workload may vary over time, idle vehicles can be expected. A vehicle becomes idle upon completing a transport request when no new assignments are available. It is important to determine the position where idle vehicles should go, that is, dwell points, so that the vehicles can quickly respond to new transport requests when generated. Ventura et al. (2015) have optimised the dwell points of an AGV system within a certain guidepath design that minimises the response time to transport requests. However, not only the localisation of the dwell points is important but also how the vehicles are dispatched to them. Kabir and Suzuki (2018) have suggested that natural idle times in operations should be used to recharge AGVs.

2.1.4. Fleet size

The fleet sizing of an AGV system entails determining the number of vehicles required for the material flow under consideration (Le-Anh and de Koster, 2006; Vis, 2006). Therein, the number of vehicles is significant as the driver of investment costs. If too many vehicles are introduced, then there is a risk of causing congestion, which can reduce the throughput of the AGV system (Choobineh et al., 2012). At the same time, if too few vehicles are introduced, then there is a risk that transport requests will not be completed on time. Fleet sizing is influenced by several other components and factors of AGV systems, including guidepath design, dispatching, the number and location of load transfer points (Choobineh et al., 2012), unit load size and load capacity (Lee and Srisawat, 2006; Vis, 2006). Although the required fleet size can also be influenced by aspects of the work organisation dimensions regarding the other components, for example, routines for traffic management and failure management processes, fleet sizing is not considered to have a work organisation dimension of its own.

Using a load capacity larger than one unit, multiload AGVs can reduce the required fleet size because fewer vehicles are needed to meet the transport demand and, in turn, reduce the effects of congestion. However, research on multiload AGVs has been scarce (Yan et al., 2022; Dang et al., 2021). Although dispatching and scheduling for multiload AGVs have featured in some studies (e.g. Dang et al., 2021; Ho et al., 2012; Ho and Liu, 2009), or maintenance activities for both single-load and multiload AGVs (Yan et al., 2022), issues like the load capacity's impact on the required fleet size and an AGV system's performance have seldom been examined.

2.1.5. Battery management

Because AGVs are usually battery-powered, it is important to consider the location of battery swapping or charging stations in the layout of AGV systems as well as when those activities should occur (Kabir and Suzuki, 2019). If charging is used, then various recharging strategies may be applied. Full-recharging requires vehicles to be fully recharged before continuing operation, whereas partial recharging, as the name suggests, allows partial recharging, which can improve performance by reducing the length of charging times (Jun et al., 2021). Amongst schemes for when charging should occur (Kabir and Suzuki, 2018), opportunity charging involves having AGVs charge their batteries during natural idle time, whereas automatic charging involves having AGVs charge once a certain threshold has been reached for the battery. Those two methods can be combined. If battery swapping is used, then there is generally less downtime, because discharged batteries are swapped for recharged ones and the AGVs do not have to wait to recharge before continuing operation. However, swapping also requires several spare batteries to be available so that AGVs do not have to wait to receive a charged battery, which imposes higher investment costs (Zou et al., 2018). According to Fragapane et al. (2021a), newer high-capacity batteries (e.g. lithium-ion batteries) reduce downtimes due to the charging or swapping of batteries, thereby making battery-related setbacks less prominent. In around-the-clock operations, battery charging and swapping continue to be significant component in AGV systems (Zou et al., 2018).

Regarding the dimension of work organisation, battery swapping may need to be manually performed by an operator (Kabir and Suzuki, 2018). When battery charging is used, by comparison, AGVs automatically go to charging stations when a predetermined battery threshold has been reached or when there is idle time. However, such thresholds may have to be updated over time if changes occur in the AGV system or in the environment in which the AGVs are used.

2.1.6. Failure management

AGVs occasionally present failures that need to be managed in order to not lose operational time (Fragapane et al., 2021a). Yan et al. (2018) have underscored the importance of considering failure management and maintenance strategies to achieve high availability, particularly by showing that corrective maintenance can improve the throughput of an AGV system. Failures and maintenance for multiload AGVs have been further analysed by Yan et al. (2022), who investigated different maintenance strategies and evaluated the impact of including backup AGVs to cover for failed vehicles. They concluded that the impact of vehicle failures can be reduced by performing appropriate maintenance.

Monitoring and intervening in cases of operational failures are needed in an AGV system (Fragapane et al., 2021a), and this represent the work organisation dimension of the component of failure management. Intervening can involve different activities, from resetting the AGV to be operational to manually moving the AGV from the floor when serious failures occur, followed by pinpointing solutions for the failure. Normally, AGVs stop and require manual assistance if a failure occurs; however, if the AGV has more advanced functionality, then it may be better able to avoid failures and, in some cases, even recover from failures themselves (Fragapane et al., 2021a). Such AGVs also react more robustly to dynamic entities within the environment that can cause failures to occur. By extension, Yan et al. (2022) demonstrated that predictive maintenance can improve an AGV system's performance, and the frequency of the activity is important to decide. Maintenance activities represent another part of the work organisation dimension.

2.1.7. Load-carrying mechanism

AGVs can carry loads in a wide variety of ways (Fragapane et al., 2021a; Ullrich, 2015), and depending on an AGV's load capacity, different options for load-carrying mechanisms are available. A common load-carrying mechanism for AGVs is the forklift. As the name implies, forklift AGVs are equipped with forklifts for carrying loads in units such as EUR-pallets and unit loads that fit forklift transports. The load capacity of forklift AGVs is usually only one.

An underride AGV is another load-carrying mechanism (Ullrich, 2015). Underride AGVs position themselves underneath a load and lifts the load onto their carrying platform. For unit loads such as racks or carts that are equipped with wheels, underride AGVs do not have to lift the load but only connect to the rack or cart and drag the unit load along using the unit load's own wheels. Underride AGVs can be used to move several unit loads at once.

Vehicles can also be equipped with different top modules (Fragapane et al., 2020), for instance, a conveyor, which allows the AGV to move a load horizontally when stationary. Another possible top module is a shooter rack, a kind of gravity flow rack in which gravity is used to move a load to the required position. When a shooter rack on an AGV is aligned with the delivery location, a gate is opened in the shooter rack so that the new unit loads can flow to the delivery location aided by gravity, while empty loads flow back to the AGV (Emde et al., 2012). The same process also works to pick up loads. Both a conveyor module and a shooter rack allow moving several loads at the same time.

AGVs can be used as tuggers, in which case carts are attached to an AGV that then tows the carts (Emde and Gendreau, 2017; Battini et al., 2015). A tugger AGV is an option when the load capacity is larger than one for large unit loads such as pallets. Each cart may also consist of several bins. When using tugger AGVs and carts, automatically transferring the load to and from the carts is often difficult. Adenipekun et al. (2022) have explained a solution for automated transfer using a smaller AGV that moves together with the tugger AGV transporting the loads; when an AGV tugger train has arrived at a delivery location, the cart is detached from the train, the smaller AGV picks it up and delivers it to the final location before returning to the train. Shooter racks can be used for tugger trains as well, such that each wagon is equipped with such a rack (Emde and Gendreau, 2017).

The guidance technology used can impact the load transfer. Some AGVs pick up loads based on their position and can handle only small deviations of the placement of loads, whereas AGVs using vision-based navigation can manage larger deviations while remaining able to pick up the load. The precision in the placement may have to be addressed in the work procedures if operators deliver loads to the AGV system, which may have to include fixed infrastructure at the load transfer positions to ensure that loads are placed in the same spot every time (Sabattini et al., 2013). Depending on the load-carrying mechanism that an AGV is equipped with, operators may have to manually move the loads from the pick-up position to the AGV during loading or unload the AGV at a delivery position. The load-carrying mechanism can thus involve a work organisation dimension.

2.2. Requirements for the AGV system configuration

Sources of requirements from where requirements that influence the configuration of an AGV system can come from, are presented in this section. Regarding the requirements that influence the configuration of AGV systems, Granlund and Wiktorsson (2014) have stated that one of the most important steps when considering such automation technology is to develop a well-formulated specification of requirements. With respect to this thesis's purpose, it is important to understand and develop an overview of requirements to support the design of an AGV system.

The requirements presented in this section are derived from three streams of literature on the respective topics of material handling equipment (MHE) selection, AGV systems and human factors and ergonomics (HF/E). As for the first, MHE selection seeks to find the most suitable choice of MHE from attributes of the setting where the MHE will be used (Anand et al., 2011) related to, for instance, the environment and the unit loads. Characteristics of different MHE are assessed in light of the setting's attributes to determine appropriate MHE (Cho and Egbelu, 2005). Although the literature on MHE selection mostly refers to a broader scope of MHE than AGVs, the attributes of the setting taken into account in such selection decisions are considered to be relevant for deriving requirements for the configuration of an AGV system. Requirements are also derived from the literature on AGV systems, wherein requirements from MHE selection literature complements the requirements derived from AGV system literature. Because introducing automation technology often leads to changes for operators, considerations of humans in the design is necessary which is why human factors and ergonomics (HF/E) are included.

Table 2.1 presents five sources of requirements derived from the three literature streams. Those five sources resulted from studying the attributes in MHE selection and the categorisation made in the literature on such selection and connecting them with the requirements from the literature on AGV system. Requirements regarding HF/E are added to those requirements to give consideration to humans operating alongside AGVs.

Not all aspects of MHE selection were considered to be relevant to identifying requirements and are thus excluded from the Table 2.1. For instance, in their suggested selection framework, Bouh and Riopel (2015) have created a category concerning the equipment, including load capacity and battery, which are considered to be part of the configuration. Bearing strength, engine type and gripping equipment are also in that category but are not relevant to this thesis because they are not especially relevant for deciding the AGV system components. As stated previously, the literature on MHE selection often has a wider scope and includes many other types of transport equipment, storage and retrieval systems, and it is therefore expected that not all attributes or categories would fit for identifying requirements for an AGV system.

Table 2.1. *Requirements and sources of requirements derived from literature on MHE selection, AGV systems and HF/E coming from five sources of requirements.*

		MHE selection							AGV systems								HF/E		
Sources of requirements	From the literature	(Anand et al., 2011)	(Bouh and Riopel, 2015)	(Mirhosseyni and Webb, 2009)	(Chakraborty and Prasad, 2016)	(Chu et al., 1995)	(Cho and Egbelu, 2005)	(Maniya and Bhatt, 2011)	(Le-Anh and de Koster, 2006)	(Berman et al., 2009)	(Aized, 2009)	(Lee and Srisawat, 2006)	(Vis, 2006)	(Scholz et al., 2019)	(Oleari et al., 2014)	(Sabattini et al., 2017)	(Vijayakumar et al., 2021)	(Neumann et al., 2021)	(Karltun et al., 2017)
Internal logistics environment	Movement characteristics	x	x	x	x	x	x												
	Manufacturing system layout	x					x					x							
	Environment / area constraints		x	x															
	Planning and control												x						
	Facility layout					x			x			x	x						
	Pick-up and delivery locations								x			x	x						
Characteristics of transported load	Material	x		x	x	x	x												
	Unit load		x						x										
Technical interoperability	Interoperability													x					
Performance	Demand in the material flow	x							x										
	Flexibility	x						x											
	Cost	x						x	x				x						
	Controllability							x											
	Accuracy	x						x											
	Range							x											
	Repeatability	x																	
	Reliability	x						x											
	Maintainability	x																	
	Throughput								x	x	x	x	x						
	AGV utilisation								x	x	x								
	Response time										x								
Integration of humans and AGVs	Human factor aspects*																x	x	x
	Humans and AGVs														x	x			
	Safety														x	x			

*Additional details regarding human factor aspects are presented in Table 2.2.

2.2.1. Internal logistics environment

As indicated in Table 2.1, the internal logistics environment is important in the literature on MHE selection. Hassan (2010) has stated that the type and layout the of production system like a production line or a job shop, for instance, influences the movement paths available in the facility, which imposes constraints on the transport equipment. Physical restrictions such as columns, multiple floors and ceiling height can create such constraints. Narrow areas of the layout, for instance, due to columns that cannot be moved may require control zones to be used to limit the activity of AGVs in the area. Movement characteristics relate to e.g. overall distances, available paths in the layout and the frequency of transports (Mirhosseyni and Webb, 2009). Along those lines, the width and length of aisles have been considered by Bouh and Riopel (2015), as has the availability of floor space, all of which can influence where MHE can be used. The facility's layout can additionally constrain where AGVs can move as well as the guidepath design, and, for that reason, it is important to identify potential bottlenecks in the layout when designing the AGV system (Bechtsis et al., 2017).

The overall demand placed on the AGV system and at what points in time the demand occurs impact the system's fleet size (Vis, 2006). Related to the dispatching and scheduling in 2.1.3, the planning and knowledge of incoming transport orders can put constraints on the control of an AGV system. Thus, the planning and control can create requirements.

On top of that, a material handling system may have several load transfer positions, and Le-Anh and de Koster (2006) have stated that the locations of pick-up and delivery points are often considered to be fixed, meaning that they create a requirement that the AGV system's configuration has to meet. Moreover, Lee and Srisawat (2006) found that the manufacturing system's layout places constraints on the paths available in that layout, which limits the applicability of bidirectional traffic. In their study, the layout of the manufacturing system indeed significantly impacted the most suitable dispatching rule for the AGV system that they investigated.

2.2.2. Characteristics of transported loads

Table 2.1 highlights a second source of requirements relating to the transported material, namely, the characteristics of the transported material. This refers to for example the type of unit loads (e.g. pallets or boxes), the general shape and the dimensions of the loads. Cho and Egbelu (2005) have posited that a mix of different types of material and unit loads can be handled in one system, which can create additional requirements compared with a set-up using only a single type of unit load. The weight of the unit loads should also be considered (Chakraborty and Prasad, 2016). As stated in Section 2.1.8, there are numerous ways in which an AGV can carry a load, and the characteristics of transport loads can affect which load-carrying mechanism is most suitable.

In research on part feeding, the transport vehicle is often considered to be fixed in the feeding of certain unit loads for example, forklifts for pallets and tugger trains for boxes (Adenipekun et al., 2022; Schmid and Limère, 2019). However, the several options for delivering a certain type of unit load and the most appropriate transport vehicle should be determined (Nourmohammadi et al., 2021; Battini et al., 2015). The characteristics of the loads may put requirements on what is possible to deliver in a multiload AGV.

2.2.3. Technical interoperability

Given the increased use of automation and the Internet of Things in manufacturing, interoperability has become pivotal within Industry 4.0 (Lu, 2017). Interoperability refers to the ability of systems and/or devices to understand and use the functionality of other systems (Chen et al., 2008), as well as to communicate with each other and even across different versions of the same system or device (Zeid et al., 2019). However, because AGV system suppliers typically have their own standards, interoperability is often lacking between AGV systems from different suppliers (Scholz et al., 2019). Oleari et al. (2014) state that AGV systems are often controlled by a warehouse management system or something similar and information about transport tasks has to be provided to the system (De Ryck et al., 2020).

2.2.4. Performance requirements

Requirements may also stem from goals set for the AGV system. As shown in Table 2.1, various measures can be used to specify and measure the performance of an AGV system. Throughput is a measure which is often used to measure performance of an AGV system. Yan et al. (2018) use throughput, defined as the number of transport requests that the system delivers in a certain time period, along with the operational cost to determine the optimal maintenance strategy for the AGV system to improve reliability. Another measure, AGV utilisation, has been defined by Aized (2009) as the portion of total time when the AGV moves loads, including idle time and wait time due to interactions with other traffic. Flexibility may concern the system's adaptability to handle changes in the layout (De Ryck et al., 2020) and can also refer to a system's ability to manage variations in volume demands. Maniya and Bhatt (2011) have developed a MHE selection method of selecting the most appropriate AGVs and identified six variables of performance, including flexibility and reliability, as shown in Table 2.1.

2.2.5. Integration of humans and AGVs

In mixed environments, integrating an AGV system with human operators can become challenging with the interaction of manual operations and AGVs (Oleari et al., 2014), thereby making safety a vital consideration (Sabattini et al., 2017). Klumpp (2018) has suggested evaluating the interaction between manual and automated systems before their implementation, otherwise, the risk of failure is high. Added to that, Cho and Egbelu (2005) have posited that a particular MHE may need to operate and connect with other MHE, for example, in transports potentially involving many material flows and several transport vehicles.

Humans are important in determining the benefit of new technologies. After all, humans who interact with the technology decide whether to adopt or reject the technology based on what they perceive and thus determine its benefits and costs (Winkelhaus and Grosse, 2020). If humans are ignored in the design, then they may resist putting effort towards utilising the new technology. Resistance to adopting a new technology slows the development of new competencies and hinders the acceptance of the technology (Nayernia et al., 2021), both of which can reduce performance.

According to Neumann et al. (2021), ignoring, or addressing human factor (HF) aspects in isolation from other aspects in design, there is a risk of developing a system that underperforms and creates a poor work environment. As stated in Chapter 1, attention to humans in research on Industry 4.0 and AGVs has been limited. HF/E are especially relevant in designing systems in which the needs of humans should be considered (Kadir and Broberg, 2021). The definition of human factors and ergonomics used in this thesis is the one used by the International Ergonomics Association (IEA, 2022):

> Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance.

IEA (2022) state that the terms ergonomics and human factors can be used interchangeably. Thus, in this thesis the term human factor (HF) will be used.

Introducing a new technical solution can induce many changes for humans, create new interactions between humans and technology and result in changes in workplace practices (Kadir and Broberg, 2021). The way in which work is performed can affect individuals in different ways, including psychosocial, cognitive and/or physical aspects (Carayon, 2009). For that reason, the tasks performed influence psychosocial aspects (e.g. control over the pace of work), cognitive aspects (e.g. information processing) and physical aspects (e.g. work postures and fatigue). Table 2.2 shows human factor aspects identified in the literature.

Table 2.2. *HF aspects from literature.*

Categories of HF aspects used in this thesis	HF aspects used in the literature	(Daniellou, 2001)	(Neumann et al., 2021)	(Vijayakumar et al., 2021)	(Karltun et al., 2017)	(Sgarbossa et al., 2020)	(Kadir et al., 2019)	(Longo et al., 2019)	(Carayon, 2009)
Physical	Physical		x	x	x	x	x	x	x
	Biological	x							
Cognitive	Perceptual		x	x		x			
	Cognitive	x	x		x		x	x	x
	Mental			x		x			
	Knowledge		x						
Psychosocial	Psychosocial		x	x		x			x
	Psychological	x			x			x	

As Table 2.2 shows, the HF aspects can be categorised in different ways. This thesis uses three categories, physical, cognitive (i.e. including perceptual, mental and/or cognitive processes and knowledge) and psychosocial aspects, all of which are explained in the following three subsections. Considering HF aspects in design can increase performance, reduce the number of errors and improve the well-being of operators (Neumann et al., 2021).

Physical aspects

Physical aspects of HFs may be affected when a new technology such as automation technology is introduced (Vijayakumar et al., 2021). Such aspects include manual work tasks, safety and health, posture, fatigue and the repetitiveness of work (Vijayakumar et al., 2021; Kadir et al., 2019). Such physical aspects can significantly influence a person's performance. for example, fatigue may have a negative impact (Longo et al., 2019). Poor work conditions requiring awkward posture and repetitive work can also cause musculoskeletal disorders, which can lead to several indirect costs such as increased errors and sick-leave (Neumann et al., 2021). Neumann et al. (2006) have shown how operator-AGV interaction can result in poor posture in the workplace and increase the risk of musculoskeletal disorders amongst operators. Although limited attention has been paid to HF aspects in designing Industry 4.0 systems (Neumann et al., 2021), the literature that does consider such aspects mostly addresses the physical human factor aspects (Sgarbossa et al., 2020).

Cognitive aspects
Cognitive HFs focuses on how work affects the mind and how the mind affects work (Hollnagel, 1997). One cognitive aspect of human factors, perception, refers to perceiving the environment. In manufacturing settings, a worker may be exposed to a large amount of information and signals and thus have to sort through all input to make decisions (Longo et al., 2019). The signals and information are detected by the sensory system, including sight, sound, touch, taste and smell. Inputs from the sensory system become factors of the cognitive processes and, as such, determine which actions are considered to be appropriate to take. Such inputs are processed based on memory and training, after which an employee determines what action, physical action, for instance, should be taken in response to a certain situation (Neumann et al., 2021). The cognitive aspects of memory, reasoning and knowledge can be improved with training (Longo et al., 2019), and if any change in the environment occurs, for example, the introduction of an AGV system, operators may need to be (re)trained.

Psychosocial aspects
According to Netterstrøm et al. (2008), psychosocial aspects of a job such as work content and relations with colleagues can cause stress and, in turn, lead to impaired functioning and reduced well-being. When performing tasks, an operator can experience several emotions, anxiety, vulnerability, motivation, and stress, amongst others that can affect the operator's performance (Longo et al., 2019).

The job demand-control model developed by Karasek (1979) allows predicting the mental strain of performing work. The level of employees' control over their work impacts the mental strain of the job's demands such that a low sense of control and high workload creates high mental strain. When automation technology is introduced in the workplace and the pace of work for operators is enforced by the automation, employees' sense of control will likely decrease which could result in that the mental strain increases (Neumann et al., 2021). In their study, Neumann et al. (2006) discovered that AGVs controlled the pace of the operators' work, thereby reducing their sense of control over their own work. Support from supervisors and co-workers are critical dimensions of the well-being of operators and can influence and reduce the mental strain that they experience (Netterstrøm et al., 2008). Thus, not considering psychosocial aspects can impact operators' health and performance in terms of work satisfaction, boredom, motivation and well-being.

2.3. Design process models in production, materials supply systems and materials handling systems

Although the processes of designing AGV systems are not the focus of this thesis, the knowledge developed in the research conducted for the thesis can be useful input for AGV system design. Along those lines, this section provides an overview of design process models related to designing materials supply systems, production systems, and materials handling.

As shown in section 2.2, several requirements can influence the configuration of AGV systems. Following a structured approach for the design is vital (Johansson, 2007), so that the requirements for the design are captured and that appropriate choices can be made in the design process in consideration of all relevant requirements. This section presents examples of design processes suggested in the literature for designing material supply systems, production systems and materials handling systems. The design processes provide a structured approach to designing complex systems and are thus seen as relevant to designing AGV systems, even if the scope of such models is broader than AGV systems. This thesis seeks to develop knowledge to support AGV system design, and the processes presented in this section exemplify ones to which the thesis seeks to contribute. At the same time, the presented processes are in no way exhaustive of design processes in the literature but show how such processes are structured.

Johansson (2007) has presented a design process for designing material supply systems that includes, amongst other system components, transport in internal logistics. The suggested process consists of four phases: planning, concept development, system-level design and detailed design. In the planning phase, requirements for the design should be identified and analysed, and objectives for the design set. In the concept development phase, different alternative conceptual designs should be developed based on the requirements and objectives in the planning phase. The conceptual designs should be compared with each other to identify the most suitable one. In the system-level design phase, the selected concept should also be designed from a holistic perspective, which involves defining the different material flows in the material supply system in which each flow consists of multiple areas such as transport, handling and packaging. In the last phase, detailed design, the details of the materials supply system are configured regarding, for example, the packaging design, storage areas and specific transport equipment for a material flow. The phases may not have strict boundaries but can overlap and require an iterative approach.

A design process for production systems has been presented by Wu (1994), who states that the first step is to set objectives for the design process and analyse the current situation including information about requirements. Wu (1994) also suggests that the existing system should be considered in designing the new system in order to facilitate the adoption of a realistic starting point. That step is followed by conceptual modelling and detailed design; whereas conceptual modelling entails developing a framework for the system and establishes basic principles for how it will work, detailed design involves preparing a detailed specification from the general framework in conceptual modelling that includes decisions about layout, manufacturing equipment and internal transport. Decisions about which choice to pursue in the design process should be made after conceptual modelling and consider the initial objectives set for the design process in the first step. Therein, alternative designs should be evaluated and discarded during the design process.

Tompkins et al. (2010) have suggested a six-step design process model for designing materials handling systems. Step 1 is defining objectives and the scope for the materials handling system to be designed, while step 2 is to analyse requirements for all parts of the materials handling (i.e. moving, storing, protecting and controlling material). In step 3, several design alternatives are developed that can meet the requirements identified in step 2. In Step 4, the alternatives are evaluated based on the established objectives, and in step 5, the preferred alternative for each of the parts is determined. Last, step 6 involves implementing the selected design, which entails installing the equipment and training employees. Tompkins et al. (2010) have also stated that the completed configuration may not initially operate perfectly but should be improved continuously to improve the operation of the material handling system.

The presented models have many similarities, including that they all begin with identifying and analysing the requirements that need to be considered in the design process and setting objectives to be achieved. Wu (1994) has suggested starting with an existing system in order identify a realistic starting point for the design process. The three design processes also suggest developing and evaluating several conceptual designs before advancing the most suitable one to the phase of more detailed design. Johansson (2007), Wu (1994) and Tompkins et al. (2010) include transport and transport vehicles are included amongst what needs to be designed, although those processes have far broader scopes than AGV systems. Because transport and transport equipment relate to other parts of the materials supply system, production system and material handling system, the other parts of those systems can impose requirements for the AGV system, for instance, the environment and characteristics of the transported loads as described in Section 2.2. Tompkins et al. (2010) have also indicated the need to educate and train employees in the final configuration of the design. Related to that, because an AGV system introduces many changes for operators, educating employees in new work procedures, routines and responsibilities is necessary for them to work efficiently with the AGV system.

3. Methodology

The method is presented in this section. Firstly, the research process for the PhD process so far is presented. The research design is presented in the second section. This is followed by a section on the methods applied in the appended papers. The final section of the chapter is a discussion on research quality.

3.1. Research process

The research presented in this thesis was performed as part of the Flexible Automation in Kitting, Transport and Assembly (FATKA) research project funded by the strategic innovation programme Produktion2030 via Vinnova. The project is a collaboration between Chalmers University of Technology and several industrial actors in Sweden. Some are users of automation technology applied in production and logistics processes, whereas others are developers of such technology, for example, robotics, conveyor systems and enabling equipment (e.g. grippers). Beyond that, another actor provides consultancy services especially for production and logistics firms. Because the FAKTA project focuses on kitting, transport and assembly, many of the industrial representatives are experts in internal logistics and/or production. The overall objective of the FAKTA project is to support the design of flexible, high-performing automated internal logistics systems. By extension, this thesis and the research conducted for it support the fulfilment of that objective by focusing on the automation of transport in internal logistics. Indeed, the case studies conducted in the studies performed for this thesis primarily examined the companies involved in the FAKTA project. The FAKTA project commenced in November 2019 and is scheduled to conclude in October 2022. The research process is illustrated in Figure 3.1, along with a timeline of the process, as can be seen in the figure, the author's doctoral studies began in February 2020, about three months after the start of FAKTA.

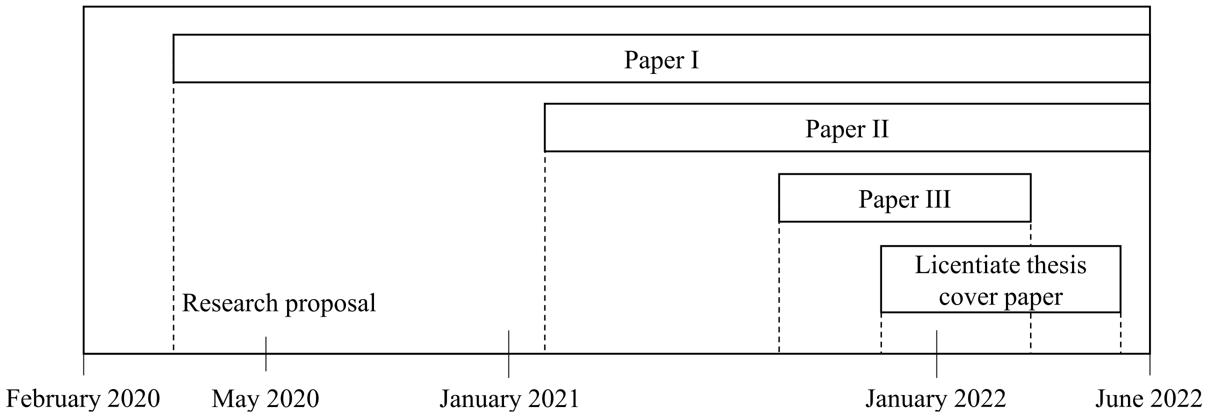


Figure 3.1. *Research process since the beginning of the author's doctoral study.*

3.2. Research design

This section describes the research design followed in the research for this thesis. Interacting with the industrial parties involved in the FAKTA project clarified their interest in AGV systems. Although some of the parties had introduced AGV systems, they had confronted issues related to, for example, organising the work and securing the system's acceptance amongst members of the organisation. It was clear that further knowledge on AGV systems could assist the industrial parties with their plans to utilise such systems in their internal logistics. Guided by that possibility, literature was also reviewed, and once the problems in the industry and the literature were assessed, a direction for the research could be determined.

Both qualitative and quantitative methods were used in the research conducted for the three papers. Papers I and III are based on case studies, whereas Paper II is based on simulation modelling real-world industrial material flow. Figure 3.2 shows the relationships between the papers and the thesis's research questions.

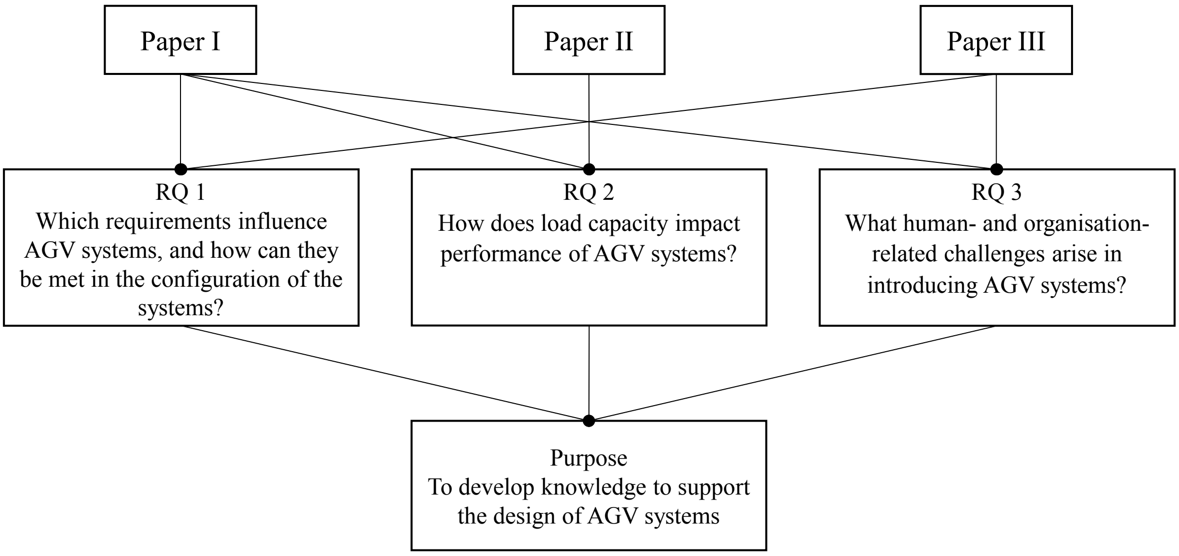


Figure 3.2. *How the three papers in this thesis contribute to answering the thesis's RQs and to fulfilling its overall purpose.*

In Paper I, a tentative framework was developed for sources of requirements from which requirements on the AGV system configuration can come from. Requirements for an AGV system configuration had in literature mostly dealt with specific requirements for a particular component as stated in chapter 1. This framework was then used to collect data and analyse three case to understand which requirements that influenced the design from each of the sources and then how the requirements were met in the configuration of the AGV systems. Paper I sought to understand which requirements influence AGV systems and how they influence on the AGV system configuration and a case study was considered to be appropriate for this aim since case studies can provide answers which requires relatively full understanding of the phenomenon (Voss et al., 2002).

The research for Paper III took a more explorative approach to investigating challenges in introducing AGVs related to humans and the organisation. Another strength of case research is their explorative power within investigations (Voss et al., 2002). Because human factor aspects and the organisation of work related to AGV systems had only seen limited research in the technical focus in research on AGV systems, conducting case studies was considered to be suitable to fulfil the more exploratory purpose of the research for Paper III. Performing case research for both Papers I and III was deemed to be appropriate owing to the method's power in analysing phenomena in real-world contexts (Yin, 2014).

For Paper II, a simulation study was conducted wherein different environments and design variables that can be important in modelling AGV systems and also performance measures were identified from the literature. Although past studies have not focused on how load capacity impacts the performance of AGV systems, reviewing those studies that involved modelling AGV systems allowed identifying parameters that could be used to model the material flow considered in Paper II. Simulation modelling allows testing changes or improvements without altering the existing system (Banks, 2010). Because there was no real-world industrial material flow in which different load capacities were tested or in which experiments with load capacity could be performed, developing a model allowed testing how performance was influence by using AGVs with different load capacities. As such, simulation was considered to be an appropriate method of analysing load capacity's impact on the performance of AGV systems.

3.3. Methods applied in the appended papers

This section presents the research methods applied in the three papers appended to this thesis. Papers I and III are based on case studies, while Paper II is based on simulation modelling that itself was based on a real-world industrial material flow. The following subsections detail the methods used and their application in the research for each of the papers in terms of case selection, data collection and analysis. For Paper III, a new case study on human- and organisation-related challenges in introducing AGV systems was performed on the same physical application of AGV systems studied in relation to their requirements in two of the cases in Paper I. Thus two separate case studies were performed in Paper I and Paper III. Despite the separate case studies, general data collected regarding the AGV system in Paper I was part of the basis for the case studies in Paper III. Table 3.1 offers an overview of the cases presented in both papers.

Table 3.1. *Main characteristics and environments for the cases in research conducted for Paper I and III*

Paper	Case	Short case description
Paper I	Case A	The AGV system is used in a manufacturing setting, wherein material is prepared for delivery to an assembly line. The system includes two AGVs that transport racks to and from a logistics supermarket. Which requirements stemming from four sources of requirements that influence AGV systems were investigated and how the requirements were met in the configuration.
	Case B	The AGV system is used in logistics to transport racks of material from an inbound flow to storage and from storage to an outbound destination. The system includes three AGVs. Same focus as in case A.
	Case C	The AGV system transports items from storage to several production cells as well as finished items to designated outbound areas. The system includes 17 AGVs. Same focus as in case A.
Paper III	Case D	The same, physical application of AGV system as in Case C, for instance, the same AGVs and material flows. The study focused on the organisation of work, the humans involved in operations and the challenges related to those aspects. Organisational structure, roles of different operators, routines and work procedures and the experiences of individual operators related to the HF aspects were studied.
	Case E	The same, physical application of AGV system as in Case A, for instance, the same AGVs and material flows. The same focus as in case D.

3.3.1. Methods applied in the research for Paper I

The aim of the research for Paper I was twofold: to provide an understanding of which requirements influence AGV systems and to propose guidelines for how those requirements can be met in the configuration of such systems. The framework developed for the paper consists of two parts: issues in the AGV system configuration and requirements that can influence such configurations. Paper I contributes to answering RQ 1 of the thesis. The work organisation and humans in the environment were highlighted as important in the paper. This served as input for the research for Paper III, which focused on the challenges related to those two.

Case selection

The research for Paper I was aimed at studying cases with different features and unique characteristics while still having similarities. One case had a relatively large fleet of AGVs, whereas the two other cases had fewer vehicles, and the environment in which the AGVs were used was in logistics in two cases but in manufacturing in the third. The unit loads moved by the AGV systems also differed between the cases; racks were moved in two cases and two types of pallets in the other. Unit loads with different characteristics and the environment in which AGV systems are used can pose requirements for the AGV system in different ways. The degree of interaction between the AGV system and the humans involved also varied between the cases. As for their similarities, the load-carrying mechanism was forklifts in all three cases, and all of the cases involved using virtual guidepaths for navigation. Even so, the guidance technology in two cases used natural features for navigating, whereas the other used laser-based guidance with reflectors. Taken together, those differences and similarities between the cases allowed identifying, comparing and understanding a large number and variety of requirements and, in turn, how they may influence and be met in the configuration of AGV systems. The cases for the studies were thus considered to be appropriate to fulfilling the overall purpose of the research for Paper I.

Data collection

The framework was developed before any data were collected by reviewing literature. As mentioned, the framework consisted of two parts. The first part was design issues of AGV systems. The second part of the theoretical framework was identifying sources of requirements from where requirements for the configuration of the AGV system could stem from. From the framework, a structure for data collection was created, for example by creating interview guides for the interviews.

Once the framework was finalised, data were collected via semi-structured interviews, some conducted in person but most conducted online using Zoom and Microsoft Teams since this was during the COVID-19 pandemic and the companies did not allow visits. The interviews were semi-structured. Semi-structured interviews allow interviewers to follow up on topics addressed and interviewees to raise new issues. In the cases studied, project managers involved in the design of the AGV systems were interviewed. An interview guide was created based on the theoretical framework, as mentioned, and followed during the interviews. Before each interview, the interview guide was sent to the interviewees to allow them to review the questions in advance. The approach helped in performing the interviews so that the interviewers could acknowledge that all questions and topics in the interview guide were covered. Each interviewee consented to having the interview audio-recorded as a means to allow the later review of the interview's content. All of the researchers were present during all interviews. In general, that strategy increases the likelihood that all interviews proceed according to a common approach, which is important when multiple cases are being studied that involve multiple interviews (Voss et al., 2002)

Data were also collected during site visits involving the direct observation of the AGV systems in operation in two of the three cases. During each site visit, a guide explained the different components of the AGV system being observed. During the guided tours informal conversations with employees in various roles (e.g. logistics operators, team leaders and technical specialists) allowed gathering their perspectives on the AGV system for example regarding safety and experiences with working with the AGVs. Notes were taken during the guided tours, and any lingering questions were asked to the guide. In one case, however, site visits were prohibited during the pandemic. As an alternative, additional attention was paid to how AGV system's operation in the online interviews, and the project managers of the system presented photographs from the shop floor as well as drawings of the system's layout and guidepaths in the environment. They detailed the system's operation to afford a good understanding of the flow of the AGVs and the operations in lieu of a site visit.

To supplement the primary data, secondary data were collected in the form of internal reports, organisational charts, work routines and educational material for the operators. Such documents showed the different ways in which AGVs and humans interact and how their procedures and routines have changed in response to the AGV system's interaction with the environment.

Following primary data collection via semi-structured interviews, site visits and documents, case descriptions capturing the identified requirements of AGV systems and their influence on the AGV system's configuration in each case were created from the compiled data. The case descriptions were sent to the respective case companies to verify that the data collected had been correctly understood.

Analysis

The analysis for Paper I was performed in two stages: a within-case analysis and a cross-case analysis. In the within-case analysis, the cases were analysed individually on how requirements influence each component in the AGV system. Subsequently, the cross-case analysis of all three cases focused on comparing the requirements of the AGV systems, particularly their similarities and differences in and of themselves as well as the similarities and differences in how they were being met in each AGV system's configuration. From the analysis, tentative design guidelines were derived that connecting the identified requirements to the AGV system's configuration and showed how the requirements were being managed in the cases.

Once written, Paper I was presented at the 2020 *PLANs forsknings- och tillämpningskonferens*, and comments on the paper's findings were received. The paper was also presented to the industrial parties in the FAKTA project and their feedback received as well.

3.3.2. Methods applied in the research for Paper II

The purpose of the research for Paper II was to identify how load capacity impacts the performance of AGV systems. To that purpose, three performance measures were analysed: mean tardiness, AGV utilisation and load capacity utilisation. A cost model was also developed to summarise the total investment and operational costs and thereby compare the impact of load capacity from a cost perspective. Paper II contributes to answering RQ 2 of the thesis.

Data collection

A real-world industrial material flow was the basis for the simulation model in Paper II regarding deliveries of EUR pallets from a single storage point to several kitting, sequencing and supermarket locations in connection with an assembly line. To create the model, data were collected from the real-world case material flow. Drawings of the factory's layout and the routes of the carriers in the material flow were collected from the company, including the positions of the delivery locations and the distances in the layout. The historical transport demand for the material flow was also collected; for each of the delivery locations, such data included the times when requests were made and fulfilled. Beyond that, to observe the material flow in operation, a site visit was performed that was guided by an expert (i.e. the company's expert on the factory's internal transport and the studied material flow) who explained the flow in detail. In parallel, a cost model was developed to compare alternative AGV systems with varying load capacity in relation to investment and operational costs. The costs for the model were collected by interviewing an internal logistics expert from one of the industrial parties in the FAKTA project who has worked with AGV systems for many years. The data collected included the investment cost for the AGVs, both single-load vehicles and an AGV tugger for the multiload solutions. Also included in the data were costs for charging stations and the number of charging stations needed per vehicle, based on previous investments that the industrial party had made. Meanwhile, operational costs for AGVs were derived from the literature.

Model implementation
The route of the carriers was created in the simulation software to represent the distances in the real-world case. The localisation of the starting point and the delivery locations along the route were also implemented in the model to represent the real-world material flow. The data collected regarding transport demand were fitted to statistical distributions that were later implemented in the model to generate transport requests. Therein, each delivery location was assigned its own statistical distribution in order to generate transport requests for the location. Next, a dispatching algorithm was developed to determine when to initiate a delivery; the algorithm was explained to the material flow expert in the case and found to be an appropriate method of dispatching the AGVs in the model.

The impact of load capacity on the AGV system's performance was studied in terms of mean tardiness, AGV utilisation and load capacity utilisation. Those three factors were identified from the literature as being important for load capacity's effects on the performance of AGV systems. In the simulation, five environment- and design-related variables were set to vary between two levels, except for load capacity, which had four levels. In addition to the load capacity, the variables were production rate, traffic interference, strictness of time windows and AGV speed. The levels for each variable were determined in discussions with the expert of the material flow at the company while the variables themselves were derived from the literature. The load capacity of the AGVs was also varied to identify the minimum required fleet size for a particular load capacity for each combination of the variables.

In the simulation, 352 experiments were run, each with 10 replications, for a total of 3520 runs. The period for each run was set to 6 months of daytime shifts. Day time shifts were the basis for the transport demand mentioned in the previous subsection. The principal performance variable was mean tardiness, which was used to determine a minimum fleet size for a particular load capacity. Added to that, AGV utilisation and load capacity utilisation served as operational performance measures used to analyse the load capacity in greater detail. Assumptions and simplifications regarding the material flow made in the model were discussed with the expert at the company along with members of the FAKTA project group who work with simulation and AGV systems. Further details on the model's development appear in Paper II.

Analysis
Mean tardiness was used to identify viable alternatives regarding load capacity and fleet size. To qualify as a viable alternative, a mean tardiness of less than 0.5 seconds should be achieved by a combination of load capacity and fleet size. The required tardiness value was determined in discussion with the expert. Using that threshold value, a minimum fleet size could be identified for each alternative load capacity, which was done for all of the environment and design variables set to vary in the experiments. The minimum fleet size for different load capacities were compared within one setting of the variables and also between variables to see the effect of the variables. Next, the minimum fleet size for each load capacity was analysed in relation to AGV utilisation and load capacity utilisation, and the effect of the environment and

design variables were analysed as well. The final step of the analysis involved developing a cost model to compare the alternatives in terms of an annual cost. The model, consisting of both investment costs for AGVs and for the carts pulled by them as well as operational costs relating to the total travel time, was used to evaluate the minimum fleet sizes from the analysis of operational performance.

Paper II was presented to the FAKTA project group on two occasions: one chiefly addressing simulation-related issues and the other to present a draft version of the paper. During both presentations, the industrial parties were invited to provide feedback and comments on the paper, the implementation of the simulation model and its results. The feedback from those presentations was used to further develop the simulation model and the paper.

3.3.3. Methods applied in the research for Paper III

The aim of the research for Paper III was to explore human- and organisation-related challenges in the introduction of AGVs in production organisations. The paper thus contributes primarily to answering RQ 3 of the thesis and, in a secondary way, to answering RQ 1, namely by indicating the need to include requirements related to HF aspects in the design of AGV systems.

The theoretical framework for Paper III was based on the human, technology and organisation (HTO) model (Karltun et al., 2017), developed to analyse the interaction between the three (i.e. humans, technology and the organisation). To apply the HTO model, each subsystem has to be defined for the phenomenon being studied; thus, the subsystems were defined based on the literature in order to explore challenges in introducing AGVs. The HTO model was applied in a multiple-case study on challenges in the interaction between the AGVs and humans, between the organisation and the AGVs and, finally, between all three subsystems.

Case selection

For the research for Paper III, two cases were studied to allow both breadth in exploring challenges in multiple cases while at once allowing each case to be studied in depth. As stated in Table 3.1, the same physical applications of AGV systems in Paper I were the focus of the case study in Paper III. The cases complemented each other in ways (e.g. the size of the AGV fleets introduced) that contributed to fulfilling that purpose. Two AGVs were introduced in one case and 17 in the other, and the varying scope of introducing the vehicles was expected to influence challenges. For example, a larger fleet used meant that most traffic in the manufacturing was AGV traffic which could impact the acceptance of AGVs among the human operators because it entailed a significant change from the established working conditions. In the case in which only two AGVs were introduced, the change from the established state without AGVs was expected to be smaller and potentially easier to acclimate to and thus accept. The scope of introduction can also affect challenges in the work tasks for various employee roles in the facility (e.g. with the division of responsibility for work tasks). For instance, the task of failure management may change because a larger fleet requires the monitoring and maintenance of more vehicles.

Data collection

A similar approach to the data collection in Paper I was followed in Paper III. The data collection was performed at a time when the AGVs were in steady state in the operations, i.e., the introduction was finished. Interviews comprised the main body of the data collection. In this paper, interviews with operators, project managers, team leaders, and production support employees including AGV superusers and production technician were performed. An AGV superuser is a team leader for a group of operators but has additional received education to be able to manage AGV failures and thus has additional responsibilities to ensure that the AGVs are in operation. These employee roles were significantly affected by the introduction of the AGV system. They are involved in the daily operation of the AGV system and/or were involved during the introduction. The relevance of these roles for the purpose of the study was confirmed by the case companies.

To structure the interviews and ensure that the same topics and questions were addressed in all interviews, an interview guide was created and sent to the interviewees before the interviews to allow them to review the questions in advance. For Paper III, the questions asked in interviews referred to the HTO model, and each of the subsystems (i.e. H, T and O). Questions in each subsystem were developed that would allow exploring human- and organisation-related challenges in introducing AGVs.

Site visits were also conducted for the cases to observe the AGV system in operation, how the AGVs interact with operators and how operators support the system. During the visits, an expert on each the AGV system explained the material flow, the AGV system and the system's interactions with the operators.

The final source of data was company documents describing the AGV processes, work tasks for different operators and the responsibilities and authority of different roles in relation to the AGV system. Educational material and documents indicating what different roles are required to know regarding the AGV system were collected as well. After the case data were collected, case descriptions were sent to the respective companies to verify that the information had been understood correctly.

Analysis

The HTO model was used to analyse the collected data, with each subsystem (i.e. H, T and O) consisting of multiple aspects. The analysis focused on the interaction between the subsystems of the model and challenges in introducing AGVs related to the interactions between AGVs and humans, between AGVs and the organisation and between all three subsystems simultaneously. To that end, the aspects of humans (HF aspects), the technology (i.e. AGVs) and the organisation structured the analysis, and it was possible to identify and understand the challenges related to each kind of interaction in the two cases as well as compare between the cases. Because the focus of the research for Paper III was to explore human- and organisation-related challenges with introducing AGVs, the interaction between humans and the organisation, which is independent of the AGVs in Paper III, was beyond the research's scope. Paper III was also presented to the industrial parties in the FAKTA project.

3.4. Research quality

Of the different criteria that can be used to assess research quality, this thesis adopts Yin's (2014) four criteria, construct validity, internal validity, external validity and reliability, each of which is addressed in one of the following subsections in relation to the research conducted. Because the research for Paper II involved a simulation study, criteria relating specifically to the quality of simulation were used to complement Yin's (2014) criteria. Following Bank's (2010) recommendation, model verification and validation are important, and are addressed in section 3.4.5.

3.4.1. Construct validity

Construct validity, defined as "identifying correct operational measures for the concepts being studied", can be challenging in case research (Yin, 2014). Multiple sources of evidence that converge, support construct validity. Establishing a chain of evidence that ensures the traceability of data over time and that no evidence is lost is another way to improve construct validity. Having key informants review draft case-study reports also supports construct validity.

As concerns construct validity, Papers I and III are based on multiple sources of data, namely interviews, direct observation and internal documents as stated in subsections 3.3.1 and 3.3.3. Because triangulation using multiple sources of data can strengthen construct validity (Voss et al., 2002), using the three sources of data provided opportunities for triangulation by comparing the data collected from the various sources. The case descriptions created from three sources of data were emailed to the key informants, and any comments received on the case descriptions were used to refine the descriptions.

By contrast, Paper II is largely based on archival data of historical transport requests and drawings of the layout, including the measurements and the localisation of pick-up and delivery points. Interviews with the material flow expert and direct observations during a site visit during which the expert answered questions were also performed to ensure that the material flow was understood correctly. Triangulation with multiple sources of data was utilised in the research for Paper II as well. The model's development and its results were discussed on several occasions with the expert involved in the case and with industrial parties involved in the FAKTA project.

As a final means to ensure construct validity, before the papers were finalised the results of all three papers were presented to the industrial parties involved in the FAKTA project, who were invited to comment on the results as a means to further improve the papers.

3.4.2. Internal validity

Internal validity refers to "the extent to which causal relationships can be established whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships" (Voss et al., 2002).

Whenever an event cannot be directly observed in case research, an inference is made, and those inferences have to be correct in order for the results to achieve internal validity (Yin, 2014). In the research for Papers I and III, the processes of designing and introducing the AGV systems had already been completed by the time of data collection, meaning that direct observation of either process was not possible. Thus, Papers I and III rely on inferences made about events that could not be directly observed, but through the interviews, observations and internal documents the findings could be distinguished from spurious relationships. Voss et al. (2002) have posited that cross-case analysis can improve internal validity by countering conclusions made based on limited data. A cross-case analysis was performed for Paper I, and although no cross-case analysis was conducted for Paper III, the two cases were compared, which could support internal validity to some extent. In Paper II, the expert on the material flow was contacted on several occasions during the model's development via email and Teams meetings to ensure that the model was correctly developed and to follow up on any lingering questions regarding the data. That strategy ensured that the material flow in the simulation followed the same logic as the real-world material flow.

3.4.3. External validity

According to Yin (2014), external validity refers to whether a case study's results are generalisable to other cases. Although attaining external validity can be problematic in case research, especially in single-case studies, it can be improved by studying multiple cases (Voss et al., 2002). Beyond that, because case research relies not on statistical generalisation but on analytical generalisation (Yin, 2014), external validity can be achieved by using replication logic, for example, by finding similar results in additional cases or by comparing the results with findings in the literature. Along those lines, because the research for Papers I and III involved multiple cases, three and two cases, respectively, this could improve external validity. Moreover, the results of the papers were compared with findings in the literature, which also improved their external validity.

For Paper II, a simulation model was developed for a real-world industrial material flow. That strategy strengthened the external validity versus basing the model on a non-real-world flow because it captured the difficulties of a material flow implemented in practice. Similar settings could be found at other companies and factories and the results applicable there as well. Furthermore, performance measures and environment- and design-related variables were based on the literature. The levels of the variables in the experiments were also agreed upon with the material flow expert as being appropriate for the real-world material flow.

3.4.4. Reliability

Yin (2014) has defined reliability as "demonstrating that the operations of a study, such as the data collection procedure, can be repeated, with the same results". To ensure reliability, following study protocols and maintaining a database for the research are recommended (Yin, 2014), for they allow careful documentation of the process and the collected data. For the research in Papers I and III, a database was created to store all interview-related material, notes from direct observations, internal documents and the case descriptions derived from the data. A protocol for data collection was developed and followed in each case. Voss et al. (2002) have stated that the reliability of data can be improved if multiple sources of data are used when studying a single phenomenon, and multiple sources of data are indeed used in all three papers.

When studying multiple cases, it is important to follow the same approach in each case. If interviews are conducted, for example, then the reliability can be improved by having multiple interviewers present, which increases the likelihood that a common approach is followed in all interviews in all cases (Voss et al., 2002). Having multiple interviewers can also reduce the risk that personal biases will influence how the data are interpreted. In the research for Papers I and III, the first author and at least one of the co-authors were involved in the interviews and the site visits, which further improved the reliability of the research.

For Paper II, a database was created for the archival data and the drawings of the material flow. The material flow that was modelled is described in the paper so that it can be replicated in future research in terms of layout, the assumptions and simplifications made, and the dispatching rule developed. Although data representing the transport demand cannot be shared due to confidentiality, the data are described so that future researchers can collect the same sort of data again.

3.4.5. Model verification and validation for Paper II

The purpose of model verification is to make sure that the model is accurately implemented in the simulation software, for example whether assumptions and simplifications are accurately represented in the model (Banks, 2010).

The author of the thesis had gained basic experience with discrete event simulation before commencing the research for Paper II but had never developed a model of the same scope before. By iteratively improving the model one step at a time (e.g. adding one piece of functionality, testing it and revising the functionality if it fails to provide the expected results), the simulation model was developed. One of the co-authors of Paper II with extensive experience in working with discrete event simulation supported the model's development by discussing and providing input regarding the model. The model was also discussed with the expert of the material flow and was verified by reviewing its functionality with the expert and another expert in simulation from the FAKTA project on several occasions. Animations in the simulation model were also used to visually determine whether the model was behaving in the expected way. Altogether, the iterative way in which the model was developed, combined with support from the co-author with experience in simulation and the two experts, ensured that the model was developed in an appropriate way and could thus be verified.

In contrast to model verification, validating a model involves ensuring that the model represents the modelled system. As an aspect of model validation, face validity concerns whether the model appears to behave in a reasonable way for someone who is knowledgeable about the real-world flow (Banks, 2010). Thus, the model's face validity was discussed with the material flow expert, and its assumptions and simplifications were agreed upon. As mentioned, the results of the simulation experiments were also presented and discussed with the material flow expert and found to be reasonable.

4. Results

This chapter describes the results of the thesis and presents answers to each of its three research questions.

4.1. Which requirements influence AGV systems and how can these be met in the AGV system configuration?

This section answers to RQ 1 of the thesis, focusing on the requirements that influence the design of AGV systems. Paper I is the main contributor to answering RQ 1, but Paper III complements the findings from Paper I.

In Paper I, design area is the term used to denote what is in the cover paper called AGV system components. Operator training and instructions was a design area in the paper, whereas in the cover paper, this is considered to be part of the work organisation dimension of the components. Furthermore, whereas AGV organisation is suggested as an addition to the design areas in the paper, the work organisation is a dimension of the components in the cover paper. Such reworking was performed to better accommodate the results from all three papers in the thesis.

In Paper I, the source of requirement “integration with existing systems” consisted of technical integration requirements such as IT systems and interoperability as well as requirements due to the integration of manual operations and AGVs in the environment. In the cover paper, this is separated into two sources of requirements as presented in Table 2.1, technical interoperability and integration of humans and AGVs. This human-related integration is the same as it was in Paper I with the addition of the HF aspects from Paper III. HF aspects were not directly studied in Paper I, but several requirements from the integration of humans and AGVs could impact the HF aspects. The HF aspects from Paper III were thus added to the sources of requirements in Table 2.1 in the cover paper.

The following subsections present the requirements from each of the five sources of requirements listed in Table 2.1, internal logistics environment, characteristics of transported loads, technical interoperability, performance and integration of humans and AGVs, are explained and how they influence the configuration of AGV systems.

4.1.1. Internal logistics environment

There are requirements that come from the physical constraints of the internal logistics environment, narrow aisles, limited area in the facility, pick-up and delivery localisation which put requirements on the AGV system configuration.

Creating guidepaths to limit the interaction of AGVs with other traffic in the environment may be needed. For example, in Case A in Paper I, the interaction between the AGVs and tugger trains needed to be eliminated because the aisles were too narrow for passing and overtaking, and neither the AGVs nor the tugger trains were able to move in reverse. Here there is interplay between the requirements from the internal logistics environment and the integration of humans and AGVs. Control zones can be utilised in narrow aisles in order to control AGV-AGV interactions. Sharp corners force AGVs to decelerate and reducing them in guidepaths can improve their speed. However, constraints in the environment can limit the possibilities to reduce the sharp corners. The limited availability of free space influences the localisation of idle vehicle positions and battery-charging facilities, which could not always be placed in ideal locations in all of the studied cases.

Requirements from the internal logistics environment influence the guidance technology as well. Features of the layout such as racking and delivery locations change frequently, and the guidance technology for AGVs has to be flexible in order to accommodate such changes with adjustments that do not require significant effort. From the other direction, the guidance technology places requirements on the internal logistics environment as well. As in Case B in Paper I, the AGVs were not capable of navigating certain parts of the layout due to the lack of unique features in the layout that AGVs use to navigate. In such ways, the internal logistics environment put requirements on the choice of guidance technology, and the guidance technology in turn put requirement on the internal logistics environment.

Meanwhile, the pick-up and delivery locations place requirements on the load-carrying mechanism. Differences in the layout of the production cells that the AGV system deliver material to, as in Case C in Paper I, created a requirement for using forklift AGVs of two different lengths of the forks because only AGVs equipped with long forks could complete missions for certain production cells. In turn, having two different load-carrying mechanisms imposes requirements on the control of the AGV system because the AGVs cannot be freely assigned to all missions, which reduces flexibility. Thus, multiple different AGVs for example, different load-carrying mechanisms imposes requirements and constraints on the other components of the AGV system.

As a source of variation in the demand for transport, production planning can additionally impose requirements on the control AGV system. This is also exemplified in Case C, in which the transport demand for the AGV system varied significantly because batches began and ended in different production cells at the same time. Planning production in such a way that increases the evenness of demand for the transport could positively influence the performance of AGVs as well as reduce the need for excess capacity and thereby reduce the fleet size required.

4.1.2. Characteristics of transported loads

Requirements relating to the characteristics of the transported loads include the general dimensions and weight of the loads as well as the compatibility between the AGV and the load. Furthermore, considering using the same AGV for different material flows and the mix of unit loads relate to this source of requirements.

Characteristics of transported loads related to their dimensions and weight primarily affect the load-carrying mechanism of the AGV system components. In addition to whether the AGVs can physically pick up and transport loads, the compatibility between the load and the AGV may impose requirements as well. For example, in Case B in Paper I, the navigational sensors of the AGVs were partly blocked by the unit load when loaded, which created the risk that the AGV would lose track of its position in the facility and consequently require manual intervention to be restarted.

When designing an AGV system, potential future material flows for the system should be taken into consideration. The choice of load-carrying mechanism, for example, should be made so that the AGVs can be used in other material flows as well. Such accommodations were made in Case A, and can allow the same AGVs to be used in various material flows and to collaborate between the flows, thereby making the AGV system more flexible and not limiting AGVs to certain flows due to their load-carrying mechanism.

The results of Paper I show that the AGV system's configuration is additionally influenced by the mix of unit loads, which consequently place requirements on the system. Although the unit load may have the same dimensions, other aspects of the physical configuration of the unit load can impose requirements on and influence the AGV system's configuration. In Case C in Paper I, two half pallets with slightly different physical configurations were being used, which caused issues for detecting the different pallets for the AGVs. To manage the difference in the half pallets, the load transfer positions where both types of pallets were handled required a special configuration to ensure the detection of both types of pallets.

4.1.3. Technical interoperability

Interoperability between AGVs in the AGV system can also place requirements on the system's configuration in situations when not all AGVs are the same. In Case C in Paper I, 17 AGVs purchased at different times were being used. Between purchases of AGVs, new versions of the same model had been developed however, meaning that several generations of the same model of AGV with different sensor localisation and functionality were being used, all of which need to be interoperable. Adjustments in the environment were necessary to accommodate for the difference in sensor localisation to ensure that the AGVs detect the features of the environment in the same way. Meanwhile, functionalities in the software had to be adjusted so that the AGVs, regardless of generation, would behave in the same way. That situation shows how interoperability-related requirements can influence the AGV system's configuration, even when the same model of AGV from the same supplier is used.

4.1.4. Performance requirements

To meet performance-related requirements in terms of completing transport requests on time, excess capacity can help with managing variation due to fluctuating demand and interactions between manual and automated systems (e.g. the blocking of aisles). Even though excess capacity in terms of a larger fleet size can mitigate some of the effects of variation, it may be insufficient when the AGV system is overloaded with requests, which can result in tardy deliveries. It can also be expensive to invest in a large number of AGVs, and requirements related to cost may limit possibilities to increase the fleet size. Furthermore, using more vehicles increases traffic and thus potentially increases variation in transport time. Ideally, variation in the system should thus be reduced, for instance, via better traffic solutions with unidirectional traffic, as in Case A in Paper I (see section 4.1.5) or improved production planning to reduce the variations as suggested in 4.1.1.

Another performance-related requirement concerns the downtime and reliability of the AGV system. Efficient failure management involving operators and/or team leaders is required to eliminate excessive downtime (see section 4.1.5).

4.1.5. Integration of humans and AGVs

Requirements for integration of humans and AGVs stem from considerations of safety, the need for changes in work procedures as well as the creation of new procedures to enhance the efficiency of manual and AGV operations.

Interactions between AGVs and forklifts create requirements that influence the AGV system's configuration when AGVs are introduced into an existing internal logistics system. Safety considerations pose requirements that influence the AGV system's components. Modifying guidepaths for both manual and AGV operations can facilitate the integration of different modes of traffic, for example, by separating the picking aisles and the transport aisles, to create a smooth flow for both AGVs and other vehicles and to reduce the risk of accidents, as was performed in Case B. New traffic routines are also needed. An AGV system automatically performs transports of loads and can perform loading and unloading automatically as well depending on the load-carrying mechanism. The integration of humans and AGVs also requires that other work procedures in the manually performed material flow where an AGV system is to be used for, to be assigned to other employees.

Ensuring the reliability and reducing downtime of the AGVs in the system requires developing new work procedures, routines and responsibilities for different employees related to failure management, which creates another interaction between the AGV system and the operators. For the AGV system to work efficiently, it is necessary to educate the operators on the new work procedures and routines as well as to develop their understanding of the AGV system.

In addition to creating new work procedures, responsibilities and routines specifically for the AGV system, the integration of humans and AGVs requires adjustments to the existing organisation of work, including changes in the traffic rules and developing operators' understanding of how to behave when working together with an AGV in the work environment. In Case A in Paper I, the requirements due to integration related to traffic were partly managed by making nearly all aisles unidirectional, simplifying the traffic flows in the facility and reducing variation in travel times. Beyond that, all items, equipment and tools are strictly required to be placed in their assigned areas when not in use to prevent the AGVs from detecting and stopping for an out-of-place object.

Last, there are also requirements related to the integration of humans and AGVs when unit loads are delivered to the AGV system by manual operators. The AGV system requires loads to be accurately placed in predetermined pick-up positions or else loads cannot be picked up by the AGVs. Guiderails installed at the load transfer positions can facilitate the placement of loads for manual operators given the difficulty of consistently placing unit loads with accuracy. In all the cases in Paper I, the use of guide rails resulted from matching the operators' capabilities with the accuracy required by the AGV in transferring loads.

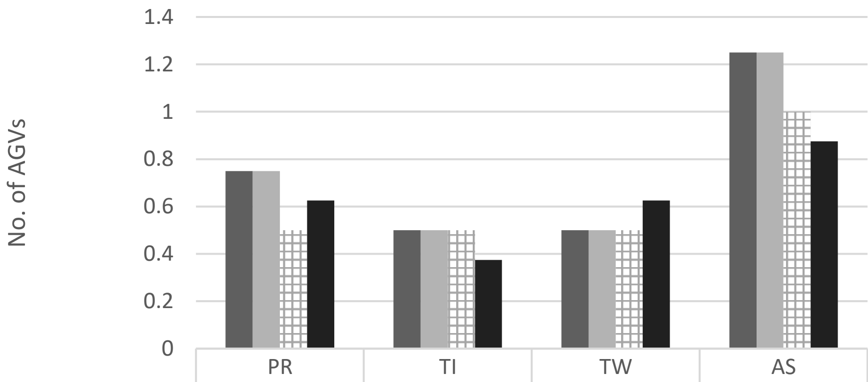
4.2. How does load capacity impact the performance of AGV systems?

This section presents the results from Paper II, which deals directly with RQ 2 concerning how load capacity impacts an AGV system's performance. Added to that, Paper I makes a partial contribution to answering RQ 2 because the sources of requirements discussed therein provided a starting point for determining environment- and design-related variables as well as performance measures that are important to include when modelling an AGV system. As shown in Paper II, four environment- and design-related variables, each with two levels, were set to vary in the simulation-based experiments along with the load capacity of the AGVs. The figures in this section use the following abbreviations to denote those variables (i.e. the analysis settings): production rate (PR), traffic interference (TI), strictness of time windows (TW) and AGV speed (AS). This section describes the major results concerning the minimum fleet size and the cost model. Further details concerning AGV utilisation and load capacity utilisation appear in appended Paper II.

4.2.1. The impact of load capacity on the minimum fleet size

Mean tardiness, referring to the average time by which deliveries are delayed, reflects how well the AGV system can meet its delivery requirements. In that context, an on-time delivery has a tardiness of 0. Figure 4.1 shows the minimum fleet size needed for achieving a mean tardiness of less than 0.5 seconds with each mode of load capacity considering the relative effects of each analysis setting. The relative difference is calculated by taking the effect on the high level and subtracting the effect on the low level for each factor and mode of load capacity.

As the relative effects in Figure 4.1 show, AGV systems with low load capacity of 1 and 2 are affected more by changes in the rate of production. A load capacity of 4, meanwhile, is more sensitive to such changes than a load capacity of 3. Such a difference indicates a trade-off between higher delivery frequencies enabled by a smaller load capacity and the ability to carry more loads on a single trip due to a larger load capacity.



	PR	TI	TW	AS
Load capacity 1	0.75	0.5	0.5	1.25
Load capacity 2	0.75	0.5	0.5	1.25
Load capacity 3	0.5	0.5	0.5	1
Load capacity 4	0.625	0.375	0.625	0.875

Figure 4.1. *Relative effects (difference between the effect at high and low level) of the environment and design variables on the minimum fleet size for the four load capacity modes.*

Traffic interference lengthens transport times, thereby making it more difficult for larger load capacities to utilise their full capacity. Reducing the fleet size by one AGV when the load capacity is 4 significantly changes total available capacity and, in some situations, reducing traffic interference may preclude reducing the fleet size while still achieving the required mean tardiness with a load capacity of 4. Thus, traffic interference's effect when the load capacity is 4 is less than for the other modes of load capacity.

As for the effect of time windows with stricter time windows, vehicles cannot wait as long to fill the available load capacity, thereby reducing the load capacity utilisation and making the additional capacity offered by the higher load capacity alternatives less useful. Therefore, to accommodate stricter time windows or higher rates of production, larger fleets of AGVs with small load capacities may be preferable given their capacity for more frequent deliveries.

Concerning AGV speed, load capacities of 1 and 2 benefit more from higher speeds (i.e. 1.25 fewer AGVs required) than higher capacities (i.e. 0.875 fewer AGVs required with a load capacity of 4). The average distance per completed delivery request associated with the lower load capacities is longer, especially for a capacity of 1, whereby increased speed has a stronger impact. Higher AGV speeds can allow larger load capacities to be used even amidst strict time windows or high production rates, because higher speeds reduce the transport time and thus allow the AGVs to better utilise their load capacity.

Figure 4.2 shows the absolute effects on the minimum fleet size in the studied material flow, which varies considerably under varying analysis settings. Between two to six vehicles are needed to meet the requirement, and the fleet size generally increases with more demanding analysis settings in terms of higher production rates, more traffic interference, stricter time windows and slower speeds. Although alternatives with less load capacity generally seem to require a larger fleet, the difference between any of the levels of load capacity under any given analysis setting is never more than two AGVs. Thus, this indicates that the number of AGVs required in the fleet to meet the tardiness requirement is not solely determined by the load capacity of the individual vehicles.

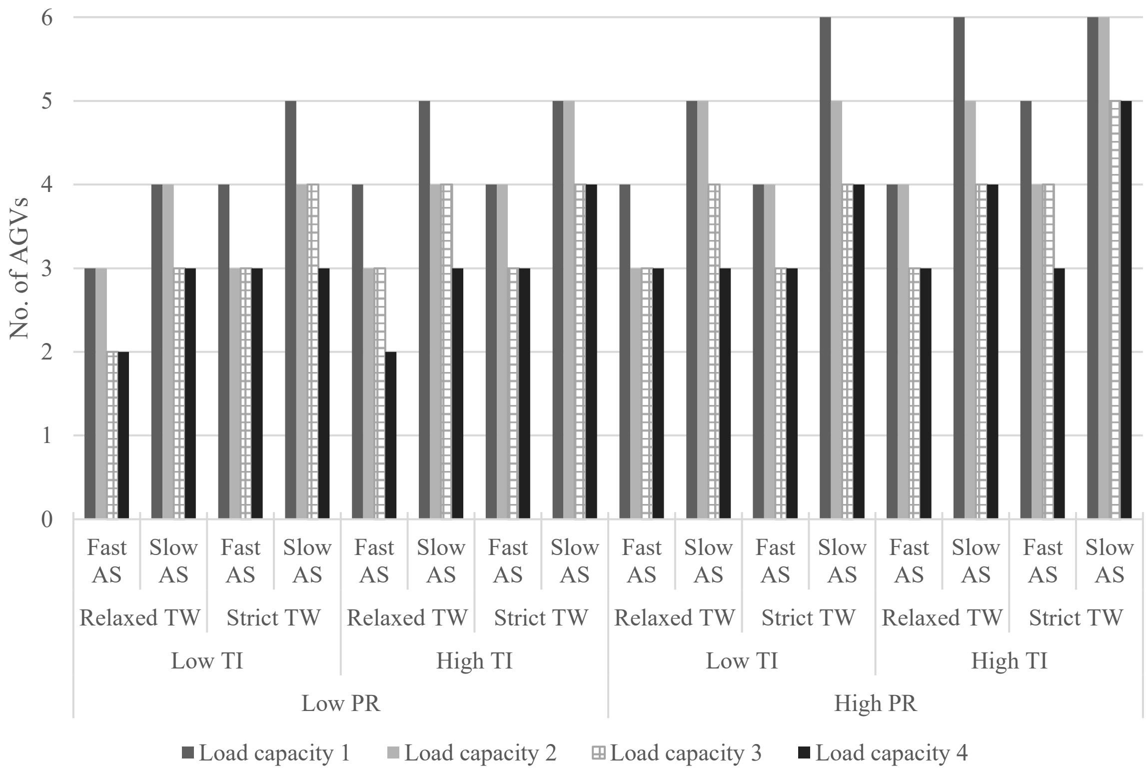


Figure 4.2. *Minimum fleet size for different modes of load capacity under different analysis settings.*

4.2.2. The impact of load capacity on costs

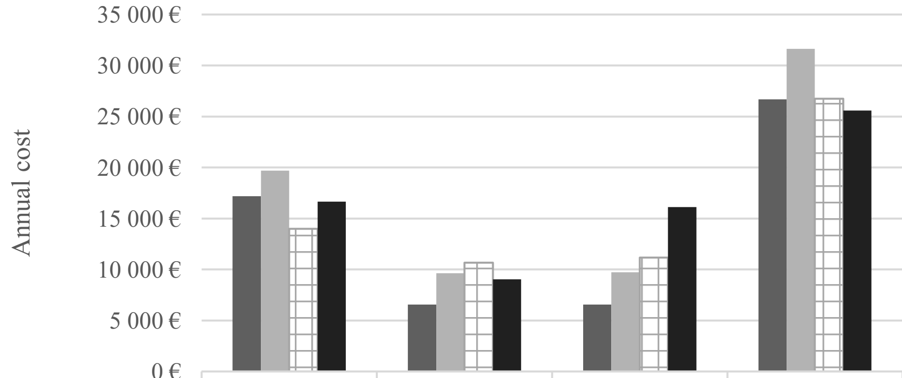
This section presents the results from the cost model in Paper II. The cost for the AGVs, the carts, the charging stations and an operational cost related to the travel time of the vehicles are included and presented as an annual cost. The cost for the AGVs is divided into the cost for AGVs with a load capacity of 1 and the cost for an AGV tugger (i.e. with a load capacity greater than 1). The relative effects with respect to total cost are shown in Figure 4.3.

Figure 4.3 shows that regarding production rate, none of the modes of load capacity offers a clear benefit weighed against the cost. That outcome may be due to a trade-off between more frequent deliveries, as associated with lower modes of load capacity, and being able to carry more loads per delivery tour, as associated with higher modes of load capacity.

With respect to traffic interference, the load capacity mode with the least impact is a load capacity of one. With a load capacity of one, the vehicles can take shorter routes through the plant, whereby they can avoid some of the traffic. Higher load capacities are impacted more, because the interference reduces the amount of time that the vehicles can wait, reducing the benefit of a large load capacity.

Considering time windows, modes with larger load capacity are more sensitive because they need more time per tour to complete all delivery requests. Moreover, because it is less costly to add carts instead of AGVs, greater load capacities become more cost-effective with relaxed time windows.

The AGV speed has the largest effect on the costs, as was expected given that speed is also the parameter with the largest relative effect on the minimum fleet size showing that investing in an AGV with higher speed can be valuable.



	PR	TI	TW	AS
Load capacity 1	17 192 €	6 565 €	6 548 €	26 684 €
Load capacity 2	19 703 €	9 632 €	9 712 €	31 623 €
Load capacity 3	13 976 €	10 681 €	11 181 €	26 745 €
Load capacity 4	16 656 €	9 026 €	16 126 €	25 571 €

Figure 4.3. *Relative effects of the analysis settings on the annual costs for the modes of load capacity.*

Figure 4.4 shows the absolute annual cost effects for each analysis setting. There are notable differences in annual cost between the AGV systems and between the settings. Under the strictest requirements, as represented in the right-most group of bars in Figure 4.4, the difference in annual cost is substantial (i.e. >50,000) compared with the left-most group of bars representing the most relaxed settings. The figure also shows that under most analysis setting, an AGV system with a load capacity of 2 is the costliest approach. At the same time, the differences between the costs associated with the various load capacities depend heavily on the analysis settings, for instance, the two left-most groups of bars show considerable differences even though nothing but speed has been changed.

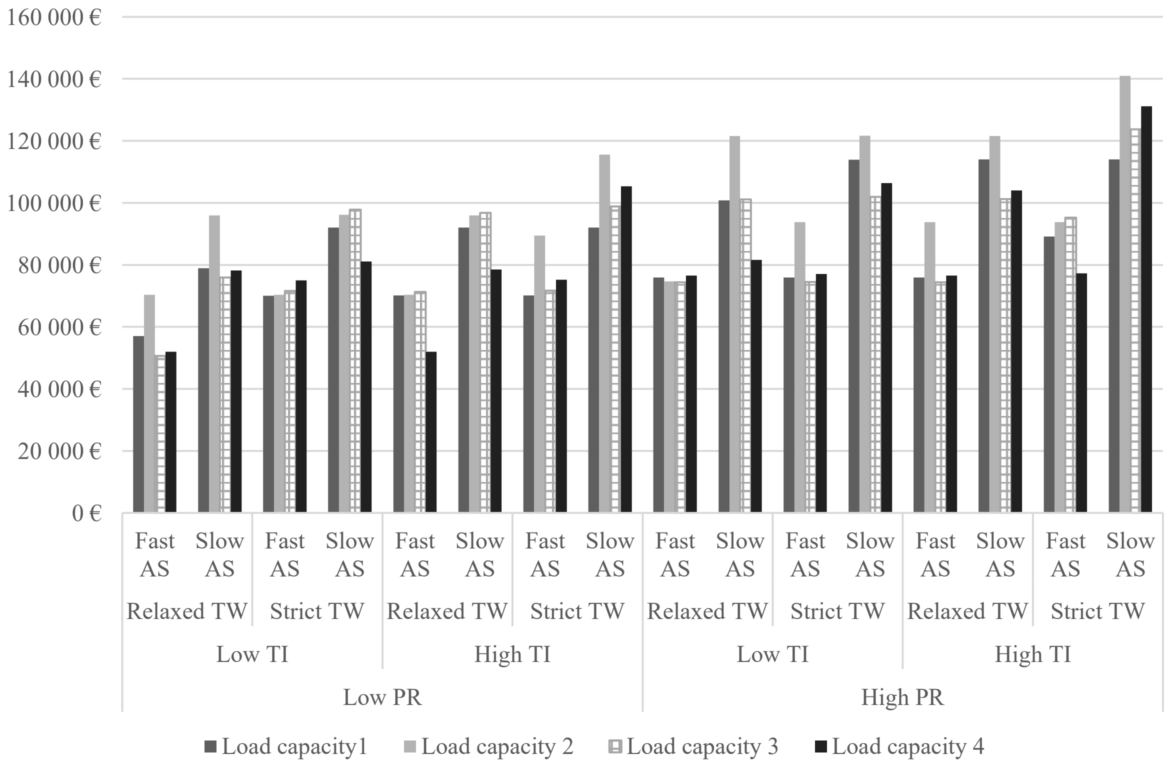


Figure 4.4. *Annual costs for different modes of load capacity under the analysis settings for the minimum fleet size.*

To summarise the results answering RQ 2, at the high level the time windows appear to favour a load capacity of 1, whereas at low level it seems to favour a load capacity such as 4. When production rate and time windows at the high level, a higher frequency of deliveries seems to be preferable to a larger load capacity. Reducing traffic interference benefits all modes of load capacity, while larger load capacities can utilise capacity better because more loads can be assigned to the AGVs during dispatching since less time lost due to interference during transport. Of all analysis settings, AGV speed has the greatest effect on the performance of the variables. Faster speeds can greatly reduce the costs of AGV systems with all types of load capacities, as seen in Figure 4.3, and can make using a load capacity of 4, for example, beneficial even when the time windows are strict. Under some analysis settings, there is no clear difference between the different load capacity modes in terms of annual costs.

4.3. What human- and organisation-related challenges arise in introducing AGV systems?

The results of Paper I show that the work organisation and having humans working in the same environment as the AGV system are important for the system's operation. By extension, Paper III explores the organisation- and human-related challenges that arise in introducing AGV systems. In this section, challenges related to failure management and how the technical dimension of an AGV system's components may pose challenges for the work organisation are presented followed by challenges in developing and improving the AGV systems. Challenges related to educating employees and human-related challenges are then explained concerning the acceptance of AGV systems and cognitive aspects of HFs.

Failure management is important for an AGV system's operation, as stated in section 4.1.4. Failure management requires new work procedures and routines, and in the cases in Paper III, none of which had operated with AGVs before, those procedures and routines had to be developed. There are many ways of performing failure management. At the organisational level, failure management needs to be arranged by creating an organisational structure for it, with responsibilities performed by certain employee roles and teams. Giving such responsibilities to all employees risks having employees ignore and not fulfil their responsibilities for it can be difficult to monitor how well the procedures are being followed, which can prolong downtimes in the AGV system.

The technical dimension of the AGV system's components influences how the work organisation is developed for failure management, referring to fleet size, the size of the area in which AGVs move and the guidepaths therein. A larger fleet size and area may be more challenging to manage in relation to the work organisation given the larger number of AGVs to keep track of and maintain. Paper III shows in Case D that having many AGVs in a large area required giving responsibility for failure management to all operators involved in production. This created challenges in following up on the failure management, since not operators performed the assigned work tasks. In Case E, by comparison, having only two AGVs in a smaller area allowed placing the responsibility on team leaders and technicians, whereas the operators were tasked with informing them about AGV failures.

Changes in the environment in which an AGV system is used or general improvements to the system require having work procedures for the system's development. Such procedures can refer to making changes to both the technical and work organisation dimensions of the system's components. Just as for failure management, it can be challenging to consider all of the aspects involved in those procedures, for instance, who does what, how should suggestions for improvement be generated and whether a change in the system will require new effort in educating employees, as shown by the different approaches in the cases.

Education of the employees is important for several reasons such as explaining the changes in the work organisation with new procedures, routines and responsibilities as well as for reducing doubts and improving acceptance for the AGV system. The need for education is in itself something that creates challenges. How such education is to be performed should be decided in terms of, for example, theoretical and practical education and which employee role is the most appropriate for performing the teaching and creating educational material. What individuals in different roles need to know has to be determined as well, because involvement in failure management requires a distinct education. If all employees are involved in failure management, then all employees need to be educated in the codes for different failures and how to manage them. If only the team leaders and the technicians are involved, only they need to be educated. In any case, education is substantial a work task, one that is challenging to manage when there are many employees involved in the same environment as the AGV system.

Accepting and understanding the AGV system are important for the system's success, as underscored in Papers I and III. However, creating acceptance of the AGV system can be challenging due to psychosocial and cognitive HF aspects. In the cases in Paper III, the AGV systems initially suffered from low acceptance, partly due to operational problems in the start-up phase of the system and partly due to the addition of new responsibilities and work procedures that were not viewed positively by all operators. Education can help to improve the acceptance of the system, and such acceptance itself can be improved over time as operators acclimate to cooperating with the system and come to understand its benefits.

Perceptual challenges related to cognitive HFs aspects are created by the AGVs' alarm signals. The AGVs sound an alarm to attract the attention of nearby operators in many situations, including when encountering a failure, when the safety sensors are temporarily switched off and when moving in reverse. Such alarms can include sirens or other noises and flashing lights and can make it challenging for operators to differentiate when assistance is in fact needed or when the AGVs are merely alerting the surroundings of their presence. The dual possibility risks having the operators ignore the alarm signals out of annoyance, even though manual intervention may be required, as seen in both cases in Paper III. In what situations an alarm is needed and when it is not has to be decided. The alarm signals were changed so that failures requiring manual intervention and only the most important safety situations initiated an alarm.

To summarise the results for RQ 3, introducing an AGV system entails several challenges in the organisation of work and in relation to the humans who work together with the system. In addition to the technical dimension of an AGV system's components, the work organisation needs to support the system, and developing routines, work procedures and responsibilities to that end is challenging. Introducing an AGV system also requires accommodating for failure management, developing and improving the system and educating operators about it. Regarding the human-related challenges, introducing an AGV system creates a new situation with interaction between the AGVs and the manual operations, as well as creating changes in the work organisation which together impact HF aspects that therefore create challenges. Considering the cognitive and psychosocial HF aspects can be challenging but is important for the operation and acceptance of the AGV system.

5. Discussion

This chapter discusses the results of the research conducted for the thesis. To begin, section 5.1 discusses the results in relation to each of the thesis's three research questions, focusing on the theoretical contribution. Next, section 5.2 discusses how the answers to the research questions contribute to the thesis's purpose where the focus is on the practical contribution. After a discussion of the generalisability of the results in section 5.3, section 5.4 concludes the chapter by identifying directions for future research based on the results.

5.1. Discussion of the results in relation to the RQs

The following three subsections discuss the results of the thesis in relation to each of the thesis's three research questions, respectively.

5.1.1. RQ 1: Which requirements influence AGV systems, and how can they be met in the configuration of the systems?

The literature on AGV systems mostly details how a small number of requirements influence particular components of AGV systems, including for example requirements related to the guidepath design, fleet sizing and control. A broader overview and more thorough understanding of those and other requirements can complement the detailed focus in literature. By reviewing literature on MHE selection (e.g. Bouh and Riopel, 2015; Anand et al., 2011), requirements suggested in AGV system literature (e.g. Le-Anh and de Koster, 2006; Vis, 2006), and integration of human and AGVs requirements with additions connected to the HF aspects identified in answering RQ 3, a broader overview and improved understanding of such requirements have been achieved by the answer to RQ 1.

The requirements for the configuration of AGV systems derived from the literature have been shown to stem from various sources. For this thesis, by investigating the sources of such requirements in a case study, it was possible to understand which requirements there are and how they influence the configuration of AGV systems. Beyond that, an understanding emerged about how requirements interact and influence one or more components of AGV systems, as well as about how meeting certain requirements can generate new requirements. That enhanced understanding complements the somewhat more detailed focus on requirements in relation to particular components of AGV systems, as shown in literature reviews (e.g. Fragapane et al., 2021a; Le-Anh and de Koster, 2006; Vis, 2006) which provide good overviews of the decisions involved, but less so regarding requirements. With a broader overview of requirements, it is easier to see possible interactions between them. Furthermore, this adds to the sustainability-oriented decision-making framework for AGV systems in supply chains, as suggested by Bechtsis et al. (2017), whose decision-making framework indeed provides an overview of decisions for the configuration of AGV systems but does not focus on how requirements influence such decisions.

Paper I shows that interactions can occur between the requirements placed upon the configuration of AGV systems, for example, between flexibility and the accuracy of load transfers. On that topic, frequent changes in the environment make virtual guidepaths more appropriate than physical ones. De Ryck et al. (2020) have shown that virtual guidepaths simplify making changes in the environment without requiring too much effort in redesign, which the answer to RQ 1 in this thesis corroborates. At the same time, the choice of guidance technology consequently places requirements on the internal logistics environment, as shown by the results for RQ 1 indicating that the guidance technology may not function in certain areas of the environment. In that case, the AGV system itself, owing to the guidance technology, may impose requirements on the environment. Although virtual guidepaths indeed allow enhanced flexibility, such benefits are reduced when the guidance technology cannot be used fully. Assessing the fit between such guidance technology and the environment is thus pivotal.

The answer to RQ 1 also shows requirements that conflict with each other. For example, the accuracy required by load transfers can necessitate including fixed guiderails at the load transfer positions to enable manual operators to place the unit loads correctly every time. Meanwhile, the AGV system has to be flexible enough in managing changes because frequent changes in the environment require frequently adapting the system. Those two requirements conflict because the fixed infrastructure involved with the guiderails makes the AGV system less flexible in managing changes. On that topic, Sabattini et al. (2013) have suggested using fixed infrastructure as little as possible in order for AGV systems to remain flexible in the event of changes. However, because AGVs stop when a unit load is not correctly placed within approved boundaries, the guiderails ensure that load transfers can be performed correctly and, as such, are vital for an AGV system's operations. In that example, because meeting the requirements for load transfers is clearly more important than ensuring flexibility, the guiderails should be included even at the expense of reducing the AGV system's flexibility. Even so, following the suggestion of Sabattini et al. (2013), the use of fixed infrastructure should be limited as much as possible.

As the example of the guiderails and the AGV system's flexibility also shows, the requirements vary in how strictly they need to be fulfilled. Because load transfers are central to the system's operations, fixed infrastructure such as guiderails is needed to help the operators. By contrast, the system's flexibility is not strictly essential for its operation but, makes it easier to make changes in the system when necessary. Another strict requirement is the interoperability of the AGVs, as shown in the answer to RQ 1, such that the AGVs in the fleet behave in the same ways despite being from different generations of technological advancement.

Another dynamic to consider is that requirements from two or more categories may interact and mutually influence an AGV system's configuration. For instance, requirements for guidepath design may emerge due to narrow aisles with limited free space in the internal logistics environment, along with the need to integrate AGVs with tugger trains or other forklifts due to integration of humans and AGVs.

In fact, several requirements influencing an AGV system's configuration stem from the integration of humans and AGVs. The technical dimension of the components of AGV systems need to be supported by the work organisation dimension, which can influence HF aspects. It is thus important to account for requirements imposed by the HF aspects amongst different employee roles that are directly involved in the operations of the system or work alongside the system in the internal logistics. Although HF aspects were not directly analysed in Paper I, the requirements identified in the research for this thesis stemming from the integration of humans and AGVs and knowledge about how they influence AGV systems contributes to the largely technical focus in previous research on such systems (Fragapane et al., 2021a; Benzidia et al., 2019). Challenges related to the work organisation and humans when an AGV system is introduced are further discussed in section 5.1.3.

5.1.2. RQ 2: How does load capacity impact the performance of AGV systems?

Although the choice of transport vehicle and its load capacity impact the costs of part feeding, those aspects have seldom been examined (Nourmohammadi et al., 2021; Battini et al., 2015). The answer to RQ 2 shows that the load capacity impacts both the operational performance and annual costs of AGV systems, knowledge that adds to the literature on such systems, in which load capacity has mostly been regarded as a variable while studying other phenomena such as scheduling and dispatching (Dang et al., 2021; Ho et al., 2012; Ho and Liu, 2009) or otherwise not have examined in detail on how the load capacity influence performance. In those studies, Dang et al. (2021) have tested the performance of different look-ahead scheduling algorithms in various scenarios wherein the load capacity is a variable that is varied. Ho et al. (2012); Ho and Liu (2009) analysed the most suitable dispatching rules for multiload AGVs in a job shop environment. The answer to RQ 2 add to the knowledge about AGV systems and load capacity by showing the latter's impact on the systems' performance and what kind of design- and environment-related variables may influence the performance achievable by an AGV system with various load capacities, providing insights into what types of situations are most suitable for different load capacities.

As implied, the answer to also provides greater detail about the operational performance of different load capacities than what is presented in the literature. Yan et al. (2020) compared the performance of one multiload AGV with increasing load capacities from 1 to 10 with an AGV system consisting of 1 to 10 single-load AGVs in different scenarios regarding information about incoming transport requests. More recently, Yan et al. (2022) investigated different maintenance strategies for a multiload AGV system and found that the gradient for the curve for throughput for larger load capacities was higher than smaller load capacities, thereby indicating that a large load capacity benefits higher throughput. However, neither Yan et al. (2022) nor Yan et al. (2020) analysed how load capacity impacts an AGV system's performance in different situations. The answer to RQ 2 by contrast, adds details regarding operational performance and offers insights into when a large versus small load capacity is preferable in different situations.

Although the speed of an AGV is often fixed in many models (e.g. Dang et al., 2021; Yan et al., 2020; Ho et al., 2012), the answer to RQ 2 shows that it is in fact important that should be considered in making investment decisions. Considering all of the effects of the environment- and design-related variables examined for RQ 2, AGV speed had the largest effect. It can thus be beneficial to invest in an AGV that has higher speeds. At the same time, the speed that can be achieved in a facility may depend on, for example, traffic interference, aisle widths, the presence of pedestrians in the layout and the traffic rules. In that light, the speed of an AGV stated in the supplier's specifications may not be possible to attain in a facility.

The answer to RQ 2 additionally shows that investment decisions need to consider the trade-off between the number of AGVs and the number of carts needed. Battini et al. (2015) have developed a cost model for selecting the best transport vehicle for part feeding, in which AGV trains have a fixed load capacity (i.e. single-load or multiload where the number of carts is fixed). Because the cost for a cart is less than the cost for an additional AGV, a cost perspective it is beneficial to have a large load capacity if at the same time the fleet size can be reduced. However, as shown by the results for RQ 2, an increased load capacity is not always enough to reduce the minimum fleet size. In situations when both single-load AGVs and AGVs with a large load capacity are applicable, there could be additional parameters that impact the load capacity choice. When AGVs with small load capacities are used, they can be expected to have a larger impact on the traffic in the facility because a larger fleet is needed than a multiload alternative requires in most cases. More traffic in the facility can also increase traffic interference and increase the risk of delayed transports. Those considerations should also influence the investment decisions.

5.1.3. RQ 3: What human- and organisation-related challenges arise in introducing AGV systems?

When introducing an AGV system, numerous challenges arise related to the work organisation. Even so, such challenges have seldom been examined in research, which has instead largely focused on the technical dimension of AGV systems (Fragapane et al., 2021a; Benzidia et al., 2019). Nevertheless, Benzidia et al. (2019) have explained how the roles of employees change and that new roles need to be created when an AGV system is introduced in a hospital. Added to that, Bechtsis et al. (2017) have posited that regulations for safety procedures are also needed when introducing such systems. In line with those findings, the answer to RQ 3 in this thesis confirms that AGV systems create changes, involve new roles and need new procedures to be introduced. The answer to RQ 3 delves into the challenges involved in the work organisation when AGV systems are introduced in relation to creating new procedures, routines and divisions of responsibility for the new procedures as it is not straightforward how these should be determined. In general, managing AGV failures, developing and improving the AGV system, educating operators and implementing new routines all present challenges. As such, the answer to RQ 3 contributes to the literature on AGV systems by showing the challenges related to the work organisation when such systems are introduced.

According to Kadir and Broberg (2021), changes in work tasks are needed when automation technology is introduced, and managing those changes can be challenging. They may involve, for example, teaching operators and new divisions of work, both of which present challenges in the introduction of AGV systems, as shown by the results used to answer RQ 3. For instance, challenges can arise in providing education geared towards developing employees' acceptance of the systems and teaching new work procedures, related to the cognitive and psychosocial aspects of HFs, as well as in determining the processes and responsibilities for the education, which are related to the work organisation. Having an understanding of the human- and organisation-related challenges in introducing AGV systems can help to develop a work organisation that considers human aspects when introducing an AGV system into a new facility or in a new material flow, for awareness of such challenges affords opportunities to better manage them in the design. The education of employees about the AGV system was also found to be important, as the answers to both RQ 1 and 3 show, and entailed challenges, both human-related and organisation-related.

In developing the work organisation for an AGV system, the HF aspects need to be accommodated in order to avoid creating a system that results in poor well-being for its operators (Neumann et al., 2021). As stated in Chapter 1, further research is needed about considering HF aspects in the design when Industry 4.0 technology is used (Winkelhaus et al., 2022; Neumann et al., 2021; Sgarbossa et al., 2020). The answer to RQ 3 shows that HF aspects are important but challenging to address in introducing an AGV system as well as influence and are influenced by the system's configuration. Many challenges related to the HF aspects are presented in the answer to RQ 3, including inexperience, AGV alarm signals and the introduction of new work procedures and routines, all of which influence and are influenced by the work organisation dimension of the AGV system's components. As such, the answer to RQ 3 can facilitate the development of AGV system configurations that take into account human needs. After all, humans decide whether to accept or reject new technology (Winkelhaus and Grosse, 2020), and if the HF aspects are ignored, then the operators may not accept the system.

5.2. Knowledge to support the design of AGV systems

This thesis set out with the purpose *to develop knowledge to support the design of AGV systems*, namely as input for the design of AGV systems. Three research questions guided the research, and work was performed to generate the three appended papers, all of which contribute to achieving the thesis's purpose. The research for the thesis began by reviewing the literature and identifying problems in industry in need of further research. The problems addressed in the thesis are threefold: (1) understanding and getting an overview of which requirements there are for AGV systems and how their configuration can meet those requirements, (2) identifying how an AGV system's performance is impacted by load capacity and (3) understanding the challenges related to the work organisation and the humans when an AGV system is introduced. This section focuses on the practical contributions of the thesis's results and relates the answers to the RQs to the phases of the design process models presented in section 2.3. Overall, the results of the thesis provide input to different phases of the design of an AGV system.

Many design process models start by developing a set of requirements and objectives (e.g. Tompkins et al., 2010; Johansson, 2007; Wu, 1994) as an important step the design. As stated in section 5.1.1, requirements identified in the literature on AGV systems are often limited to a few requirements that are important for only a particular AGV system component. The understanding and overview of the requirements from the answer to RQ 1 and how they influence the configuration of AGV systems can thus support the design of an AGV system. In particular, they could help to make the process less time-consuming, as is often the case in real-world implementations (Draganjac et al., 2020), and reduce the need for costly, time-intensive changes to the configuration in later phases of the design (Slack et al., 2013). An overview of requirements can reduce the risk for sub-optimisation which can be a problem when a subset of requirements is considered in isolation. For instance, considering HF aspects in isolation may lower worker well-being in a production system (Neumann et al., 2021).

The results of the thesis provide support for early phases of a design process concerning whether an AGV system is an appropriate transport alternative given the requirements identified in the intended site of application. In Johansson's (2007) model, such decisions can relate to the concept development phase. AGVs are only one type of equipment that can be used for transport, and as presented in the literature on MHE selection (e.g. Bouh and Riopel, 2015; Anand et al., 2011), there are many other ways in which material can be transported, including by using manually operated equipment or another automated solution such as a conveyor system. By carefully mapping the requirements in the intended site of application related to the five sources of requirements and by considering how the requirements influence the AGV system's configuration, as shown in the answer to RQ 1, it can be decided whether an AGV system is a suitable option. Such decisions also need to account for the work procedures in the manual flow, if an existing manual flow exist. An AGV system can perform transport and load transfers only, if there are other work procedures in the manually operated material flow, they need to be assigned to other employees if an AGV system is introduced. If that is not possible, an AGV system may not be a suitable option.

The results of the thesis can be useful when new factories are built that intend to use an AGV system. The answers to RQ 1 and 3 regarding what kind of requirements and challenges there are and how the requirements may influence the AGV system's configuration in different ways can support the designers of new factories with establishing good conditions for an AGV systems. For example, the internal logistics environment imposes several requirements on an AGV system's configuration, as seen in the answer to RQ 1, but the environment is difficult to alter because the facility is already built. When building a new factory, aisle widths, localising charging facilities and idle positions and guidepath design can all be considered from the outset in the new environment so that good prerequisites for developing an efficient AGV system in the factory are established. In turn, that understanding can reduce challenges related to humans working together with the AGV system in such environments.

The answer to RQ 2 by extension, provides support for a later phase of the design process after the decision to use an AGV system has been made, namely when the load capacity of the AGVs needs to be determined. The answer to RQ 2 shows that the load capacity can exert a large impact on many operational performance measures and annual costs and, as such, is important to consider regarding an AGV system's configuration. As discussed in section 5.1.2, the findings related to answering RQ 2 indicate variables that are important to consider when deciding on the load capacity that would be appropriate for a particular AGV system's application. The choice of load capacity can impact various components of the system, including fleet size, load transfer mechanisms and potentially the guidepath design, for if single-load vehicles are used, then it may be possible to use a guidepath design unlike the guidepath required if multiload AGVs are used (Battini et al., 2015). It would be possible to develop several conceptual configurations with different potentially viable load capacities, relating to the conceptual design phases in the design process model (Johansson, 2007), and those configurations can be evaluated in the next phase, as suggested by Tompkins et al. (2010) before going into the details.

At the operational level, the answers to RQ 1 and 3 support the development of the work organisation dimension regarding the challenges in the work organisation in operating an AGV system, especially related to failure management, traffic routines and rules, safety considerations and the education of employees. This connects with the final step of Tompkins et al. (2010) process in which instructions are provided to the operators. As stated by Neumann et al. (2021), it is important to consider in the design of systems using Industry 4.0 technologies in order to reduce the risk of developing underperforming systems and inducing poor worker well-being, both of which are risks if the HF aspects are considered in isolation. Considering HF aspects in the design of an AGV system is also important because cognitive aspects of HFs may be influenced by the system's new routines and work tasks, and psychosocial aspects may be affected related to the understanding of for example, the AGVs' behaviour in different situations. Awareness of the challenges involved related to human workers and the work organisation can help with developing strategies for managing them. Moreover, including HF aspects in the requirements for AGV systems can support the development of systems that consider the well-being of operators. This can enhance the entire system's performance (Neumann et al., 2021; Vijayakumar et al., 2021). Considerations of humans are also central in the human-centric designs of Industry 5.0 (European Commission, 2021; Reiman et al., 2021). In sum, all of those results can benefit the more detailed design phases in the design process models developed by Johansson (2007) and Wu (1994).

Employee roles that could benefit from the results of the thesis are project managers and system designers involved in the design of AGV systems, from selecting AGVs to designing the system for the specific facility. The results of the thesis can support the design of AGV systems in many phases of the process, ranging from determining whether an AGV system is viable for a material flow and deciding upon the load capacities of the AGVs to detailed phases of the design, related to the work organisation and HF aspects. The thesis can provide support with identifying and understanding requirements and how they could be accounted for in the configuration of an AGV system. Furthermore, the thesis's findings related to the challenges connected to the HF aspects in the answer to RQ 3 highlight that the operators in the same environment as the AGV system should be considered and can help in devising strategies to manage the challenges.

5.3. Generalisability of the results

This section discusses the generalisability of the thesis's results to settings beyond those in which the research was conducted.

Amongst the three papers appended to the thesis, Papers I and III are based on case studies, whereas Paper II is based on simulation model of a real-world industrial material flow. The cases in Paper I and III are all from a manufacturing industry in which AGV systems are used to deliver material either directly to the manufacturing process or to supermarkets connected to the manufacturing. The material flow analysed in Paper II is also in a manufacturing setting. Therefore, it should be possible to generalise the thesis's findings to similar manufacturing settings, e.g. in terms of the characteristics of the transported loads and the environment.

The settings of the cases studied in Papers I and III as well as the material flow in Paper II are described so that the results from the papers can be understood and interpreted in relation to the settings examined. The settings of the cases are detailed in Papers I and III by explaining the type of environment in which the AGV system is implemented, the unit loads used and the types of AGVs used in terms of guidance technology and load-carrying mechanism, all of which improves the generalisability of the results by making the setting of the cases clear. The material flow is described clearly in Paper II as well, as is the assumption and simplifications made in the modelling, all of which also improves the generalisability of those results by clarifying how the model was developed.

5.4. Possible areas for future research

The cases studied in the research for this thesis were all in manufacturing settings, settings in which AGV systems are often used, such systems can be used in other settings outside manufacturing, and studying cases therein could improve the generalisability. Hospitals, for instance, could impose additional requirements related to the integration of humans and AGVs. In manufacturing settings, it is possible to teach the employees who interact with the AGVs what to expect from the automated equipment, for those employees will likely remain in the environment for the foreseeable future. In a hospital, by contrast, there could be interactions between AGVs and people who have never encountered an AGV before, which could pose additional requirements. Indeed, Benzidia et al. (2019) have highlighted the changing roles for employees in hospitals when an AGV system is introduced. More recently, Fragapane et al. (2021b) have investigated AGVs in hospital logistics in terms of several performance measures, including flexibility, productivity and quality, but not in terms of the integration of human and AGV. Thus, to extend the results from the cases studies in this thesis, examining cases outside manufacturing settings could provide a further understanding of the requirements influencing the configuration of AGV systems.

AGV systems that are fully enclosed in their own environments, for example, the robotic mobile fulfilment system used for example by Amazon (Sabattini et al., 2017), could be studied as well. Although no cases of enclosed AGV systems were examined for this thesis, the thesis has shown that numerous interactions occur between such systems and humans, the latter of which are needed to support the system's operation. In situations in which the AGV system is enclosed, AGVs interact only amongst themselves, integration between human and AGVs could imposes fewer requirements, and the work organisation dimension may be less prominent. However, in such a system, the pace of work of operators who receive items from the AGVs might be largely determined by the system, which could create additional requirements concerning the psychosocial aspect of HFs. The interaction between humans and AGVs might even pose different requirements although they are separated, which could be studied in future research as well.

AGVs with more or less advanced functionality could also be studied in greater depth. More advanced AGVs, called autonomous mobile robots or autonomous intelligent vehicles in the literature, have advanced functionality in terms of obstacle avoidance, decentralised decision making, guidepath-free navigation and artificial intelligence, which could influence the requirements for the AGV system's configuration as well as HF aspects. In situations in which a less advanced AGV might fail and require manual assistance, a more advanced AGV could be able to solve the problem by itself (Fragapane et al., 2021a), thereby reducing the need for manual monitoring and intervention. When working in the same environment, more advanced AGVs' behaviour could also be less predictable, which might also influence HF aspects. Advanced functionality could additionally influence, for example, how precisely items need to be placed for load transfers. On top of that, more and less advanced AGVs could be studied together to determine, for example, situations in which advanced functionality is beneficial and in which more basic functionality is sufficient.

Last, the answer to RQ 3 shows the challenges of introducing AGV systems both for humans and the work organisation. On that topic, further studies could examine how to manage those challenges in greater detail. Challenges for the work organisation is influenced by the technical dimension of the AGV system's configuration and HF aspects. There are also many ways in which the work organisation can be developed concerning the division of responsibilities and work procedures. Developing a strategy for decisions of that sort would extend the answer to RQ 3.

6. Conclusions

This thesis has on focused developing knowledge to support the design of automated guided vehicle (AGV) systems. Ending the cover paper, this chapter presents the thesis's main findings and the ways in which they were developed considering the research approach used. Amidst growing interest in AGV systems in both industry and academia as a result of functional improvements in AGVs and attention to Industry 4.0, studies on such systems have mostly focused on requirements for individual components of the AGV system. With a largely technical focus, however, studies on AGV systems have seldom considered humans or the work organisation. Furthermore, the impact of the load capacity of the AGVs has not been investigated in detail in previous studies. Knowledge about those topics could help to design high-performing AGV systems that ensure the well-being of workers.

To begin the research for the thesis, the literature on AGV systems was reviewed to pinpoint the current state of such research and areas in which further research is needed. Meanwhile, interactions with industrial parties involved in the main research project encompassing the thesis's research allowed identifying industry-based issues related to AGV systems. Three research questions were formulated for the thesis and three studies conducted: two multiple case studies and one study based on simulation modelling. The first multiple case study aimed to clarify which requirements influence configurations of AGV systems and how they can be met, while the second one focused on human- and organisation-related challenges in introducing AGV systems. The simulation modelling, by comparison, focused on the load capacity of AGVs and how it impacts the performance of AGV systems.

The thesis's findings can support AGV system design processes, by offering input to different phases of such design. First, by providing an overview of requirements and an understanding of how they influence the configuration of AGV systems, the findings can support decision-making about whether an AGV system is an appropriate option or while constructing new factories in which AGV systems will be used. Second, the findings show that the load capacity of AGVs is important in the configuration of AGV systems because it impacts operational performance and annual costs, and different load capacities are suitable in different situations. Input into later phases of the design process could benefit from this knowledge, when it has been decided that an AGV system is a suitable option. Third, the findings also offer guidance regarding numerous challenges related to the work organisation and the humans who work in the same environment as the AGV system. Knowledge and awareness of those challenges can support the development of strategies to manage them, which is important input in more detailed design phases in the design process in order to create an AGV system configuration that supports workers' well-being.

Last, the thesis's findings show several opportunities for future research geared towards supporting the design of AGV systems. For one, researchers could investigate AGVs' functionality by comparing situations in which more or less advanced AGVs are suitable. For another, case research in settings wherein humans interact significantly with the AGV system (e.g. hospitals) or in which the system is used in an enclosed area could reveal new challenges and requirements from the sources derived from literature. A final suggestion is to develop strategies for managing the challenges identified in the thesis. For instance, a multiple case study could be performed to achieve an understanding of different ways that the challenges can be addressed.

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