THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Design of Automated Guided Vehicle Systems Considering the Human, Technical, and Work Organisational Subsystems

NILS THYLÉN

Department of Technology Management and Economics

CHALMERS UNIVERSITY OF TECHNOLOGY

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NILS THYLÉN
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Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Nils Thylén
Department of Technology Management and Economics
Division of Supply and Operations Management
Chalmers University of Technology

Abstract

This thesis focuses on the design of automated guided vehicle (AGV) systems. AGVs are unmanned transport vehicles that are often used in manufacturing and warehousing environments to transport materials automatically. Advances in artificial intelligence and navigational technologies for the AGVs together with an increased interest in automation has resulted in a growing number of applications of AGV systems in industry. Previous research has largely focused on the technical aspects of designing AGV systems. However, there is a risk of suboptimisation when only the technical subsystem is considered, including undermining the well-being of the employees involved in the system and failing to achieve intended performance. The need for a joint consideration of technical and social systems is emphasised by the socio-technical systems perspective, and this thesis conceives of AGV systems as comprising human, technical, and work organisational subsystems. Therefore, the purpose of this thesis is to develop knowledge to support the design of AGV systems considering the human, technical, and work organisational subsystems.

Four multiple case studies and one discrete event simulation study were conducted. The case studies focused on developing an understanding of the requirements and challenges associated with AGV system design and how they influence the design. Given the mostly technical focus in previous research, the case studies provided a suitable approach to studying the human and work organisational aspects of real industrial AGV systems. The discrete event simulation study was inspired by a real-world industrial material flow. It focused on analysing the interaction between AGV fleet size and load capacity. The research was guided both by knowledge obtained from previous research and observations of challenges faced from a practical perspective through involvement in research projects with representatives from industry that apply AGV systems in their operations.

The theoretical contribution of the thesis consists of showing the importance of the human and work organisational subsystems in AGV systems. The studies conducted for the thesis show that the work organisational subsystem requires careful consideration together with the technical subsystem, both of which are influenced by and influence the human subsystem. The work organisational subsystem is, among other things, needed to develop acceptance and create a safe work environment. This perspective of going beyond the technical subsystem contributes to the current research on AGV system design. With the limited attention given to human and work organisational subsystems in the current research literature, the practical contribution of the thesis consists of guidance for the design of AGV systems by considering these subsystems.

Keywords: automated guided vehicle system design, socio-technical systems, internal logistics, materials handling, Industry 5.0

List of appended papers

This thesis is based on research presented in five appended papers.

Paper I

Thylén, N., Hanson, R., and Johansson, M. I. “Requirements influencing the design of automated guided vehicle systems”. An earlier version of this paper was presented at PLAN Forsknings- och tillämpningskonferens, October 2020.

Paper II

Thylén, N., Medbo, P., Fager, P., Frantzén, M., and Hanson, R. (submitted). “AGV part feeding: The impact of load capacity and fleet size”. An earlier version of this paper was presented at The Swedish Manufacturing R&D Cluster Conference, Katrineholm, May 2023.

Paper III

Thylén, N., Wänström, C., and Hanson, R. (2023) “Challenges in Introducing Automated Guided Vehicles in a Production Facility – Interactions between Human, Technology, and Organisation”. *International Journal of Production Research,* 61(22) pp.7809-7829.

Paper IV

Thylén, N., Flodén, J., Johansson, M. I., and Hanson, R. (2025). ”Requirements for the automated loading and unloading of autonomous trucks: An interoperability perspective”. The paper has been accepted for publication in *International Journal of Physical Distribution & Logistics Management*. An earlier version of this paper was presented at the Annual EurOMA conference, Leuven, July 2023.

Paper V

Thylén, N. (working paper) “Designing work organisations for supporting automated guided vehicles operations”. An earlier version of this paper was presented at the Annual EurOMA conference, Barcelona, July 2024.

Notes on researcher’s contribution to the appended papers

Paper I: The idea for the study was developed together among the authors. The data collection was conducted jointly were all authors participated. Compiling and analysing the collected data was mainly conducted by Thylén. Review of literature and analysis of the collected data was mainly performed by Thylén. Writing the original draft was performed by Thylén, while editing and revising the manuscript was performed together among the authors.

Paper II: The idea for the paper came from Thylén and literature was also reviewed by Thylén. Data collection was conducted by Thylén, and the collected data was curated by Fager, preparing the data for use in a discrete event simulation model. Frantzén and Medbo provided support in developing the simulation model, as well as in analysing the output of the model. Writing of the original draft was performed by Thylén. Editing and revising the first draft was a joint effort of all authors.

Paper III: The idea for the paper was decided among all three authors of the paper. Literature review was a joint effort between Wänström and Thylén. Hanson and Thylén worked together to collect data for the paper. Analysis was mainly conducted by Thylén with support from Wänström and Hanson. Writing of the first draft of the paper was performed by Thylén. Editing and revising the manuscript was a joint work.

Paper IV: The idea for the paper was arrived at by discussions among all authors of the paper. Literature was reviewed mainly by Thylén with assistance from Hanson. Data were collected by Thylén, Flodén, and Hanson. Analysis of the collected data was mainly performed by Thylén who also wrote the first draft of the paper. Editing and revising the paper was a joint effort of all authors.

Paper V: Thylén is the sole author and is responsible for the idea, data collection, literature review, analysis, and writing of the paper.

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These PhD years have been invaluable to me. I hope that the time we've shared together is just the beginning of long-lasting friendships and potential future collaborations!

Nils Thylén

Göteborg, January 2025

Table of Contents

1. Introduction

This thesis focuses on the design of automated guided vehicle (AGV) systems. This chapter introduces the research in the thesis. Section 1.1 presents factors that contribute to the increasing interest in automation. Section 1.2 presents internal logistics using AGV systems. Section 1.3 presents AGV systems and the definition of ‘AGV system’ used in this thesis. Section 1.4 focuses on designing AGV systems. The purpose of the thesis is then presented in Section 1.5, and its scope is outlined in Section 1.6. The chapter is concluded by providing an outline of the chapters of the cover paper in Section 1.7.

1.1. Increasing interest in automation

Interest in automation is increasing for several reasons, such as improvements in automation technology, increased attention to reshoring production, and potential to meet the challenges of an ageing workforce. This increased interest is also related to the growing focus on Industry 4.0.

Automation technologies have advanced considerably in recent years (Cilekoglu et al., 2024). The capabilities of automation technologies are improving, productivity is increasing, and prices for automated solutions are reducing (Pinheiro et al., 2023). Technological improvements to sensors, cameras, computational power, and batteries support automation; for example, the navigational capabilities of AGV systems have improved (Fragapane et al., 2021b). Additionally, developments in artificial intelligence have made automation technologies more intelligent, which has further increased interest in automation (Pinheiro et al., 2023).

The reshoring of production is becoming more prevalent. For many years, offshoring has been a common strategy among manufacturing companies to enhance competitiveness by relocating production to countries with lower labour costs (Stentoft & Rajkumar, 2020). However, recent developments indicate a shift towards reshoring, where companies move previously offshored production back to their home countries. Automation is linked to this trend of reshoring production (Arlbjørn & Mikkelsen, 2014). Pinheiro et al. (2023) concluded that automation has a significant and positive effect on reshoring. They also state that factors such as rising labour costs in offshoring destination countries, increasing disruptions to the supply chain, and opportunities to reduce transport costs are associated with the interest in reshoring and the increasing use of automation.

In 2011, the German government introduced the concept of Industry 4.0 to ensure that the German industry would remain competitive (Kagermann et al., 2013). Since then, Industry 4.0 has received significant attention in research (see Frank et al., 2019; Galati & Bigliardi, 2019; Ivanov et al., 2021; Liao et al., 2017). Automation is central to Industry 4.0 (Beier et al., 2020) and is associated with an increasing interest in research and industry. AGV systems, which can be used to automate internal transport, are considered an Industry 4.0 technology (Frank et al., 2019; Ivanov et al., 2021; Zheng et al., 2021). AGVs are driverless vehicles used to transport materials in warehouses and production settings (Zhang et al., 2021). In 2021, the European Commission introduced the concept of Industry 5.0 as an extension of Industry 4.0 (Breque et al., 2021). One of the main aspirations of Industry 5.0 is to support human-centric design (Reiman et al., 2021) complementing the predominately technology-driven focus of Industry 4.0 (Ivanov, 2023).

The ageing workforce is a growing problem in many countries (Sgarbossa et al., 2020). Decreasing birth rates, increased life expectancy, and rising retirement ages necessitate longer working lives, which entails the need for additional support and creates an opportunity for automation to play a crucial role. To enable an ageing workforce to extend its work life, the automation of industrial processes is necessary (Calzavara et al., 2020). It is important to consider human factors for ageing workers, as there are differences in their strength, stamina and cognitive abilities compared to younger workers (Ranasinghe et al., 2024). Automation can assist ageing workers by eliminating work tasks with poor ergonomic conditions, such as in work that involves transport or heavy lifting.

Automation is attracting growing interest. Automation has potential to improve internal logistics where the application of AGV systems can result in many positive outcomes, which is explored in the following section.

1.2. AGV systems in internal logistics

Internal logistics is an area that can benefit significantly from automation (Winkelhaus et al., 2022). It is a vital part of production and can constitute a large portion of a product's production cost (Esmaeilian et al., 2016). Internal logistics is expected to change due to automation, not least internal transports (Winkelhaus & Grosse, 2020). Since internal transport often involves substantial manual work, automating transport can yield significant benefits by transferring physically straining, monotonous, and time-consuming work to automated solutions (Granlund & Wiktorsson, 2014). AGV systems have been shown to improve internal transport (Bechtsis et al., 2017; Yan et al., 2022), for example, by reducing labour costs and increasing productivity.

As previously stated, AGVs are driverless vehicles used for transporting materials in settings such as warehousing and production (Zhang et al., 2021). Many terms are used in industry and in research, such as automated guided vehicles (Vlachos et al., 2024), autonomous mobile robots (Fragapane et al., 2021a), laser-guided vehicles (Ferrara et al., 2014), and automated intelligent vehicles (Hellmann et al., 2019). Although these terms differ in aspects such as navigation methods and the degree of autonomous decision-making, their applications are similar, typically involving the automatic movement of goods within a facility. Autonomous mobile robots, for example, can be seen as an advanced form of AGVs (Oyekanlu et al., 2020). In this thesis, the term AGV is used as a generic term encompassing the various names used in previous research.

AGV systems have a long history, as the first systems were introduced in the 1950s (Kumbhar et al., 2018). These early AGVs were guided by physical guidepaths embedded in the floor, which provided limited flexibility and incurred high installation costs (Schulze & Wullner, 2006). As outlined in Section 1.1, interest in AGV systems has increased in both industry and academia, driven by developments in Industry 4.0 and industrial artificial intelligence (Hu et al., 2020) as well as improvements in AGV functionality, including intelligence, sensors, and autonomous guidance (Ellithy et al., 2024; Zhan & Yu, 2018). The previously mentioned trend towards reshoring is also influencing the application of AGV systems (Vlachos et al., 2024). The demand for AGV system is experiencing a significant increase in industry (Marković, 2023). The global AGV market size is projected to grow by a compound annual growth rate of 23% until 2028 (Thormundsson, 2023).

1.3. Subsystems of an AGV system

In this thesis, AGV systems are considered to comprise three subsystems: technical, human, and work organisational inspired by the HTO model (Karltun et al., 2017). The technical subsystem encompasses the technical design areas of an AGV system, which are presented in the following paragraph. The human subsystem concerns humans at the individual level, who influence and are influenced by the technical and work organisational subsystems. The work organisational subsystem includes organisational structure, job dimensions, and competencies.

The technical subsystem of an AGV system comprises several interrelated technical design areas. These areas have received substantial attention in research, as shown by numerous literature reviews (e.g. Bechtsis et al., 2017; Dolgui et al., 2022; Fragapane et al., 2021a; Le-Anh & de Koster, 2006; Vis, 2006). The technical design areas for an AGV system can be categorised in various ways but generally involve fleet sizing, traffic management and control, zoning or guidepath design, navigational capabilities, battery management, and failure management. Many studies have focused on these areas, striving to improve, for example, scheduling and dispatching within traffic management and control (e.g. Dang et al., 2021; Ho et al., 2012; Singh et al., 2023).

The human subsystem concerns humans at the individual level. Research on AGV systems has largely focused on technical design areas (Benzidia et al., 2019; Fragapane et al., 2021a; Hrušecká et al., 2019; Kopp et al., 2023; Zuin et al., 2020), with less attention given to the human subsystem. Similarly, research related to Industry 4.0 has largely adopted a technical focus and has been technologically driven (Nayernia et al., 2021; Sony & Naik, 2020b; Tortorella et al., 2023). Sony and Naik (2020b) argued that more automation will not reduce human interactions but will require employees to acquire new and different skills. It is anticipated that automation will not replace humans in logistics; instead, humans will continue to play a crucial role in the industry (Grosse et al., 2023; Winkelhaus et al., 2022). The importance of considering humans when introducing technologies is emphasised in Industry 5.0, which highlights human-centric design as a crucial (Breque et al., 2021). Humans often work alongside AGVs in the same environment (Oleari et al., 2014; Sabattini et al., 2017), where they interact with and influence each other, making it important to consider humans in the design of AGV systems. There is a need to consider human factor aspects, such as physical, cognitive and psychosocial aspects, in the design of technical systems (Sgarbossa et al., 2020; Vijayakumar et al., 2021).

The work organisational subsystem comprises the competence, job, and structural dimensions. An organisation-focused perspective in the research on Industry 4.0 has been lacking (Nayernia et al., 2021). Reiman et al. (2021) argued that focusing exclusively on human aspects at the individual level may be too narrow, as relevant aspects of human-based work might be excluded. Similarly, the work organisational subsystem in AGV systems research requires more attention. According to Tubis et al. (2024), few research papers have addressed work organisation in relation to AGV systems. The work organisational subsystem concerns the roles, work tasks, and responsibilities of humans and technologies, as well as the division of labour, the competencies required for different roles (e.g. Cagliano et al., 2019; Cimini et al., 2021). When new technologies are implemented, changes in work organisation are necessary due to new interactions between humans and technology (Kadir et al., 2019). The changing roles of humans when technologies are introduced have often gone unaddressed (Kadir & Broberg, 2021; Neumann et al., 2021). Kadir and Broberg (2021) pointed out that changes in work should be addressed when digital technologies, including AGV systems, are introduced. In several cases that they studied, such technologies were implemented without a formal process for redesigning work, resulting in a suboptimal division of labour between humans and technologies and an incomplete understanding of training needs. The implementation and use of automation also require the development of new skills (Galati & Bigliardi, 2019).

All three subsystems need to be considered when designing an AGV system. Further details on each subsystem are provided in Section 2.1. The next section presents the current research related to designing AGV systems.

1.4. Designing AGV systems

Designing an AGV system involves jointly considering all three subsystems. The need for joint consideration of both technology and the social system when designing systems is emphasised by the socio-technical systems perspective (Fox, 1995; Trist, 1981). Focusing on only one subsystem risks the suboptimisation of the system (Grosse et al., 2023). The human, technology, and organisation (HTO) model can assist in understanding these three subsystems (Karltun et al., 2017). Although the socio-technical perspective is important when automation is introduced (Fletcher et al., 2020), it has often been neglected in the technologically oriented literature In research on AGV system design, there has been a strong technical focus, and there is a need to give further attention to both the human subsystem and the work organisational subsystem together with the technical subsystem in the design of AGV systems. Whereas the technical and work organisational subsystems are designable, the human subsystem is not; however, it influences and is influenced by the other two subsystems. Each subsystem is addressed in this section.

Designing the technical subsystem of an AGV system involves several interrelated technical design areas (as discussed in Section 1.3), and there are many decisions to make within each area that in turn influence the other design areas (Dolgui et al., 2022; Le-Anh & de Koster, 2006). The decisions in one design area must be aligned with decisions made in other design areas. Designing an AGV system is not simple; the technical design areas are often addressed in ad hoc ways in real-world applications that amount to an error-prone, time-consuming process (Andreasson et al., 2015; Draganjac et al., 2020). It is important to follow a design process when designing systems (Johansson, 2007). Following a design process can give a better overview and a full grasp of all the parts of the design. Additionally, it allows for more time to be spent on the design itself rather than on the design process (Wu, 1994).

As shown in Sections 1.1 and 1.2, automation in general and AGV systems in particular have the potential to yield many positive outcomes, such as reduced costs, the elimination of work tasks with poor ergonomic conditions, and increased productivity. However, achieving these outcomes is not guaranteed when introducing automation; it requires careful consideration of the requirements for automation in the design (Granlund & Wiktorsson, 2014; Groover, 2016). Granlund (2014) stated that having a clear understanding of the requirements facilitates the successful use and implementation of automation. When designing a product or system, such as an AGV system, it is important to understand the requirements that need to be met by the finished design (Chakrabarti et al., 2004; Johansson, 2007; Tompkins et al., 2010). The closer a design process is to completion, 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 to reduce the need to make costly design changes at later stages of the process.

As shown in Section 1.3, humans are important to consider in AGV system design. Vijayakumar et al. (2021) argued that 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 well-being (Neumann et al., 2021). On this topic, Sgarbossa et al. (2020) discussed 'phantom profits' in reference to situations in which the expected profits of introducing new technology are not realised due to the negative consequences of not taking humans into account in the design process, such as sick leave, increased errors, and reduced quality. Neumann et al. (2006) showed that the introduction of an AGV system caused reduced job control for operators and increased muscular demands when interacting with AGVs. People using new technologies may reject them if they perceive the costs to outweigh the benefits for them (Winkelhaus & Grosse, 2020). Kopp et al. (2023) explained examples of which operators deliberately sabotage AGV operations, when acceptance was not properly achieved in the implementation phase; thus, acceptance is vital. Dolgui et al. (2022) suggested that further research is needed on interactions between new technologies and human workers to determine whether the new technologies create any issues and that decision support based on the findings should be provided to companies.

Humans have been considered in the technical design of AGVs themselves in previous research, including developing algorithms to improve safety in load transfer situations (Song et al., 2020), developing algorithms to combine various sensor inputs (Indri et al., 2019), developing navigational capabilities that consider humans (Caccavale & Finzi, 2019; Indri et al., 2020; Löcklin et al., 2022), developing speed control (Liu et al., 2022a), developing more human-like movements (Bergman et al., 2020), testing wearable devices to facilitate the detection of humans (Babić et al., 2022), improving AVG safety features (Reich et al., 2022; Zamora-Cadenas et al., 2021), developing an interface to control AGVs (Mohsin et al., 2019), and developing communication between AGVs and humans through gestures (Zhang et al., 2019). While research and development of the technical capabilities of AGVs, including sensors, navigational technologies, control algorithms, communication, and safety features, are crucial for a safe work environment, it is also crucial to consider humans when designing the whole AGV system, and not only in developing the technical capabilities of the AGVs. For example, employees working with the AGVs need to understand how the safety features functions. Without this understanding there is a risk that they work in an unsafe way with the AGVs, despite the AGVs being equipped with several sensors.

Although previous research on the human subsystem in AGV system design is limited, some research has provided valuable insights. Kopp et al. (2023) highlighted acceptance as crucial when an AGV system is implemented and found that accurate perspective taking of managers can facilitate developing acceptance. Zuin et al. (2020) focused on safety aspects when designing an AGV system wherein humans and AGVs share the same work environment, considering the perspective of three roles: designer, worker, and safety expert. Three types of critical design factors were identified: technical, operational, and safety. Hrušecká et al. (2019) identified three categories of critical success factors for implementing an AGV system: technical, organisational, and safety. Tubis et al. (2024) suggested that research should focus on more issues than safety when humans collaborate with AGVs, such as errors that can occur during operations. Given how crucial the human subsystem is and the predominantly technical focus of AGV systems research, further research building on the findings of (Hrušecká et al., 2019), (Zuin et al., 2020), and (Kopp et al., 2023) are needed. Human factor aspects should be considered in system design (Neumann et al., 2021; Sgarbossa et al., 2020).

Humans should not only be considered on an individual level but also on an organisational level (Reiman et al., 2021). According to Cimini et al. (2021), many companies underestimate the costs and difficulties associated with adapting the organisation to new technologies, and organisations often lag behind technology. They argued that additional research is needed on how companies should co-design work organisation and technologies. Marcon et al. (2022) stated that the work organisation is important for the successful implementation of new technology and showed that companies which only focus on technologies risk failing. In research on technology implementations for Industry 4.0 technologies, several challenges, critical success factors, and barriers have been identified that relate to organisational aspects such as a lack of knowledge (Moeuf et al., 2020; Stentoft et al., 2021), the lack of qualified workforce (Senna et al., 2022), a lack of digital training (Raj et al., 2020) and the need for enhanced skills (Kamble et al., 2018). It has been suggested that this can be overcome with training efforts (Pozzi et al., 2023; Senna et al., 2022). It is also imperative to manage changes in an organisation. Sony and Naik (2020a) and Moeuf et al. (2020) argued that continuous improvements are crucial. Organisational resistance towards new technologies needs to be overcome (Cugno et al., 2021). Whether the challenges, barriers, and critical success factors apply to the design and operation of AGV systems or there are additional organisational challenges or barriers for AGV systems is unclear.

Kopp et al. (2023) stated that companies face organisational challenges when implementing AGV systems, and addressing these challenges is crucial for successful implementation. However, research has not focused on organisational challenges. They highlighted several acceptance factors that operators rated in a survey, including many organisational aspects such as training, communication, and clear responsibilities when problems occur. Lee and Leonard (1990) showed that implementing an AGV system changed the routines of operators, both on the shop floor and in storage areas, as well as managers and planners. Benzidia et al. (2019) demonstrated that when an AGV system replaces manual transports, new competencies are needed to manage the AGV system, and new roles are needed to ensure efficient operation. Bechtsis et al. (2017) highlighted the need to create skilled jobs for AGV systems. Current research provide some insights into the work organisational subsystem but further research is needed to support AGV system design.

1.5. Purpose

Summarising the main points from the previous sections, Section 1.2 showed that AGV systems can yield many positive outcomes for internal logistics. Although the application of AGV systems is not new, further research is needed to support the design of AGV systems by jointly considering the technical, human, and work organisational subsystems. Most previous research has focused solely on the technical subsystem. Technical design areas are often addressed in ad hoc ways in real-world applications, which may cause errors and prolong the design process (Andreasson et al., 2015; Draganjac et al., 2020). Many managers struggle to implement and make use of AGV systems (Grover & Ashraf, 2024). To avoid costly redesigns at a later stage of the design process, it is important to start with a clear requirements specification when implementing automation (Granlund & Wiktorsson, 2014). A comprehensive overview of the requirements for AGV system design could improve the design process.

Section 1.3 described the subsystems of an AGV system as it is considered in this thesis. Section 1.4 highlighted the importance of considering these subsystems when designing an AGV system and reviewed what previous research has focused on regarding these subsystems. The European Commission's concept of Industry 5.0 emphasises the importance of human-centric design (Breque et al., 2021). With its strong focus on technical issues, the literature (e.g. Benzidia et al., 2019; Fragapane et al., 2021a) does not provide clear support regarding how the human subsystem influences the two other subsystems and vice versa. Research has tended to focus on developing the technical capabilities of AGVs. Concerning the work organisational subsystem, research on the implementation of Industry 4.0 technologies has shown that organisational changes are needed. How to design the work organisational subsystem of an AGV system is not entirely clear. Tubis et al. (2024) stated that current research on AGV systems has not sufficiently addressed work organisation. There is a risk of suboptimisation when focusing on only one subsystems (Grosse et al., 2023), and the subsystems should be designed jointly (Hendrick & Kleiner, 2002). All three subsystems – human, technical and work organisational – must be considered together in the design.

The purpose of this thesis is to develop knowledge to support the design of AGV systems considering the human, technical, and work organisational subsystems.

1.6. Scope

This thesis focuses on AGV systems, which, as established in Section 1.3, consist of three subsystems: human, technical, and work organisational. The three subsystems are described in further detail in the next chapter, which presents the theoretical framework of this thesis. The human subsystem is not considered to be designable, but it influences and is influenced by the technical subsystem and the work organisational subsystem.

In this thesis, 'AGV' is used as an umbrella term. There are, as mentioned, an abundance of terms for AGVs, for example, laser-guided vehicles, automated guided carts, automated guided transports, autonomous intelligent vehicles, and autonomous mobile robots. There are technical differences between them. Autonomous intelligent vehicle and Autonomous mobile robots are for example usually considered to be able to navigate without the presence of any guidepaths and they have some decision-making capabilities. Laser-guided vehicles navigate, as the name implies, by lasers. The design of AGV systems in this thesis encompasses the design of these automated vehicles as well.

The research in this thesis has focused on AGV system applications in material flows in industrial environments for transporting goods within production facilities. In these environments, AGVs and humans work together and interact with each other. The potential to generalise the findings of the thesis to other contexts beyond these industrial environments is discussed in Chapter 6.

1.7. Outline of the thesis

Chapter 1 – Introduction: Provides background information, explains the purpose of the thesis, and defines its scope.

Chapter 2 – Theoretical framework: Presents the theoretical framework, including a section for each subsystem, a section on design processes and requirements, and the research questions.

Chapter 3 – Method: Describes the research process, research design, methods applied in the studies, and provides reflections on the research quality.

Chapter 4 – Summary of appended papers: Briefly describes each of the appended papers.

Chapter 5 – Results: Presents the results of the thesis in relation to the research questions.

Chapter 6 – Discussion: Discusses the contributions of the thesis, in relation to both the research questions and its purpose, the generalisability of the findings, its limitations and suggestions for future research.

Chapter 7 – Conclusion: Presents the conclusions of the thesis.

2. Theoretical framework

The theoretical framework of the thesis is presented in this chapter. Section 2.1 describes the definition of the AGV system and its subsystems. Sections 2.2, 2.3, and 2.4 then describe the human, technical, and work organisational subsystems, including related research, respectively. Since the purpose of the thesis is to develop knowledge to support AGV system design, Section 2.5 explains design processes in material handling and production and provides a categorisation of requirements for design. Finally, Section 2.6 presents the research questions.

2.1. AGV system definition

In Section 2.1.1, the definition for AGV systems is explained. The definition of the AGV systems is different among the appended papers and between the papers and the cover paper. Section 2.1.2 explains how the system definitions in the papers are suitable for the questions they address and why the definition in the cover paper is appropriate for the thesis.

2.1.1. System definition

In this thesis, AGV systems are considered to consist of three subsystems: human, technical, and work organisational. The division of the AGV system into these three subsystems was inspired by the Human-Technology-Organisation (HTO) model (Karltun et al., 2017). Karltun et al. (2017) developed the HTO model by drawing upon the model applied by the Swedish Radiation Safety Authority (2014) for the safe operations of nuclear power plants in Sweden. The HTO model has been applied to analyse work activities in the meat cutting industry (Vogel et al., 2013), improve production scheduling (Berglund & Karltun, 2007), and introduce new technology (Karltun et al., 2017). Figure 2.1 illustrates how AGV systems are conceived of in this thesis.

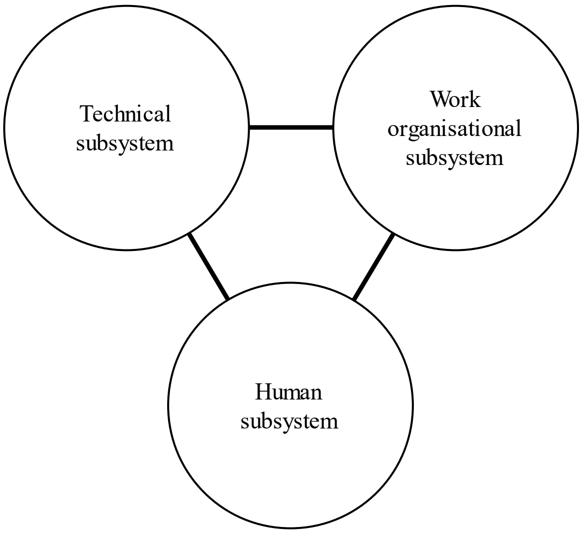

Figure 2.1. *The three subsystems of AGV systems as considered in this thesis.*

The HTO model is based on a socio-technical systems perspective (Karltun et al., 2017). Research on socio-technical systems has a long history, originating from the Tavistock Institute in the United Kingdom. The Tavistock Institute conducted research projects addressing problems in the British coal mining industry after World War II (Trist, 1981; Trist & Bamforth, 1951). These problems resulted from significant changes in the technical system, such as introducing new machinery, without considering their impacts on social structures or whether the changes were suitable for the physical environment (Fox, 1995). The work at the Tavistock Institute revealed that it was unsuitable to have separate approaches for technical and social systems and that the two systems should be considered jointly given their interdependence (Trist, 1981). Joint consideration of both technical and social systems is vital in socio-technical systems, and human needs should not be neglected when introducing technical systems, to improve the quality of working life (Mumford, 2006). Focusing on only one of the systems is likely to result in the suboptimisation of the whole system (Hendrick & Kleiner, 2002). Making changes in one part of a socio-technical system, such as the technical system, will influence the other parts of the system (Sony & Naik, 2020b).

The human subsystem concerns humans at the individual level. Humans are often needed in the operation of AGV systems, for example, to manage operational errors, handle design changes, and distribute information about the AGV system. It is crucial to consider human factors when designing and implementing new technologies (Neumann et al., 2021; Sgarbossa et al., 2020). The human subsystem influences and is influenced by the technical and work organisational subsystems. For example, humans are influenced by AGVs because they work in the same environments, which may cause worry or stress relating to the human factor aspects. Humans also influence AGV systems, since they are for example, required to manage errors. Neumann et al. (2021) argued that since humans cannot be re-engineered, human capabilities, limitations, and needs must be considered in system design. In line with this perspective, the human subsystem is not considered designable in this thesis. The human subsystem is further described in Section 2.2.

The technical subsystem of the AGV system encompasses the technical design areas presented in Chapter 1, including navigation technologies and guidepath design, traffic management and control, fleet size, failure management, battery management, and load-carrying mechanisms. These design areas must be addressed when designing an AGV system. The technical subsystem is further described in Section 2.3.

The third subsystem of an AGV system is the work organisational subsystem. Work organisation refers to three dimensions in this thesis: structure, job and competence. An example of a part of the work organisational subsystem in an AGV system is the structure, job, and competence dimensions for error management, including which roles should be involved, what work tasks are required and what kind of competencies are needed to fulfil the assigned tasks. While some studies classify work organisation as part of the technical subsystem (e.g. Carayon et al., 2015; Mumford, 2006), this thesis considers work organisation separately, in accordance with the HTO model. The work organisational subsystem and its dimensions are explained in further detail in Section 2.4.

2.1.2. System definitions in the papers and cover paper

The five papers appended in this thesis used different definitions for ‘AGV system’. In Paper I, an AGV system was considered to consist of technical design areas, which aligns with how ‘AGV system’ had been defined in previous research. The purpose of Paper I was to identify the requirements for AGV system design and how these requirements influenced the design. A similar definition was applied in Paper II, which focused on the technical design area of fleet sizing.

The findings from the case study in Paper I indicated that the case companies spent significant resources on human and work organisational aspects, extending beyond the strictly technical aspects. Building upon this insight, Paper III applied the HTO model. The technical subsystem in Paper III had a similar definition to that of the AGV system in Papers I and II. The technical subsystem in Paper III consisted of the technical design areas of an AGV system, equipment and tools, IT systems, and the physical environment. The technical subsystem interacts with humans and the work organisation.

Paper IV focused on requirements for automated loading and unloading of trucks, where the AGV system as such was not defined but was a part of the wider system for loading and unloading. In Paper V, work organisation in AGV systems in the implementation phase and post-implementation phase was examined. In Paper V, AGV systems were considered to include a work organisational subsystem that involved, for example, competencies required by various roles, new and changed work tasks, new roles and organisational structures that were part of the AGV system.

In the system definition of the cover paper, the AGV system consists of, as stated, a human, technical, and work organisational subsystem, and this definition is considered to be appropriate based on the findings of the appended papers. The system definition in Paper V is in line with this definition. This system definition, as stated in Section 2.1.1, also aligns with the socio-technical systems perspective stipulating that there is a need to jointly consider the subsystems.

The difference between the definitions in Paper I and in the cover paper influenced the name of one of the requirements categories (see Section 2.5.2). In Paper I, the category of requirements labelled ‘integration with existing systems’ encompasses requirements related to humans, safety, and interoperability. In the cover paper, since the AGV system is defined as consisting of three subsystems, the category is labelled ‘interactions within and between subsystems’.

2.2. The human subsystem

The individual human is central in socio-technical systems theory (Carayon et al., 2015). To design a well-performing system that also performs well concerning employee well-being, human factors should be considered (Neumann et al., 2021). Human factors (or ergonomics) 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, 2024). ‘Ergonomics’ and ‘human factors’ are synonyms, and from this point on, the term human factors is used. Table 2.1 provides an overview of the human factors in previous studies.

Table 2.1. *Categorisations of human factor aspects from previous research.*

Human factor categories in the cover paper	Human factors in the literature	(Daniellou, 2006)	(Neumann et al., 2021)	(Vijayakumar et al., 2021)	(Karltun et al., 2017)	(Sgarbossa et al., 2020)	(Kadir et al., 2019)	(Longo et al., 2019)	(Grosse et al., 2023)	(IEA, 2024)
Physical	Physical		x	x	x	x	x	x	x	x
	Biological	x								
Cognitive	Perceptual		x	x		x			x	
	Cognitive	x	x		x		x	x	x	x
	Mental			x		x				
	Knowledge		x							
Psychosocial	Psychosocial		x	x		x			x	
	Psychological	x			x			x		
Organisational	Organisational									x

As shown in Table 2.1, different studies have categorised the human factor aspects in different ways. For example, some studies refer to cognitive aspects as mental aspects (Sgarbossa et al., 2020), while others separate cognitive and knowledge aspects into two distinct categories (Neumann et al., 2021). The International Ergonomics Association includes organisational factors as a human factor aspect (IEA, 2024); however, in this thesis, work organisation is considered a separate subsystem. This thesis uses three categories of human factor aspects: physical, cognitive, and psychosocial. Each of these human factor aspects are explained in the next subsections. Section 2.2.4 explores how individual humans have been addressed in previous research related to AGV systems. Mental (cognitive) and physical aspects are more commonly addressed in research related to Industry 4.0, whereas psychosocial aspects have not been addressed as often (Neumann et al., 2021). Carayon et al. (2015) stated that physical, cognitive, and psychosocial factors of individuals need to be considered in socio-technical systems design.

2.2.1. Physical human factor aspects

Physical human factor aspects concern, for instance, manual tasks, work postures, repetitiveness of work, and fatigue (Kadir et al., 2019; Sgarbossa et al., 2020; Vijayakumar et al., 2021). These physical aspects can significantly influence a person's performance; for example, fatigue can have a negative impact and lead to injuries (Longo et al., 2019). 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 among operators.

2.2.2. Cognitive human factor aspects

Cognitive human factors focus on how work affects the mind and how the mind affects work (Hollnagel, 1997). They concern aspects such as learning behaviour, training and memory, which employees use to understand a situation and decide how to act (Longo et al., 2019). In manufacturing settings, workers may be exposed to a large amount of information and signals, requiring them to sort through all inputs to make decisions. Signals are detected by the sensory system, including sight, sound, touch, taste, and smell. Inputs from the sensory system become inputs for cognitive processes (Neumann et al., 2021). These inputs are processed based on memory and training, after which an employee determines what action to take in response to a situation. The cognitive aspects of memory, reasoning, and knowledge can be improved with training (Longo et al., 2019). If any change in the environment occurs, such as the introduction of an AGV system, workers may need to be (re)trained. Some researchers consider perceptual human factor aspects, i.e. those related to obtaining input from the sensory system, to be separate from cognitive human factor aspects (e.g. Neumann et al., 2021; Vijayakumar et al., 2021). In this thesis, perceptual aspects are included in the cognitive human factor.

2.2.3. Psychosocial human factor aspects

Psychosocial human factor aspects involve the perception of the social work environment and include aspects such as motivation, stress levels, manager support, and relationships with co-workers (Neumann et al., 2021). A worker's level of control over the work they perform has an impact on the mental strain they experience; low control and a high workload can cause high mental strain (Karasek, 1979). High mental strain can lead to poor mental health. When automation technology is introduced and the pace of work for operators is enforced by automation, employees' sense of control could decrease, potentially increasing mental strain (Neumann et al., 2021). Support from supervisors and co-workers is important to the well-being of employees and can help reduce the mental strain they experience (Netterstrøm et al., 2008).

2.2.4. Considerations of the human subsystem in previous research

Considerations of humans in AGV system design research are limited. Much of the attention given to humans in relation to AGV systems has focused on the technical development of AGVs' capabilities, with limited research addressing humans in system design. This section reviews the literature focusing on humans in AGV system research.

A few papers have addressed human aspects in relation to AGV systems. Berx et al. (2021) explored the psychosocial impact of introducing an AGV for collaborative order picking on humans. Their findings showed that monotony, cognitive load, and time pressures were reduced, while enthusiasm for work was increased in the experimental group. Kopp et al. (2023) conducted a survey on the acceptance of and overall satisfaction with the implementation of an AGV system among operational staff, project leaders, and managers. They explored the perspective taking of project leaders. Accurate perspective taking in relation to employees' evaluations of AGV systems is crucial for acceptance. Goli et al. (2021) addressed cell formation and production scheduling as an integrated problem, with AGVs handling transportation in cell manufacturing. A fuzzy linear programming approach was applied to the problem. Human factors in terms of the skill levels of workers, which influenced processing time and costs in manufacturing, were considered. However, human factors were not considered in the design of the AGV system. Vlachos et al. (2024) examined the impact of AGVs on flexible manufacturing systems through a case study. They found that AGV–human interactions significantly affected AGV system performance. Programming AGVs to improve operations, as well as avoid blockages and collisions, were important interactions to consider in improving system performance.

Safety has been the focus of several studies. Babić et al. (2022) developed a safety vest system for safe interactions between AGVs and humans. When an operator wearing this vest is nearby, the AGV either stops completely or slows down, depending on the proximity. This vest ensures safe operations without modifying the AGV or installing sensors in the infrastructure. Zamora-Cadenas et al. (2021) proposed and tested an ultra-wideband safety system for AGVs. Operators wore a device detected by the AGVs, which did not require any fixed infrastructure in the environment and improved the accuracy of estimating the position of obstacles in the AGV's vicinity. Reich et al. (2022) explored dynamic safety concepts for AGVs to improve operational performance by adapting AGV behaviour based on risks and capability areas. They developed and tested a model that improved efficiency compared to the previous worst-case-based safety manoeuvres in passing and overtaking scenarios.

Human interactions have been considered when developing the navigational capabilities of AGVs. Rey et al. (2019) developed an architecture for autonomous navigation that uses ultra-wideband localisation to detect humans near AGVs. Indri et al. (2020) proposed an algorithm that dynamically updates a safe path for AGVs, taking human interactions into account. Bergman et al. (2020) aimed to enhance employees' experiences with AGVs by adapting their movement and signalling. Their experiments showed that making AGV movements more human-like improved user experience and the comprehensibility of AGV actions. Kirks et al. (2020) developed a navigational algorithm based on proxemics theory, which considers humans' comfort zones to ensure that AGVs maintain a comfortable distance when passing. Löcklin et al. (2022) developed an approach for improved trajectory prediction of workers in a shared work environment, improving human–AGV interactions. The suggested approach allowed for better navigation and higher operating speeds while ensuring safety.

Sensors are a vital component of AGVs, and research has addressed their functions and roles. Indri et al. (2019) proposed an algorithm for sensor data fusion to enhance safety and efficiency in environments where humans and AGVs interact. Sabattini et al. (2017) developed an advanced sensing system to improve human–AGV interaction in busy manufacturing environments. The sensing system also assists in efficient load transfers and allows AGVs to deviate from predetermined paths to avoid obstacles.

Zhang et al. (2019) created algorithms enabling humans to control AGVs using gestures, enhancing collaboration. Song et al. (2020) developed a method to identify humans during autonomous docking at load transfer positions. Their method calculates human positions and motions in real time, allowing AGVs to adjust their docking behaviour, ensuring a safe work environment and improving the docking process.

Humans have been considered in designing interfaces between AGVs and operators. Mohsin et al. (2019) studied human factors and tested different heights, angles, and distances of the interface control panel in experiments to determine an ergonomically suitable design. Prati et al. (2021) investigated how to include user experience in the design of human–robot interaction, focusing on the design of interfaces. In one use case, they investigated interactions between AGVs and humans, mapping various situations, such as AGV errors and regular operations. This mapping was then used to create effective interfaces between AGVs and humans.

Martin et al. (2021) aimed to improve AGV fleet sizing by developing a model that considers the degree of interactions with humans and AGVs to minimise total tardiness.

These interactions can influence how many AGVs are needed to meet the demands of material flow.

Zuin et al. (2020) investigated critical decision factors for safety in AGV system design and identified training, AGV signals, safety standards, and separating AGV and human traffic. Tubis et al. (2024) conducted a literature review focusing on humans and AGVs in mixed environments. They found that previous research had focused on human–AGV cooperation, comparisons of AGV and human work, and the design of safe work environments. One key finding was that the mainstream research on AGVs and humans focused on safety. The authors agreed that while safety is crucial, other aspects related to humans should also be considered in research.

Kopp et al. (2021) aimed to identify success factors for human–robot interactions and evaluated them through a survey. Their findings showed that safety and avoiding the fear of job loss were important to operators. Developing trust in the robot among the operators was also important; however, the results show that practitioners were uncertain about what influences trust and how to best develop it. Kadir et al. (2019) conducted a systematic literature review, exploring how publications on Industry 4.0 integrate human factors into their research. They suggested that further empirical research on how human factors are affected when technologies are introduced is needed, and case studies in industry are promoted. Kadir and Broberg (2021) proposed a framework to guide practitioners in considering human factors in technology implementation for a human-centred design. Klumpp (2018) suggested evaluating the interaction between manual and automated systems before their implementation to avoid a high risk of failure. If humans are ignored in the design, then they may resist putting effort into using the new technology.

2.2.5. Conclusions regarding the human subsystem

Many papers support the notion that human factors need to be considered when implementing new technologies. Regarding AGV systems, the human subsystem has been considered with respect to improving the technical capabilities of AGVs, such as by improving safety, navigational capabilities and sensors. Some papers have addressed interfaces between AGVs and operators, while some authors have sought to estimate fleet size based on human interactions. Although Kopp et al. (2023) did not explicitly address human factor aspects, they focused on acceptance of an AGV system and showed that it is crucial. Zuin et al. (2020) focused on safety aspects. However, overall few papers address humans in the design of the AGV system.

2.3. The technical subsystem

The design of the technology or equipment is part of the technical subsystem in the HTO model (Karltun et al., 2017). The technical design areas of an AGV system comprise the technical subsystem. Table 2.2 provides an overview of the technical design areas considered in previous review studies. Each of these technical design areas is presented in the following subsections. As shown in Table 2.2, while the categorisation of the technical design areas in the studies is similar, there are minor differences. The categorisation used in this thesis is shown in the leftmost column of Table 2.2.

Table 2.2. *Technical design areas derived from literature reviews on AGV system design.*

Design area in cover paper	Design area in the literature	(Le-Anh & de Koster, 2006)	(Vis, 2006)	(Bechtsis et al., 2017)	(Fragapane et al., 2021a)	(Dolgui et al., 2022)
Navigation technologies and guidepath design	Guidepaths	x	x			x
	AGV operating layout			x		
	Operational area				x	
Traffic management and control	Scheduling	x	x	x	x	x
	Idle vehicle positioning	x	x			
	Routing	x	x	x		x
	Path planning				x	
	Deadlock resolution	x	x			
	Dispatching		x	x	x	
	Robustness and resilience				x	
Fleet size	Number of vehicles	x			x	x
	Vehicle requirements		x			
	Fleet size			x		
Battery management	Battery management	x	x			
	Charging strategy			x		
	Resource management				x	
Failure management	Failure management		x			
	Maintenance			x		
Load-carrying mechanism	Type of vehicle			x	x	x

A review of the literature addressing the technical design areas of AGV systems is presented in the following sections, including guidepath design, traffic management and control, fleet sizing, battery management, and failure management (Le-Anh & de Koster, 2006; Vis, 2006). More recent reviews by Dolgui et al. (2022) and Bechtsis et al. (2017) – as well as the review of Fragapane et al. (2021a), which focused on AGVs with free navigation and greater decision-making autonomy – complement the reviews of Le-Anh and de Koster (2006) and Vis (2006).

Although both Le-Anh and de Koster (2006) and Vis (2006) recognised that AGVs have different navigation technologies, they did not include them in their frameworks for AGV system design. AGVs once moved along physical guidepaths, new navigation technologies now allow AGVs to navigate completely without guidepaths (Fragapane et al., 2021a). Navigation technologies and guidepath design are addressed together in Section 2.3.1.

There are a variety of load-carrying mechanism of AGVs (Ullrich, 2015). Fragapane et al. (2021a) presented several different possibilities for load-carrying mechanisms. The load-carrying mechanism is included as a design area of AGV systems and is presented in Section 2.3.6. The next six sections cover the main issues related to each of the technical design areas and review the research that has been undertaken in them

2.3.1. Navigation technologies and guidepath design

Navigation technologies for AGVs have improved in recent decades (De Ryck et al., 2020). Figure 2.2 shows different guidance options, each offering different levels of flexibility in altering AGV movement. The choice of guidance technology impacts investment costs for the AGVs.

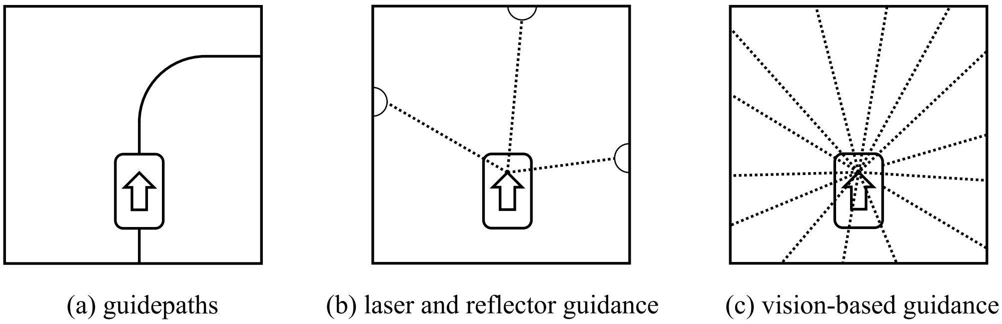
(a) guidepaths (b) laser and reflector guidance (c) vision-based guidance

Figure 2.2. *Navigation technologies (adapted from Fragapane et al., 2021a).*

Figure 2.2(a) illustrates an AGV following guidepaths, which can be either physically installed in the environment or virtually programmed into the AGV's software. Physical guidepaths can be created in several ways, such as using tape for optical or magnetic navigation or by embedding inductive wires in the floor (Le-Anh & de Koster, 2006). Since these guidepaths are physical, altering the paths can be challenging. Additionally, magnetic or optical tape on the floor is subject to wear and may need to be reapplied periodically. With virtual guidepaths, the guidepath information stored in the software allows for easier adaptation if changes occur in the environment. This flexibility is advantageous, as it enables quick adjustments to the AGV's navigation paths without the need for physical modifications.

Figure 2.2(b) shows an AGV using laser and reflector guidance technology. The AGV is equipped with a laser scanner that detects reflectors in the layout to calculate its position. Once several reflectors are detected, the AGV can determine its position by triangulating the reflectors' locations, allowing it to navigate through the layout (Fragapane et al., 2021a). Navigation based on lasers and reflectors can be combined with virtual guidepaths.

Figure 2.2(c) shows an AGV using vision-based navigation based on simultaneous localisation and mapping (SLAM), a technology for real-time vehicle navigation (Bloss, 2008). SLAM involves two activities: creating a map of the environment and calculating the vehicle's position within that environment. By comparing input from vision sensors with the reference map, the vehicle can determine its location, allowing for free navigation without the need for reflectors or physical guidepaths (Fragapane et al., 2021a). Vision-based navigation can make obstacle avoidance possible. With this guidance technology, there is often no need to design strict guidepaths for AGVs. Instead, the AGV determines its path to the destination. It is necessary to identify the areas of the facility where AGVs are permitted to move (Fragapane et al., 2021a). This approach provides greater flexibility and adaptability in AGV navigation.

Guidepath design involves determining how to connect different pick-up and drop-off points, charging facilities, and idle positions to minimise the total travel distance (Le-Anh & de Koster, 2006). Guidepath design is influenced by whether bidirectional traffic or only unidirectional traffic is possible. While bidirectional traffic can improve performance, it also complicates the control of the AGV system (Małopolski, 2018). Multiple lane routes are also possible, with at least one unidirectional lane in each direction of travel. Lee and Srisawat (2006) found that the manufacturing system's layout constrains the available paths, limiting the applicability of bidirectional traffic. Additionally, the facility's layout can constrain AGV movement, making it important to identify potential bottlenecks when designing an AGV system (Bechtsis et al., 2017).

Various guidepath configurations have been developed and evaluated (Rezapour et al., 2011), including single loop, tandem guidepaths and networks of guidepaths (Asef-Vaziri & Goetschalckx, 2008). The control and traffic management design area is influenced by the decisions made in the guidepath design (De Ryck et al., 2020). Deadlocks can occur in guidepaths when two or more vehicles block each other from performing a task, preventing any from continuing operations.

2.3.2. Traffic management and control

The control of an AGV system, which includes vehicle routing, scheduling, and dispatching (Vis, 2006), typically aims to ensure that transport requests are completed in a timely manner and that traffic flows smoothly. AGV control can be either centralised or decentralised. Traffic management involves preventing deadlocks and collisions and is crucial for controlling AGVs.

Centralised and decentralised control

Control for an AGV system can be divided into centralised and decentralised control (Le-Anh & de Koster, 2006). Centralised control involves a central controller making all decisions about routing, scheduling, and dispatching (De Ryck et al., 2020). While the aim of centralised control is to find optimal solutions, this can be computationally challenging with large fleets and numerous tasks. Draganjac et al. (2020) showed that a large fleet size can hinder the effectiveness of centralised control. By contrast, decentralised control allows each AGV to make decisions based on local information and communication with other AGVs. Although decentralised control rarely finds optimal solutions, it scales better with the number of vehicles and is more flexible from a computational perspective (De Ryck et al., 2020). More advanced AGVs tend to use decentralised control (Fragapane et al., 2021a).

Dispatching

Dispatching involves selecting an AGV from a set of available AGVs to perform a transport request from a set of active requests (Miyamoto & Inoue, 2016). Various simple heuristic dispatching rules have been investigated, such as the shortest travel distance, first come first served, the earliest due date first, and the longest waiting time (Ho & Liu, 2009; Ho & Chien, 2006; Hu et al., 2020; Liu & Hung, 2001). Dispatching performance can be improved by considering multiple rules simultaneously. Dispatching becomes complicated for AGVs with a load capacity larger than one, especially in job shop environments. 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 & Liu, 2009;

Ho et al., 2012). With a load capacity greater than one, dispatching may involve new decisions on how long to wait to fill the capacity, which loads to pick up and in what order the loads should be delivered (Chen et al., 2011; Chen et al., 2015).

Scheduling

Scheduling involves determining arrival and departure times along the route as well as at pick-up and delivery locations to perform tasks (Vis, 2006). Several studies have developed various algorithms for scheduling vehicles (Dolgui et al., 2022). Scheduling can be conducted either online or offline (Le-Anh & de Koster, 2006). In offline scheduling, transport requests within a certain future time horizon are known, allowing for optimised scheduling of transport request completion (Dang et al., 2021). Online scheduling must handle transport orders as they occur in real time due to the randomness of incoming orders or a limited future time horizon (Liu et al., 2022b; Zhang et al., 2023). Whether incoming transport requests can be planned in advance significantly impacts scheduling. While many studies have focused on scheduling vehicles in job shop environments, others have addressed scheduling for assembly lines (e.g. Chen et al., 2015; Mumtaz et al., 2024).

Routing

Routing involves determining the path that an AGV should travel to make a delivery (Vis, 2006). In routing decisions with multiple AGVs, it is important to consider that the shortest distance may not always result in the shortest travel time due to congestion. When routing vehicles in AGV systems, guidepaths are typically used as input for routing decisions. By contrast, AGVs using vision-based navigation use a map of the environment to find the shortest route to the destination while avoiding conflicts (Jun et al., 2021). With vision-based navigation, an AGV creates a new path each time it needs to move.

Control zones

Control zones are areas designated to avoid conflicts by limiting the number of vehicles allowed at a given time (De Ryck et al., 2020). Segments of a guidepath or specific areas of the facility layout can enforce this limit. When a control zone is occupied, vehicles that wish to enter must either replan their routes or wait until the zone becomes available. Control zones can help manage traffic flow and prevent congestion.

Control of idle vehicles

Another aspect of control in AGV systems concerns handling idle vehicles (Vis, 2006). Since workloads can vary over time, idle vehicles are expected. A vehicle becomes idle upon completing a transport request when no new assignments are available. It is important to determine where idle vehicles should go, known as dwell points, so that they can quickly respond to new transport requests. Ventura et al. (2015) optimised the dwell points of an AGV system within a specific guidepath design to minimise the response time to transport requests. In addition to the localisation of dwell points, how vehicles are dispatched to them are important. For example, Kabir and Suzuki (2018) suggested that natural idle times in operations should be used to recharge AGVs.

2.3.3. Fleet size

Fleet sizing for an AGV system involves determining the number of vehicles required to handle the material flow (Dolgui et al., 2022; Fragapane et al., 2021a). Fleet size significantly impacts AGV system performance (Małopolski, 2018). The number of vehicles is crucial, as it is a main driver of investment costs. Introducing too many vehicles can increase the risk of traffic congestion, which can reduce the throughput of the AGV system (Choobineh et al., 2012). Conversely, having too few vehicles may result in transport requests not being completed on time. Fleet size is influenced by several other design areas of AGV systems, including guidepath design, dispatching, the number and location of load transfer points (Choobineh et al., 2012), unit load size, AGV speed, overall material flow demand, and AGV load capacity (Lee & Srisawat, 2006; Vis, 2006).

Load capacity refers to how many loads each vehicle can carry, and AGVs with different load capacities can be used (Le-Anh & de Koster, 2006). Load capacity is important in fleet sizing. AGVs with a load capacity of one handle a single transport request at a time, whereas AGVs with larger load capacities can manage multiple requests simultaneously (Dang et al., 2021). AGVs with large load capacities offer the potential to increase throughput and enable the use of a smaller fleet size, as fewer vehicles are needed to meet transport demand (Bilge & Tanchoco, 1997; Le-Anh & de Koster, 2006). Consequently, having fewer vehicles can reduce the risk of traffic congestion. Yan et al. (2020) suggested that using AGVs with a load capacity of one can reduce the average completion time of transport requests – the time from starting to finishing a request – compared with AGVs with a greater load capacity, as the requests are completed one by one. AGV load capacity and fleet size impact the inventory required at receiving stations (Battini et al., 2013; Zhou & He, 2021) as well as investment and operational costs (Battini et al., 2015). AGVs with various load capacities may be suitable for use in different situations. However, AGVs with a load capacity greater than one have received less attention than AGVs with a load capacity of one (Dang et al., 2021; Yan et al., 2022).

2.3.4. Battery management

Since AGVs are typically battery powered, it is important to consider the locations of battery swapping or charging stations and when these activities should occur (Kabir & Suzuki, 2019). If charging is used, then various recharging strategies can be applied such as always requiring full recharging or if partial recharging is allowed (Jun et al., 2021). Among the schemes for determining when charging should occur (Kabir & Suzuki, 2018), opportunity charging involves AGVs charging their batteries during natural idle times, while automatic charging involves AGVs charging once the battery reaches a certain threshold.

Battery swapping generally entails less downtime because discharged batteries are swapped for recharged ones, allowing AGVs to continue operation without waiting for a recharge. However, swapping also requires several spare batteries, which imposes higher investment costs (Zou et al., 2018). Battery swapping also involves the challenge of removing the discharged battery and inserting a fully charged one into an AGV. According to Fragapane et al. (2021a), newer high-capacity batteries (e.g. lithium-ion batteries) reduce downtimes associated with charging or swapping. In around-the-clock operations, battery charging and swapping remain significant design areas in AGV system design (Zou et al., 2018).

2.3.5. Failure management

AGVs occasionally experience failures that must be managed to avoid operational downtime. Yan et al. (2018) emphasised the importance of failure management and maintenance strategies to achieve high availability of the AGVs, demonstrating that corrective maintenance can improve the throughput of an AGV system. Failures and maintenance for AGVs were further analysed by Yan et al. (2022), who investigated various maintenance strategies and evaluated the impact of including backup AGVs to cover for failed vehicles. Typically, AGVs stop and require manual assistance if a failure occurs; however, more advanced AGVs may be better equipped to avoid failures and, in some cases, even recover from them (Fragapane et al., 2021a). Supervising AGV operations is required (Benzidia et al., 2019). Soltani et al. (2019) developed an expert system to manage errors in AGV operations. This expert system summarises previous error experiences and knowledge on how to manage them, aiding technicians in quickly assessing and addressing errors.

2.3.6. Load-carrying mechanisms

AGVs can carry loads in various ways (Fragapane et al., 2021a; Ullrich, 2015). A common load-carrying mechanism is the forklift. Forklift AGVs are equipped with forklift forks for carrying loads in units such as EUR-pallets and unit loads suitable for forklift transports. Another load-carrying mechanism is the underride AGV (Ullrich, 2015), which positions itself underneath a unit load and lifts it onto its carrying platform. For unit loads such as racks or carts with wheels, underride AGVs connect to and drag the load using their own wheels. AGVs can also be equipped with various top modules (Fragapane et al., 2020). For example, a conveyor can allow an AGV to move a load horizontally when stationary. Another option is a shooter rack, a type of gravity flow rack that uses gravity to move a load to and from the required position (Emde et al., 2012). An AGV could also be equipped with a robotic arm to pick up and deliver unit loads. AGVs can also function as tuggers, towing carts attached to them (Battini et al., 2015; Emde & Gendreau, 2017).

2.3.7. Conclusions regarding the technical subsystem

The technical subsystem of AGV systems has been well studied and the individual design areas have been researched thoroughly. However, it is only from a technical perspective and for example how AGV system design is influenced by the human subsystem is unclear. There could be relevant requirements that influence the design areas.

As stated in Section 2.3.3, fleet sizing that considers the load capacity of AGVs is an area to which further research can bring clarity and support the design of AGV systems. Dispatching and scheduling for AGVs with load capacities greater than one have been analysed in previous studies (e.g. Dang et al., 2021; Ho & Liu, 2009; Ho et al., 2012); maintenance activities for AGVs with different load capacities have also been analysed (Yan et al., 2022). However, fleet sizing that considers AGVs with various load capacities has received limited attention in research.

2.4. The work organisational subsystem

The organisational subsystem in the HTO model refers to individuals at the collective level (Karltun et al., 2017). Cimini et al. (2021) applied a socio-technical perspective and reviewed literature to determine sub-dimensions of the organisation. They identified three sub-dimensions: organisational structure, competence, and job. The authors used the developed framework to study how Industry 4.0 technologies influence organisational change. Given that Cimini et al.'s (2021) framework is applied, and shown to be useful for analysing organisational change when Industry 4.0 technologies are introduced, and given that an AGV system is one such technology, this thesis divides the work organisational subsystem into the three aforementioned dimensions. Each of these three dimensions are explained in the next sections. This is followed by a review of literature addressing work organisation in relation to AGV systems and implementing Industry 4.0 technologies.

2.4.1. Organisational structure dimension

Organisational structure is expected to change due to automation and digitalisation (Klumpp & Ruiner, 2022). This structure impacts the employees' working conditions (see e.g. Daniellou, 2006; Karltun et al., 2017) and includes aspects such as the type of organisation, level of hierarchy, managers' span of control, chain of command and communication channels. Cimini et al. (2021) and Cagliano et al. (2019) also included number of hierarchical levels and the span of control of managers in the organisational structure. Granlund (2014) argued that roles and responsibilities need to be established concerning automation. The structure of teams within an organisation, such as size, group composition, complementary skills, and job roles, may also need to be decided (Katzenbach & Smith, 2015). Neumann et al. (2021) stated that it is crucial to understand which roles are affected by technology implementation.

2.4.2. Job dimension

Jobs encompass several work task characteristics that focus on work procedures and the nature of the tasks (Morgeson & Humphrey, 2006). These characteristics include task variety, identity, significance, autonomy, complexity, skill variety, and specialisation (see e.g. Campion, 1988; Hackman & Oldham, 1976; Humphrey et al., 2007; Morgeson & Humphrey, 2006). Cagliano et al. (2019) included job breath and job control as dimensions of work organisation. Bechtsis et al. (2017) stated that introducing AGVs requires standards and further regulations for the safety of operators and AGVs. Cimini et al. (2021) included job specialisation, referring to the number of different tasks and levels of autonomy; job formalisation regarding the standardisation and regulation of employee behaviour; and training. Parker et al. (2001) argued that work characteristics at the individual level should be considered at the team level. Hackman and Oldham (1976) highlighted the importance of designing group tasks to achieve group effectiveness. There could be job dimensions to consider on both individual and group level.

2.4.3. Competence dimension

The competence dimension involves the skills of employees (Cimini et al., 2021). When introducing new technologies, new competencies are often needed (Kadir & Broberg, 2021). Cimini et al. (2021) recognised four categories of competencies: technical, methodological, personal, and interpersonal. It is important to understand the need for developing new skills and competencies; otherwise, new technologies may not be used effectively. When automation is introduced, it is necessary to map current competencies and plan how to develop them (Granlund, 2014). Marcon et al. (2022) argued that developing the technical competencies needed to properly use new technologies is vital and that training is crucial for achieving this. New technologies can also influence job profiles, as employees with different skill sets may be required. Employees may also resist changes to work caused by the introduction of a new technology if the proper competencies have not been taught (Senna et al., 2022).

2.4.4. Considerations of the work organisational subsystem in previous research

Like the human subsystem of AGV systems, the work organisational subsystem has received less attention than the technical subsystem. Zuin et al. (2020) focused on safety in the design of AGV systems considering the perspectives of three roles: designer, worker, and safety expert. They identified three types of critical design factors: technical, operational, and safety. The operational category includes training and task rescheduling. The safety category includes the separation of human and AGV paths and identifying the number of pedestrian crossings.

Benzidia et al. (2019) found that new roles were needed in an organisation when AGVs were introduced in logistics operations that had previously been manual. These roles involved new work tasks that required new competencies to be developed through training or the recruitment of new employees. In their survey evaluating acceptance of AGV system implementations, Kopp et al. (2023) investigated a number of acceptance factors, including clear communication, education and training, support after the introduction of the system, and responsibilities regarding errors, all of which relate to the work organisational subsystem in this thesis. They highlighted differences in the perceived relevance of these factors among the operational staff.

Chivilò and Meneghetti (2023) developed an Industry 5.0 framework for feeding production lines. The framework comprises three dimensions – human centricity, sustainability, and resilience – and it was evaluated in the implementation of an AGV system. The framework helped improve acceptance by involving operators in implementation and clearly explaining the functions of the AGV. In addition, interactions between the AGV and other traffic were reduced. Operators were involved in the maintenance of the AGV and completed courses to learn how to handle the AGV in different situations. Lee and Leonard (1990) studied the changing roles of humans when an AGV system is used and concluded that extensive changes in the work performed by employees are required for success. Various employee roles are affected in different ways, such as those of logistics operators, production operators, production planners, managers, and supervisors. Some employees gain increased responsibility, while others experience reduced decision-making possibilities and their work is controlled by the AGV system. New work tasks have to be introduced for some roles, and correct training is highlighted as important for success.

Hrušecká et al. (2019) identified three categories of critical success factors for implementing AGVs, one of which refers to organisational aspects. This category includes work standardisation, decision-making aspects, and human resource management aspects, such as respecting rules and training personnel. Grover and Ashraf (2024) studied the moderating factors for the assimilation of AGVs into internal logistics, focusing on the interaction between the end users of AGVs and service providers (e.g. the suppliers of AGV systems). They stated that service providers facilitate the assimilation process, as end users often lack internal technical AGV expertise. Training is also key in the assimilation process, and a close relationship between the various actors is crucial for progressing end users towards later stages of assimilation. In these later stages, employee willingness to embrace change is crucial for success. Fear of job loss or lacking competencies can affect this willingness. Additionally, having in-house AGV experts helps ensure that the AGV system meets organisational needs.

Organisational aspects have been addressed in the literature concerning the implementation of Industry 4.0 technologies. Cagliano et al. (2019) conducted a multiple case study to investigate how smart manufacturing technologies influence work organisation. They found that although these technologies, including automation technologies, strongly influence the work organisation, previous literature had mostly focused on technological aspects and operator competencies. Their results show that introducing technologies affect operators' job breadth and autonomy – reducing their monitoring, control and decision-making roles – and also potentially empower them with increased cognitive demands. Marcon et al. (2022) explored socio-technical factors in the implementation of Industry 4.0 technologies by analysing survey data. They found that companies tend to focus on increasing productivity and reducing labour costs, an organisational perspective is necessary to support Industry 4.0 implementation. Workers are increasingly important in assisting with the implementation and use of these technologies. Integrating work-related aspects in the implementation improves the implementation of Industry 4.0 technologies. Training was also identified as essential to developing technical competencies.

Cimini et al. (2021) investigated the implementation of Industry 4.0 and its impacts on competencies, organisational structure, and job through a case study. They found that new structures are needed when technology is implemented. They also found that new job profiles are required, which could involve performing a wider range of tasks for employees and necessitate the development of new competencies through training. They argued that organisations need to be co-designed with introduced technology. Sony and Naik (2020a) highlighted critical success factors for the implementation of Industry 4.0 identified in the literature, one of which was that 'employees will be important for the success for Industry 4.0'. Employees require new skills, which affects both the recruitment of new employees and the skills of the current workforce. The authors also argued that managing changes in organisations is imperative and that there will be changes in the structures of work when implementing Industry 4.0 technologies.

Moeuf et al. (2020) conducted a Delphi study to identify critical success factors, risks, and opportunities associated with the implementation of Industry 4.0. They identified a lack of expertise as a risk, highlighting the need for employee training to develop the necessary skills. Substantial organisational change is required, and a critical success factor is to have a continuous improvement strategy. Communication is also crucial. Stentoft et al. (2021) conducted a survey and in-depth follow-up interviews to identify and understand the drivers of and barriers to Industry 4.0 readiness. Their results show that having the right competencies among employees is one of the most challenging aspects of readiness. Pozzi et al. (2023) conducted a multiple case study involving eight manufacturing companies to identify critical success factors for the implementation of Industry 4.0 technologies. The factors identified in their literature search, such as top management support, clear goals, cross-functional teams, a project plan, and training, were identified in all the studied cases.

Senna et al. (2022) focused on barriers to implementing Industry 4.0 technologies. They highlighted barriers identified in the literature that were then assessed by industry experts. Organisational barriers included the need for adaptive modifications at the organisational and process levels, the lack of a qualified workforce, and the lack of a digital strategy. The authors suggested that formal training is required to prepare employees. The results show that organisational barriers depend on other barriers. Nayernia et al. (2021) conducted a systematic literature review on implementing Industry 4.0 from an organisational perspective. They categorised their findings into five levels: industry and firm, smart factory, data, human resources, and supply chain. At the human-resources level, they found that Industry 4.0 would redefine roles and work content, competencies, education, and health and safety. Brodeur et al. (2023) investigated characteristics of organisational changes that companies could introduce to manage their transformation to towards Industry 4.0. These changes involved five elements: 1) announcing the new technologies, 2) involving stakeholders and naming a superuser for the technology, 3) training employees on the new technology, 4) establishing technical support to manage issues with the technology and 5) making continuous improvements.

Cugno et al. (2021) used a mixed methods approach to analyse barriers to and incentives for implementing Industry 4.0. They found that the most significant barriers are inadequate information on the potential of Industry 4.0 technologies, organisational resistance, and the perception that the business sector does not require investment in Industry 4.0. Raj et al. (2020) examined barriers to the implementation of Industry 4.0 in both a developing country (India) and a developed country (France). In both contexts, a significant barrier was the lack of internal digital training. Kamble et al. (2018) identified barriers to the adoption of Industry 4.0 technologies by first reviewing the literature and then assessing these barriers with input from industry experts and academics. Their results indicate that organisational barriers, such as employment disruptions, organisational and process changes and the need for enhanced skills, are linkage barriers. These barriers are highly influential and dependent on other barriers, meaning that a small modification in one barrier can influence other barriers and the overall outcome of Industry 4.0 adoption.

2.4.5. Conclusions regarding the work organisational subsystem

Research on the implementation of Industry 4.0 technologies has identified several important organisational aspects that should be addressed for a successful implementation. Training needs, organisational changes, acceptance, new roles may be needed, and continuous improvements have been identified in previous research. Despite the work organisational being crucial for the successful implementation of technologies, few studies have examined this topic for AGV system design. A few studies indicate that new roles are needed, and responsibilities can change when an AGV system is introduced, as well as the importance of developing acceptance. Safety has also been identified as important when AGVs and humans work together. However, further research on the work organisational subsystem in AGV system design can contribute to the mostly technical research.

2.5. Production and logistics design processes and requirements

The thesis focuses on AGV system design, and it is important to understand the different stages of design processes to show where the thesis can contribute. Accordingly, Section 2.5.1 provides an overview of design process models related to materials supply systems, production systems, materials handling systems, and for developing automation, illustrating the structure and common steps in design processes. A crucial part of the design process is clearly specifying the requirements of the completed design. Section 2.5.2 presents a categorisation of the requirements.

2.5.1. Design process models

This section presents examples of design processes suggested in the literature for designing material supply systems, production systems, and materials handling systems and for developing automation. These design processes offer a structured approach to designing complex systems and are therefore relevant to AGV system design, even if their scope extends beyond AGV systems. While the presented processes are not exhaustive of all design processes in the literature, they provide an indication of how such processes are structured.

Wu (1994) suggested a design process for production systems that begins with setting objectives for the design process and analysing the current situation, including gathering information about requirements. If an existing system is in place, it should be considered in the design of the new system to ensure a realistic starting point. The next step is conceptual modelling, which involves developing a framework for the system and establishing basic principles for its operation. Next, the detailed design step involves preparing a detailed specification based on the conceptual model, including decisions about layout, manufacturing equipment, and internal transport. After both conceptual modelling and detailed design, an evaluation of concepts is suggested to determine whether the design meets the requirements. The final step is deciding which design to pursue.

Johansson (2007) presented a design process for material supply systems consisting of four phases: planning, concept development, system-level design, and detailed design. In the planning phase, requirements for the design are identified and analysed, and objectives are set. During the concept development phase, various alternative conceptual designs are developed based on the requirements and objectives established in the planning phase. These conceptual designs are then compared to identify the most suitable one. In the system-level design phase, the selected concept is designed from a holistic perspective, which involves defining the different material flows within the material supply system. In the final phase, detailed design, the specifics of the material supply system are configured, including packaging design, storage areas, and specific transport equipment for material flow. The phases may overlap in practice and may require an iterative approach.

Tompkins et al. (2010) proposed a six-step design process model for materials handling systems. The first step involves defining the objectives and scope of the materials handling system to be designed. This is followed by an analysis of the requirements for the different parts of the materials handling system. The third step involves developing several design alternatives that meet the requirements identified in the second step. In the fourth step, these alternatives are evaluated based on the objectives established in the first step. The fifth step involves selecting the preferred alternative for each part of the materials handling system. Finally, the sixth step involves implementing the selected design, which includes installing the equipment and training employees. The authors also noted that the completed design configuration may not initially operate perfectly and should be continuously improved.

Granlund (2014) presented a framework for facilitating automation development in internal logistics systems. The first two stages of the framework involve setting objectives and analysing the current situation in internal logistics which results in a requirements specification. This is followed by the development of design concepts that fulfil the requirements. The design concepts are evaluated, and a decision is made regarding their appropriateness. If the design concepts are deemed appropriate and automation is a suitable solution, the next step is planning for automation, in which further requirements specific to an automated solution are identified. Conceptual solutions are then designed and evaluated, leading to another decision gate where the best solution is selected or rejected if none are suitable. A detailed solution design follows. The final two steps consist of implementation and follow-up evaluation.

The presented models share several similarities. They all include the initial steps of identifying and analysing the requirements that need to be met as well as setting objectives to be achieved. The presented design processes also involve several similar design steps, from conceptual modelling to detailed design. The presented design processes suggest developing and evaluating several conceptual designs before advancing the most suitable concept to the detailed design phase. Johansson (2007) included a system-level design process step that is not included in the models of Granlund (2014), (Tompkins et al., 2010) or (Wu, 1994). Implementation is included as a step by Granlund (2014) and Tompkins et al. (2010) but not by Johansson (2007) or Wu (1994). The presented models all have a requirements specification and setting of objectives phase, and at least two design phases: a conceptual phase and a detailed phase. Figure 5.3 illustrates a simplified design process based on the presented design process models.

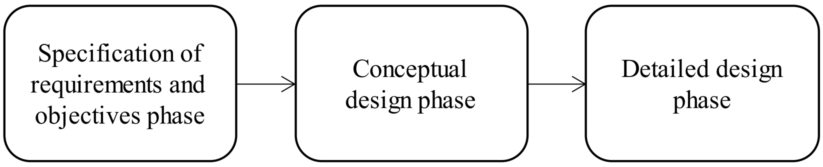

Figure 2.3. *Phases of the design process applied in the thesis.*

2.5.2. Requirements categorisation

The design process models presented in the previous section emphasise that a vital step is starting with a clear requirements specification (Granlund, 2014; Johansson, 2007; Tompkins et al., 2010; Wu, 1994). Granlund and Wiktorsson (2014) emphasised that one of the most important steps when considering automation technology is to develop a well-formulated requirements specification.

This section establishes a categorisation of requirements to consider in the design process for an AGV system, which was derived from the literature on material handling equipment (MHE) selection. The aim of MHE selection is to find the most suitable MHE based on the attributes of the context in which it will be used (Anand et al., 2011). Understanding the context in which the MHE will be used and the requirements it must meet is crucial (Saputro et al., 2015; Soufi et al., 2024). Although the literature on MHE selection is generally broader in scope than AGV systems, the attributes considered in such selection decisions are relevant for deriving categories of requirements for the design of an AGV system. Four categories of requirements were derived from the MHE selection literature: internal logistics environment, characteristics of transported loads, performance requirements, and interactions within and between subsystems.

Internal logistics environment

The first category of requirements concerns the internal logistics environment in which the MHE will be used. Hassan (2010) stated that the environment needs to be considered, particularly the layout of the facility. If the MHE is used in production, the type of production (e.g. job shop or assembly line) can influence the available movement paths in the layout, which can put requirements on the transport equipment used.

Physical restrictions such as columns, multiple floors, doors and ceiling height can create such requirements. For example, narrow areas of the layout such as aisles and the presence of columns may impose requirements on the guidepath design of an AGV system. Movement characteristics relate to overall distances, available paths in the layout, and the frequency of transports (Mirhosseyni & Webb, 2009). Along those lines, the width and length of aisles, as well as the availability of floor space, were considered by Bouh and Riopel (2015), in MHE selection.

Environmental conditions such as temperature, dust, moisture, and slopes should also be considered. Additionally, the locations where goods need to be picked up should be considered (Soufi et al., 2021), as well as whether goods are placed on the floor or on racks. Le-Anh and de Koster (2006) stated that the number and locations of pick-up and delivery points are often fixed when designing AGV systems. A requirement for the AGV system design to connect all these load transfer positions.

Requirements that influence system design can also come from regulations and standards outside the organisation (Fletcher et al., 2020). For example, the ISO standard for driverless industrial trucks entails certain requirements for AGV systems (ISO, 2023), such as speed, depending on the operating space and interactions with human operators.

Characteristics of transported loads

The second category of requirements derived from the MHE selection literature concerns the characteristics of transported loads. This includes the types of unit loads (e.g. pallets or boxes) and the general shape and the dimensions of the loads (Soufi et al., 2021). A requirement is of course that the MHE can manage the unit loads in the material flows. Cho and Egbelu (2005) suggested that handling a mix of different types of material and unit loads in one system can create additional requirements compared to a setup using only a single type of unit load since the MHE needs to be able to manage all unit loads. The weight of the unit loads should also be considered, as there may be limits to the carrying capacity of transport vehicles such as AGVs. Characteristics such as fragility, hazardousness and cleanliness can also influence MHE selection (Soufi et al., 2024).

Performance requirements

The third category of requirements concerns performance. Several measures are used to specify and assess the performance of an AGV system. Maniya and Bhatt (2011) developed a method for selecting the most appropriate AGVs and identified several performance variables, including flexibility, costs, and reliability. Costs are important to consider, such as those for purchasing, installing and operating the MHE (Soufi et al., 2024). Throughput, often used to measure AGV system performance, was defined by Yan et al. (2018) as the number of transport requests the system delivers within a certain period. The overall demand placed on the AGV system and the timing of this demand impact the system's fleet size (Vis, 2006). Flexibility may concern the system's adaptability to handle changes in the layout (De Ryck et al., 2020) and can also refer to the system's ability to manage variations in volume demands. Performance requirements for AGV system design can be expressed in many ways.

Interactions within and between subsystems

Soufi et al. (2021) acknowledged that MHE may need to interact and be integrated with other systems in a facility. The MHE may need to be able to send and receive data to and from information systems as well as to other equipment in the facility (Soufi et al., 2024). Given the increased use of automation and the Internet of Things in manufacturing, interoperability has become pivotal in Industry 4.0 (Lu, 2017). Interoperability refers to the ability of systems 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 between AGV systems from different suppliers is often lacking (Scholz et al., 2019). There could be interoperability requirements to consider in AGV system design. Additionally, Cho and Egbelu (2005) suggested that MHE may need to operate and connect with other MHE, for example, in transports potentially involving many material flows and several transport vehicles.

In mixed environments, human operators work alongside AGVs, and the interactions between manual operations and AGVs can be challenging (Oleari et al., 2014). The interactions between AGVs and manually operated vehicles as well as pedestrians makes ensuring safety a vital requirement (Sabattini et al., 2017). As stated in Section 2.1, although the human subsystem is not considered designable, it influences and is influenced by technical and work organisational subsystems. The human factor aspects described in Section 2.2 – physical, cognitive and psychosocial – needs to be considered in AGV system design. For instance, there may be concerns about new technology among employees that need to be addressed. Developing of acceptance and understanding of the introduced technology is crucial (Grosse et al., 2023; Kopp et al., 2023), which can put requirements on both the technical and work organisational subsystems.

The subsystems may involve requirements for each other subsystems. For example, the maintenance of AGVs requires the development of appropriate technical competencies, meaning that the technical subsystem imposes requirements on the work organisational subsystem. To ensure safe interaction between AGVs and humans, traffic regulations may need to be implemented in the work organisational subsystem. These regulations can influence the technical subsystem, as AGVs must adhere to the regulations, such as emitting alarm signals in certain situations or stopping when approaching areas with many pedestrians.

2.6. Research questions

This section presents the three research questions of the thesis, formulated based on the theoretical framework.

2.6.1. Research question 1

Section 2.5.1 presents four examples of design process models. In the presented models, the importance of starting from a comprehensive overview of requirements is highlighted (Johansson, 2007; Tompkins et al., 2010). Granlund (2014) states that accurate information on the requirements influences the progress and success of introducing automation. Fletcher et al. (2020) emphasise that a comprehensive understanding of requirements is essential for successfully developing systems where automation complements human work. An overview of the requirements is crucial in a design process.

Section 2.3 highlighted that AGV systems encompass several technical design areas, each involving multiple decisions that influence and are influenced by one another (see e.g., Fragapane et al., 2021a; Vis, 2006). Research on AGV systems has been technically focused (Fragapane et al., 2021a; Hrušecká et al., 2019; Zuin et al., 2020). The literature has provided a comprehensive understanding of the technical design areas in AGV system design. Le-Anh and de Koster (2006) and Vis (2006) provided examples of requirements, including facility layout, pick-up and drop-off locations, types of loads, and material flows, but the same comprehensive overview of requirements as there is for the technical design areas is lacking in the literature. It is also not only the technical subsystem with the technical design areas that needs to be considered; the human and work organisational subsystems must also be taken into account, and the literature has provided limited guidance on requirements relating to these subsystems for AGV systems. A wider perspective is needed, beyond the technical subsystem and technical requirements, which is crucial for employee well-being (Neumann et al., 2021). Tubis et al. (2024) identified a gap in the literature on AGV systems regarding the requirements for developing a shared work environment where humans and AGVs collaborate. Neumann and Village (2012) stated that if humans are not considered in the initial design, it is unlikely they will be considered in any formal way in the design process.

A comprehensive overview of requirements is needed. Therefore, to support AGV system design, the following research question (RQ) was formulated:

RQ 1: *Which are the requirements to consider in AGV system design?*

2.6.2. Research question 2

The requirements that are mapped and evaluated in the first step of the design process need to be met by the design of the system. Section 2.6.1 stated that AGV system design has been researched extensively but largely with a technical focus (Benzidia et al., 2019; Fragapane et al., 2021a). As highlighted in Section 2.2, it is crucial to consider humans in design. Not considering humans may result in designing systems that do not achieve the expected level of performance (Vijayakumar et al., 2021), and employee well-being may suffer due to stress or fatigue (Neumann et al., 2021). The need for human-centric design is one of the core dimensions of Industry 5.0 (Breque et al., 2021), which complements the technical orientation of research on Industry 4.0 (Ivanov, 2023). Section 2.2.4 showed that humans have been considered in the development of the technical capabilities of vehicles, such as navigation and sensors. However, the literature has provided limited guidance on designing an AGV system that take humans in consideration, besides improving technical capabilities.

Introducing new technologies necessitates adjusting work tasks, roles, responsibilities and division of labour between technology and human workers (Kadir & Broberg, 2021). It is essential to consider humans beyond the individual level (Reiman et al., 2021). Benzidia et al. (2019), for example, showed that new roles are needed when an AGV system is introduced, and training sessions are required to develop competence, and work tasks must be established. Lee and Leonard (1990) reported on changes in roles when an AGV system is introduced in a manufacturing context. Many studies have identified the need to develop further competencies when new technologies are introduced (e.g. Grover & Ashraf, 2024; Senna et al., 2022; Sony & Naik, 2020a). Clearly, an AGV system requires the work organisational subsystem to be designed appropriately, with changes or additions in the organisational structure, job dimensions and required competencies. Cimini et al. (2021) found that companies often underestimate the costs of adapting the organisation when technology is introduced and suggested the co-designing of the organisation and technology. Given the strong technical orientation of previous research on AGV systems, further knowledge on the design of the work the organisational subsystem is needed to support the design of AGV systems.

Socio-technical systems theory emphasises the need for joint consideration of subsystems. If only one subsystem is considered, there is a risk of system suboptimisation (Grosse et al., 2023). A joint consideration of the technical, work organisational and the human subsystems is necessary. Thus, the following RQ 2 was formulated:

RQ 2: *How can the requirements influence the design of an AGV system?*

2.6.3. Research question 3

In Section 2.5.1, it was shown that design processes involve different levels of detail, from a more conceptual level to more detailed, where all the presented design processes involve a step focusing on the detailed design of the system. RQ 3 focuses on a detailed part of AGV system design, namely fleet sizing.

Determining fleet size is a central design area in AGV system design given that it significantly influences investment costs (Choobineh et al., 2012; Fragapane et al., 2021a; Le-Anh & de Koster, 2006). Fleet sizing also has a substantial impact on AGV system performance (Małopolski, 2018). Traffic congestion can occur if too many vehicles are introduced, while late deliveries might occur if there are too few vehicles. Although the load capacity of each AGV influences fleet sizing (Vis, 2006), research has mostly focused on AGVs with a load capacity of one (Dang et al., 2021; Yan et al., 2020).

Using AGVs with a load capacity greater than one can confer a number of benefits, such as increased throughput, reduced traffic congestion, smaller fleet size, improved utilisation (Confessore et al., 2013) and reduced costs (Dang et al., 2021). However, the time it takes to fulfil individual transport requests may increase (Yan et al., 2020), which can influence the required inventory levels at the receiving stations (Battini et al., 2013; Zhou & He, 2021). The inventory levels need to ensure that there are no shortages of material until the next delivery arrives to replenish the station in part feeding.

Many potential combinations of fleet size and load capacity can be applied to a material flow, each yielding different outcomes for the required inventory at receiving stations. For instance, employing a single AGV with a large load capacity may necessitate a larger inventory at receiving stations to prevent material shortages, as deliveries occur less frequently. Conversely, using a fleet in which each vehicle has a load capacity of one could reduce the required inventory at receiving stations but would necessitate a larger fleet size. Further research on AGV combinations, specifically regarding fleet size and load capacity, can enhance existing knowledge on AGV fleet sizing and support this more detailed part of AGV system design. Therefore, RQ 3 was formulated:

RQ 3: *How do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding?*

3. Method

This section presents the method. Section 3.1 outlines the research process, detailing the research projects, studies conducted, and papers written throughout the PhD process. Section 3.2 describes the research design, including the papers and cases incorporated into the case studies. Section 3.3 details the methods applied in the appended papers, including case selection, and data collection, and analysis. Finally, Section 3.4 discusses research quality.

3.1. Research process

The research presented in this thesis was conducted across three research projects. The timeline of the research process is illustrated in Figure 3.1, which shows the duration dedicated to writing the initial versions of the papers, including planning, data collection and the actual writing phase. Subsequent rewriting of the papers, beyond their first versions, is not illustrated. The duration of writing the cover paper for the licentiate and PhD thesis is also shown.

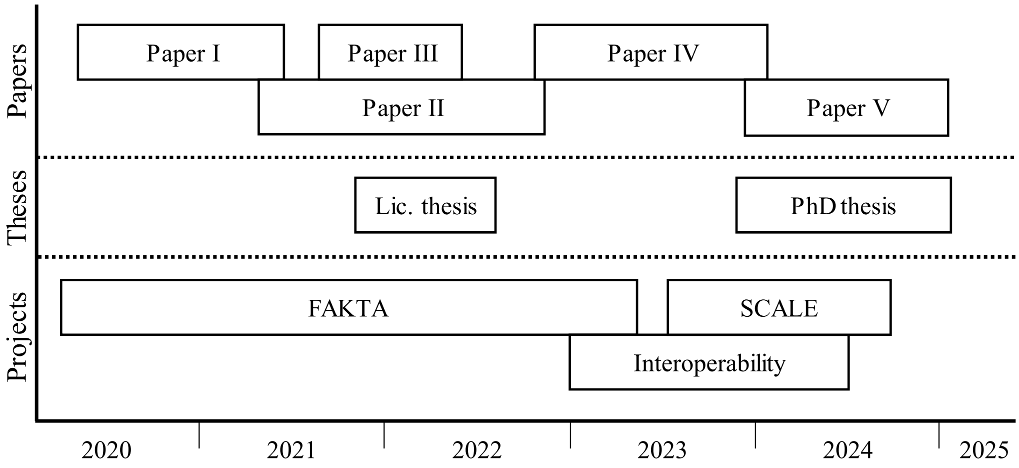

Figure 3.1. *Overview of the research process.*

3.1.1. Research projects

The first project, Flexible Automation in Kitting, Transport, and Assembly (FAKTA), was funded by the strategic innovation programme Produktion2030 via Vinnova. It consisted of a collaboration between Chalmers University of Technology (Chalmers) and several industrial actors in Sweden. Some participants were users of automation technology applied in production and logistics processes, while others were developers of such technology, including robotics, conveyor systems, and grippers. Additionally, one project participant provided consultancy services specialised in production and logistics firms. The studies for Papers I, II, and III were conducted within the scope of the FAKTA project.

The second research project focused on interoperability in automated loading and unloading and was titled ‘Interoperability for Safe, Reliable, and Efficient Interfaces Supporting Autonomous Transport’ (hereinafter, ‘Interoperability’). The project was funded by Chalmers and the University of Gothenburg and was a collaboration between these two institutions.

The third and final project, Supply Chain Automation of Loading/Unloading for Increased Efficiency (SCALE), focused on the automated loading and unloading of autonomous trucks. Several industrial parties with specialised expertise in cargo securing, AGVs, and autonomous trucks were involved in the project. The project was funded by the Swedish Energy Agency. The study for Paper IV was conducted within the scope of both this project and the Interoperability project.

The FAKTA project served as the starting point for the research from an empirical perspective. Interaction with the industrial parties involved in the FAKTA project clarified challenges they faced in designing and working with AGV systems and automation in general. Some parties had already introduced AGV systems and encountered issues such as design problems, organising work, securing systems, and developing acceptance among employees. It became evident that further knowledge on AGV systems could assist these industrial parties in their plans to use such systems in their internal logistics. Guided by this possibility, the literature was reviewed, and after assessing the problems in the industry and the literature, an initial research direction was determined.

3.1.2. The studies conducted

Five studies were conducted, resulting in five papers. These studies were carried out in industrial settings in which humans, forklifts, tugger trains, and AGVs operate together. The study associated with Paper I was the first to be conducted, and it provided input for the subsequent studies. Paper I focused on identifying the requirements for AGV system design and how these requirements influence the design.

After conducting the literature review in Paper I, it became clear that limited attention had been given to AGVs with a load capacity larger than one, and this became the starting point for the second study, which resulted in Paper II. The second study began with a further review of the literature on AGV fleet sizing and load capacity. Paper II focused on varying load capacity and fleet size to determine how these factors influenced inventory levels at receiving stations. The second study also provided an opportunity to delve into discrete event simulation.

The findings of Paper I indicated that humans and work organisation are crucial in AGV system design, regarding the acceptance of AGV systems among employees and the need for new roles, responsibilities, and work tasks. Previous research had not given much attention to these aspects. The third study, associated with Paper III, was a continuation of Paper I, focusing on the organisational and human challenges that emerge when AGVs are introduced.

The fourth study was initiated as part of the SCALE and Interoperability projects and resulted in the writing of Paper IV. Paper IV focused on requirements for automated loading and unloading. Unlike the other studies, Paper IV did not specifically address AGV systems; however, one of the cases involved using AGVs for automated loading and unloading. The findings from Paper IV provided additional details on the requirements for AGV system design, with a focus on applications of AGVs in loading and unloading.

The fifth study builds on the insights from Paper III and resulted in the writing of Paper V. In Paper III, which identified several human and organisational challenges and discussed a number of actions to manage them during the AGV introduction. Paper V used the identified organisational challenges and suggested actions from Paper III as a starting point. Paper V did not only seek to confirm the actions suggested in Paper III. Paper V also went beyond the introduction phase, which was the focus of Paper III, and analysed work organisation in the post-implementation phase, highlighting differences between the phases.

3.2. Research design

This section describes the research design. Both qualitative and quantitative methods were used in the research conducted for the papers appended to this thesis, with the majority of the research being qualitative. Papers I, III, IV, and V were case studies, which are common in qualitative inquiries (Stake, 2005). Case studies are appropriate when researching a contemporary phenomenon in real-world contexts (Yin, 2014). The FAKTA project, with its industrial actors, provided access to ample empirical data and opportunities to collect data from their operations. The SCALE project also provided access to empirical data. The four papers based on case studies all focused on phenomena in real-world contexts. Paper II, which is a discrete event simulation study, the model in the paper was inspired from a real-world material flow. The cases studied in the papers are described in Table 3.1.

Table 3.1 shows that some of the AGV systems were used in more than one study. Case 1 in Paper I is the same AGV system as Case 2 in Paper III. Case 3 in Paper I is the same AGV system as Case 1 in Paper III and Case 2 in Paper V. Naturally, some of the data collected from the interviews and observations were relevant for multiple papers despite their different aims. Table 3.2 provides an overview of the data collection process for each case, clarifying whether the data were used in multiple papers. Data on AGV system design – understanding how the system functions, how it interacts with humans in different ways and how it changes in various roles in the operations –were relevant in both Papers I and III. Additional interviews and observations were conducted in the study for Paper III to extend the data collection from Paper I within the focus of Paper III. For Paper V, further interviews were held with employees involved in the initial implementation and post-implementation phases of the AGV system, complementing the data from the case study in Paper III.

The literature has been continuously reviewed throughout the PhD process, beginning with previous research on AGV systems and their design. Scopus was the primary database used to find relevant literature. For each paper, updated literature reviews were conducted, focusing on the specific problems they addressed. From the initial search, related terms beyond ‘AGV systems’ were explored, such as ‘Industry 4.0’, ‘technology implementation’, ‘socio-technical systems’, ‘human factors’ and ‘human–robot interaction’. The concept of Industry 5.0, introduced in 2021, directed the search towards human factors, work design, and socio-technical systems, which were relevant for Paper III. Notifications on search strings in Scopus and Web of Science were used to stay up to date on new publications, specifically those related to AGV system design. These search strings included several terms related to AGVs, such as autonomous mobile robots, to ensure that relevant papers were not missed. Many of the papers on AGV systems focused on technical design, such as new algorithms for scheduling or dispatching. While papers focusing solely on specific technical design areas were reviewed, they did not constitute the core literature in the thesis or the papers.

Table 3.1. *Case descriptions.*

Paper	Case name in paper	Case description
Paper I	Case 1	The case involves an AGV system consisting of two AGVs used in the logistics part of a production facility to move racks with empty packaging material. The AGVs navigate by virtual guidepaths. The AGV system operates within a busy environment where other manually operated transports take place and many operators are moving around.
	Case 2	The case involves an AGV system consisting of three AGVs used in a logistics environment in connection with production to move racks of boxes between three stations. The AGVs navigate by virtual guidepaths. The AGV system operates within a busy environment where other manually operated transports take place and many operators are moving around.
	Case 3	The case involves an AGV system consisting of 17 AGVs used to move half-pallets. These AGVs manage nearly all the material flows in the factory. The AGVs pick up the pallets from the racking move them to, from, and between production cells. The AGVs navigate by lasers and reflectors. A few material flows are still managed with manually operated forklifts, and operators move around in the environment.
Paper III	Case 1	Case 1 in Paper III refers to the same AGV system as Case 3 in Paper I, but the focus in Paper III was on the organisational and human challenges when AGVs are introduced.
	Case 2	Case 2 in Paper III refers to the same AGV system as Case 1 in Paper I, but the focus in Paper III was on the organisational and human challenges when AGVs are introduced.
Paper IV	Case 1	The case involves the material flow of palletised goods from a warehouse of a third-party logistics provider to the assembly plant of an original equipment manufacturer (OEM). The transports are performed by a transport provider. The automated loading and unloading solution is based on conveyors inside the truck, which are matched by conveyors in the sending and receiving facilities. Truck drivers perform several activities during loading and unloading.
	Case 2	The case involves the material flow of racks from a supplier to the same OEM as in Case 1 in Paper IV. The transports are performed by a transport provider. The automated loading and unloading solution is based on conveyors inside the truck, matched by conveyors in the sending and receiving facilities. Truck drivers perform several activities during loading and unloading.
	Case 3	The case involves the material flow of palletised goods from a factory to a finished goods warehouse, both owned by the same company. The transports are performed by a transport provider using an autonomous truck. The automated loading and unloading solution is based on an AGV that performs the loading and unloading.
Paper V	Case 1	The case involves an AGV system consisting of three AGVs. One AGV is dedicated to moving kits from a kit preparation area to production and returning empty kits. The remaining two AGVs are used to move palletised goods, to, from, and between production cells, and to finished goods storage. The AGVs use SLAM-based navigation. The AGV system operates within a busy environment where other manually operated transports take place and many operators are moving around
	Case 2	This is the same AGV system as case 3 in Paper I and case 1 in Paper III. The focus is on the work organisation in the implementation phase and in the post-implementation phase.

Table 3.3 provides an overview of each paper, including the type of study, the focus of the study, data collection methods, analysis methods, outcomes and the contribution of the papers to the RQs of the thesis. Further details on the methods applied in each paper are provided in Section 3.3.

Table 3.2. *Overview of the data collection.*

Paper	Case	Collected data
Paper I	For all cases	– Interview with AGV supplier 1 to validate the framework applied in the study. – Interview with AGV supplier 2 to validate the framework applied in the study.
	Case 1	– Interview 1 with Project Manager*. – Interview 2 with Project Manager*. – Visit to the site, informal interviews with Operators and observations of the AGV system in operation. – Documents including reports from the introduction, educational materials, and responsibilities for different employees.
	Case 2	– Interview with Project Manager 1. – Interview with Project Manager 2. – Documents including educational materials and new responsibilities for employees.
	Case 3	– Interview with Reliability Engineer 1. – Visit to the site, informal interviews with Operators, and observations of the AGV system in operation.
Paper II	N/A	– Interview with global logistics specialist at the company from which the model was inspired. Explanation of data and how the material flow work – Site visit to observe the material flow – Historical demand data – Drawings of the material flow
Paper III	Case 1	– The collected data from case 3 in Paper I were used as a basis for understanding the AGV system. – Interview with Reliability Engineer 1. – Interview with Logistics Operator. – Interview with Production Operator. – Group interview with Production Manager 1, Reliability Engineer 1, and Safety Representative. – Visit to the site to observe the AGV system in operation. – Documents from the AGV introduction including work instructions, and traffic rules. – Interview to discuss the results of the paper with Reliability Engineer 2.
	Case 2	– The collected data from case 1 in Paper I were used as a basis for understanding the AGV system. – Interview with Logistics Developer 1* and Logistics Developer 2. – Interview with Production Technician. – Interview with Team Leader / AGV Superuser. – Interview with Logistics Operator. – Documents from the AGV introduction, including lessons learned, responsibilities of employees, and work instructions. – Group interview to discuss the results of the paper with Logistics Developer 1, Logistics Developer 2, and Logistics Developer 3.
Paper IV	Case 1	– Visit to the site of the recipient of goods including interviews and observations. Observations of the activities of Truck Driver 1. – Interviews with Supply Chain Engineers 1 and 2, and Truck Driver 1. – Visit to the site of the recipient of goods including interviews and observations. – Interviews with Team Leader 1 and Logistics Operators 1 and 2. – Visit to the site of the sender of goods including interviews and observations. Observation of the activities of Truck Driver 2. – Interviews with Team Leader 2, Logistics Operator 3, Truck Driver 2. – Interview to discuss the results of the paper with Supply Chain Engineer 3**.
	Case 2	– Visit to the site of the recipient of goods including interviews and observations. Observation of the activities of Truck Driver 3. – Interviews with Supply Chain Engineers 1 and 2, Logistics Operator 4, and Truck Driver 3. – Visit to the site of the sender of goods including interviews and observations. Observations of the activities of Truck Driver 4. – Interviews with Production Manager, Maintenance Employee, Logistics Operator 4, and Truck Driver 4. – Interview to discuss the results of the paper with Supply Chain Engineer 3**.
	Case 3	– Visit to the site of the sender and recipient of goods including interviews and observations. – Interviews with General Manager in Logistics, Logistics Engineer, and Process Engineer.

		– Visit to the site of the sender and recipient of goods including interviews and observations. Interviews with Logistics Engineer, Process Engineer, AGV supplier, Transport Provider Representative, and Operator. – Interview to discuss the results of the paper with General Manager in Logistics and Process Engineer.
Paper V	Case 1	– Interview with Project Manager 1. – Visit to the site to observe the AGV system in operation. – Interview with Project Manager 2 and Process Engineer. – Visit to the site to observe the AGV system in operation and seeing the developments since the previous visit. – Interview with Production Technician. – Interview with Project Manager 2 and Process Engineer. – Visit to the site to observe the AGV system in operation and developments since the previous visit
	Case 2	– The collected data from case 1 in Paper III were used as a basis for understanding the AGV system. – Interview with Production Manager who was the manager during AGV implementation. – Interview with Production Manager 2 and Reliability Engineer 2.

*Logistics Developer 1 is the same person as the Project manager in Case 1 in Paper I, this person changed roles in between the data collection.

**This was the same interview.

Figure 3.2 shows the relationships between the papers and the research questions of the thesis as well as the relationships between the papers. The dashed arrows between the papers indicate that subsequent papers were initiated partly based on insights from previous papers. Paper I led to the initiation of studies for Papers II and III. The results of Paper III provided ideas for the focus of Paper V. As shown in Figure 3.2, Paper I contributes to answering RQ 1 and RQ 2 of the thesis. Paper II is the sole contributor to answering RQ 3. Paper III addresses RQ 1 and RQ 2, focusing on the human and work organisational subsystems. Paper IV, which focuses on requirements for loading and unloading, contributes to answering RQ 1. Finally, Paper V contributes to RQ 2 regarding the dimensions of the work organisation: structure, job, and competence.

Paper I focuses on the requirements for AGV system design, while Paper IV addresses the requirements for automated loading and unloading. Paper III examines human-related and organisational challenges when an AGV system is introduced. The challenges identified in Paper III are translated into requirements for the AGV system design by analysing how each challenge influenced the system design and formulating corresponding requirements. For example, a challenge identified in Paper III was that the operators on the shop floor were worried and stressed about the AGVs in the introduction, which influenced their well-being. The requirement for the design was to overcome this worry and stress. In the cases studied in Paper III, training programmes were developed, and operators were informed about the AGV system to help them become familiar with the AGVs. By translating the challenges into requirements, Paper III contributes to answering RQ 1. Additionally, Paper III provides insights into how human-related and organisational challenges were addressed during the AGV introduction, such as operator training, new work organisational structures, and work tasks. Thus, Paper III also contributes to answering RQ 2.

Table 3.3. *Overview of the studies for the appended papers.*

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Type of study	Multiple case study consisting of three cases in production setting.	Discrete event simulation study inspired by a real-world industrial material flow in the automative industry.	Multiple case study consisting of two cases in production settings.	Multiple case study consisting of three cases of loading and unloading in deliveries between warehouses to production facilities.	Multiple case study consisting of two cases in production settings.
Focus of study	Identifying requirements for AGV system design and developing an understanding for how the identified requirements influence the design.	Research question of the study: how do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding.	Human- and organisation-related challenges arise that in the introduction of AGVs in production facilities.	Exploring automation in loading and unloading. The paper addresses the research question: which are the requirements for automated loading and unloading of autonomous trucks.	Understanding what is required of the work organisation to support AGV operations in the implementation and post-implementation phases.
Data collection methods	- Interviews - Observations during site visits - Documents related to new work tasks and educational materials	- Historical demand data - Documents related to layout, distances, and load transfer positions - Observations of material flow during site visits - Interviews with global logistics specialist	- Interviews - Observations during site visits - Documents related to work organisation	- Observations during site visits - Interviews - Video recordings - Quantitative data on the loading and unloading solutions used	- Interviews - Observations during site visits
Analysis	An analytical framework was derived from literature, consisting of four sources of requirements. The cases were analysed cross-case based on the analytical framework.	Various combinations of fleet size and load capacity were evaluated in the simulation model on their impact on inventory levels.	The cases were compared using the adapted HTO model, analysing challenges in human–technology, technology–organisation and human–technology–organisation interactions.	Based on layers of interoperability and a framework for types of functions that can be automated, an analytical framework was created and used to analyse and compare the cases and to identify the requirements for automated loading and unloading.	By reviewing literature on work organisation in relation to technology implementation, an analytical framework was developed. The analysis facilitated cross-case comparisons of the two studied cases.
Outcome	The main outcomes were the identification and understanding of requirements for AGV system design. The study was also a starting point for Paper II. Paper I also provided input for Paper III, regarding the relevance of humans and work organisation in AGV systems.	The main outcome was understanding of how combinations of load capacity and fleet size influence inventory levels at receiving stations.	Several challenges in relation to humans and work organisation when AGVs are introduced were identified. Paper V was initiated as a continuation of the outcomes of this study.	This study contributed additional knowledge about requirements in AGV system design in the application of loading and unloading, related to interoperability between sender, recipient, and transport provider.	This study clarified what is required of the work organisation to support AGV operations in the implementation and post-implementation phases.

Case studies are suitable for exploratory research (Meredith, 1998) which aligns well with the aims of the papers, except Paper II. Case studies provide depth and insight into phenomena about which little is known (Ellram, 1996). Paper I aimed to identify requirements for AGV system design, and identified requirements that were not technical which previous research had given limited attention to. Humans and work organisation had only seen scarce attention within the technical focus of previous research on AGV systems, but Paper I showed that these were important. It was therefore considered suitable to explore human-related and organisational challenges through a case study in Paper III. The work organisational design for supporting AGV systems was explored in Paper V, particularly by examining the implementation and post-implementation phases. Few papers have addressed automated loading and unloading beyond developing and suggesting technical solutions. Identifying requirements for automated loading and unloading, considering the interoperability between sender, recipient, and transport provider, through a case study was therefore appropriate. Case studies were thus considered to be suitable for Papers I, III, IV, and V. However, case studies are not without drawbacks (see Section 3.4) in relation to the research quality.

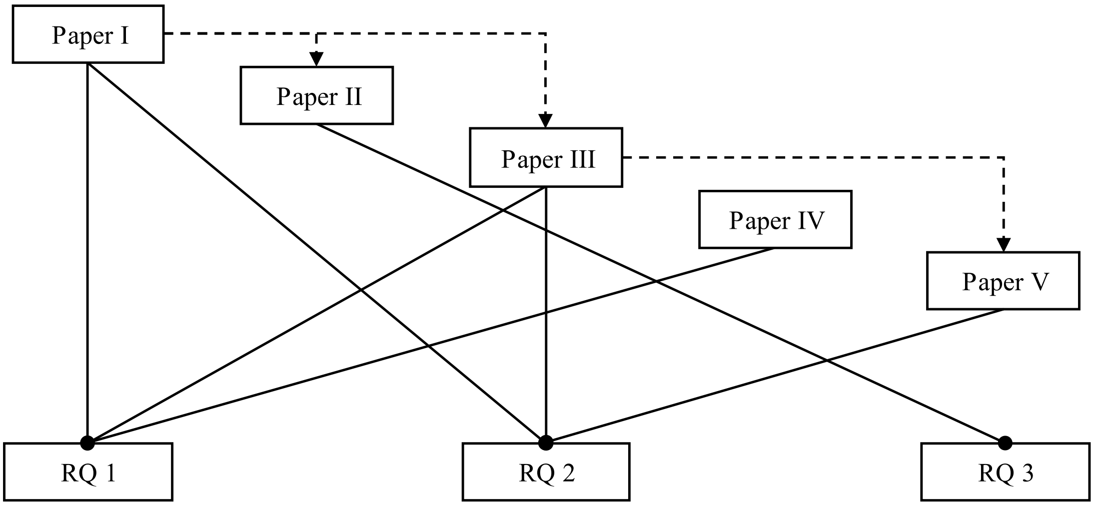

Figure 3.2. *Relationships between the papers and their contributions to the RQs.*

In Paper II, a discrete event simulation study was conducted. Discrete event simulation is a type of simulation in which changes to the modelled system occur at discrete points in time when events occur (Banks, 2010). Simulation modelling allows for testing changes or improvements without altering existing systems as well as running experiments in compressed time (Chung, 2003). Since it was not possible to perform experiments in any real-world industrial material flow regarding combinations of load capacity and fleet size, developing a simulation model enabled studying and perform experiments in the simulation model. Through one of the industrial parties in FAKTA, data from a real-world material flow were gathered, providing a good basis for developing a realistic and industrially relevant model. In total, five factors were analysed: load capacity, fleet size, speed, load transfer duration, and routing restrictions. Simulation was considered an appropriate method for the purpose of Paper II, as conducting actual experiments in the real world with these factors would not have been possible. Simulation has been applied to similar contexts and problems in previous research, indicating its relevance and appropriateness for the studied problem.

3.3. Methods applied in the appended papers

This section presents the methods applied in the five papers appended to this thesis, including case selection, data collection and analysis.

3.3.1. Methods applied in the study for Paper I

The aim of Paper I was twofold: to identify requirements for AGV system design and to develop an understanding of how the identified requirements influence that design. The framework developed for the paper had two parts: design areas in AGV system design, in terms of the technical subsystem as it is considered in the thesis, and sources of requirements.

Case selection

Three cases were studied, each with different features and unique characteristics but also some similarities. Eisenhardt (2021) stated that cases with differences and similarities should be chosen to sharpen the focus on the empirical phenomenon, mitigate alternative explanations, and improve generalisability. The design of the AGV system had recently been completed at the time of data collection, and details regarding requirements for the design and the design of the AGV system were still fresh in the interviewees' minds. The cases were considered suitable for studying the requirements for AGV system design, even though the AGV systems had already been established prior to data collection.

Fleet size was one aspect in which the three cases differed from each other. Case 3 had a relatively large fleet of AGVs, whereas cases 1 and 2 had fewer vehicles, which can influence interaction with humans and the design of guidepaths, and traffic management and control. The environment in which the AGVs were used also differed: in cases 1 and 2, the AGVs operated in logistic areas connected with production, while in case 3, they were used in cell production. The unit loads moved by AGVs also differed between the cases: racks were moved in cases 1 and 2, whereas two types of pallets were moved in case 3. As for their similarities, the load-carrying mechanisms were forklifts in all three cases, and in all the cases, virtual guidepaths were used for navigation. However, the guidance technology differed: cases 1 and 2 used natural features for navigation, whereas case 3 used laser-based guidance with reflectors. The differences and similarities between the cases allowed for identifying, comparing and understanding requirements for AGV system design and, in turn, determining how they could be met in the design of AGV systems.

Data collection

An analytical framework consisting of two parts was developed. The first part focused on the design areas of AGV systems. The second part was sources of requirements from which design requirements for the AGV system arise from. The developed framework was presented to two major suppliers of AGV systems to gather their opinions on whether the proposed framework and its sources of requirements covered the requirements they assess when working with their clients. Both AGV suppliers validated the framework.

Once the framework was finalised, data were collected through interviews. Some interviews were conducted in person, but most were conducted online using Zoom and Microsoft Teams due to the response to the COVID-19 pandemic, which restricted company visits. In the studied cases, project managers involved in the design of the AGV systems were interviewed. The interviewees had been involved in the design of the AGV and were knowledgeable about the requirements and the design of the AGV system. An interview guide based on the theoretical framework was created and followed during the interviews. Before each interview, the guide was sent to the interviewees to allow them to review the questions in advance. Each interviewee consented to the interview being audio recorded to facilitate later review of the interview's content.

Data were also collected during later site visits involving the direct observation of the AGV systems in operation in cases 1 and 3, where visits were allowed. During each site visit, the project manager explained the operation of the AGV system being observed. Informal conversations with employees in various roles, such as logistics operators, team leaders and production technicians, were conducted during the visits to gather their perspectives on the AGV system, including their experiences working with the AGVs. Notes were taken during the guided tours. For case 2, however, site visits were prohibited during the pandemic. As an alternative, additional attention was paid to the AGV system's operation during the online interviews. The project managers presented photographs and videos 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 provide a good understanding of the flow of the AGVs and the operations in place of a site visit. At least two of the authors of the paper were present during all the interviews and direct observations.

To supplement the primary data, secondary data were collected in the form of internal reports, organisational charts, work routines, and educational materials for the operators. These documents illustrated, for example, how procedures and routines for different roles changed in response to the introduction of the AGV system and the lessons learned from its introduction. Following data collection, case descriptions were created from the compiled data, capturing the identified requirements of AGV systems and their influence on the system's design in each case. The case descriptions were then sent to the respective companies to verify that the data collected had been correctly understood.

Analysis

The analysis was performed in two stages: a within-case analysis and a cross-case analysis. In the within-case analysis, each case was individually analysed to understand which requirements influence the design areas of the AGV system. For example, the analysis examined which requirements influenced the fleet sizing of the AGV system for each case. Subsequently, the cross-case analysis compared the requirements for AGV system design across all three cases, focusing on their similarities and differences, as well as how these requirements were met in each AGV system's design, based on the framework created from the literature. From this analysis, design guidelines were derived that connected the identified requirements to the AGV system's design.

3.3.2. Methods applied in the study for Paper II

The research question of Paper II was: How do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding? Required inventory levels refer to the inventory needed to avoid material shortages at the receiving stations. A discrete event simulation model was developed to achieve the aim of the study.

Data collection

A real-world industrial material flow inspired the simulation model. The material flow consisted of deliveries from a single storage point to several delivery points connected to an assembly line. This material flow within the factory of a global automotive manufacturer provided a realistic and relevant inspiration for the model. To create the model, data were collected from the material flow. Drawings of the factory's layout and the routes of the vehicles in the material flow were obtained from the company, including the positions of the delivery locations and the distances in the layout. Historical transport demand data were also collected; for each delivery location, these data included the times when demand occurred and when a delivery was completed. The demand and the overall routes, delivery locations, and distances were modelled.

In addition to collecting data in the form of drawings and historical demand, a site visit was conducted to observe the material flow in operation and gain a deeper understanding of it. The visit was guided by a global logistics specialist whose expertise lies in the factory's internal logistics and material flows. The logistics specialist provided an in-depth tour of the material flow that inspired the simulation model. They also answered questions about the historical demand data and were contacted on several occasions during model development to ensure that the aspects of the material flow included in the model had been correctly understood.

Model implementation

The route network in the material flow was created in the simulation software to represent the distances in the real-world scenario. The localisation of the starting point and the delivery locations along the route were also implemented in the model to mirror the actual material flow. The data collected on transport demand were fitted to statistical distributions, which were subsequently implemented in the model to generate transport requests. Each delivery location was assigned its own statistical distribution to generate transport requests specific to that location. The factors and performance variables relevant to the purpose of the paper were identified from previous research. These factors included load capacity, fleet size, AGV speed, load transfer duration, and the use of multiple- versus single-lane routes. The levels of these factors were also derived from previous research. The main performance variable was required inventory.

Assumptions in the model were discussed with the logistics specialist at the company and members of the FAKTA project group who work with simulations and AGV systems. Earlier versions of Paper II were presented to the FAKTA project group on two occasions: one primarily addressed simulation-related issues and the other presented a draft version of the paper, including preliminary results. During these presentations, practitioners provided feedback and comments on the paper, the implementation of the simulation model and the results of the paper.

Experimental design

The first step of the analysis was to determine viable combinations of fleet size and load capacity. A viable combination should meet the demand of material flow without the transport request queue increasing indefinitely. For each viable combination, the minimum required inventory was determined based on the cycle service calculations for the safety stock. A service level of 98% was deemed suitable for the material flow and was approved by the logistics specialist as appropriate for a real-world scenario.

To confirm the accuracy of the results, the error percentage of the required inventory level for all combinations of fleet size, load capacity, speed, load transfer duration, and multi/single lane routes was calculated. The maximum percentage error across all combinations was 2.46%. This error percentage was low enough not to affect the interpretation of the simulation experiment results.

The combinations of load capacity and fleet size, along with the required inventory, were analysed when the levels of the factors changed: first, when altering AGV speed; second, when changing load transfer duration; and finally, when varying both simultaneously for two selected combinations. The impacts of multi/single lane routes were also analysed. Graphs of the results were compared to highlight differences and similarities between the combinations of AGV fleet size and load capacity. Patterns in the graphs were compared to determine whether certain combinations of load capacity and fleet size interacted with speed, load transfer duration, and routes in different ways.

3.3.3. Methods applied in the study for Paper III

Paper III aimed to answer the research question: "What human- and organisation-related challenges arise in the introduction of AGVs in production facilities?". For Paper III, a new case study on human- and organisation-related challenges in introducing AGV systems was performed on the same AGV systems as those studied in two of the cases in Paper I. Despite the separate case studies, general data collected regarding the AGV systems in Paper I formed part of the basis for the case studies in Paper III.

Case selection

Both cases had similarities and differences identified in Paper I that were relevant to the purpose of Paper III. The cases complemented each other in many ways. Two AGVs were introduced in Case 2 and 17 in Case 1. The difference in fleet size was expected to influence the challenges encountered. For example, a larger fleet meant that most of the traffic in the manufacturing area was AGV traffic, which could impact the acceptance of AGVs among employees due to the significant change from established working conditions and the organisation required to manage the AGV fleets. In Case 1, the change from the previous state without AGVs was expected to be smaller and potentially easier to get used to and accept.

The number of AGVs introduced can also affect challenges in work tasks for various employee roles in the facility, such as 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 AGVs. From the study in Paper I, it was clear that the organisation of different activities related to the AGV systems varied between the cases, which could influence human and organisational challenges. As stated in Section 3.3.1, both cases are in production environments; case 1 is involved in cell production, and case 2 is involved in the logistics of an assembly line production.

Data collection

Data collection was performed after the AGV introduction had been completed. A similar approach to data collection in Paper I was used. The interviews comprised the majority of the data collection. Interviews were conducted with operators, project managers, team leaders, and production support employees, including AGV superusers and production technicians. An AGV superuser is a team leader for a group of operators who has received additional education to manage AGV failures and thus has extra responsibilities to ensure the AGVs are operational. These employees' roles were significantly affected by the introduction of the AGV system. They were involved in both the AGV system's introduction and daily operation.

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 beforehand, allowing them to review the questions in advance. The interview questions were based on the HTO model. Questions were developed to explore human- and organisation-related challenges of 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 AGVs. During the visits, an expert on each AGV system explained the material flow, the AGV system, and its interactions with the operators. In case 2, the main expert on the AGV system was the employee who had been the project manager during the AGV implementation project. In case 1, the reliability engineer responsible for maintaining the AGVs' operational status had considerable expertise with the AGV system.

Company documents describing the AGV processes, the work tasks of different operators, traffic rules, and the responsibilities and authority of various roles in relation to the AGV system, as well as educational materials and documents outlining the knowledge required for different roles regarding the AGV system, were also collected. After data collection, case descriptions were compiled and sent to the respective companies to verify that the information had been understood correctly.

Analysis

The analytical framework was based on the HTO model (Karltun et al., 2017) to analyse the interaction between the three subsystems: human, technology, and organisation. To apply the HTO model, each subsystem had to be defined for the phenomenon being studied; thus, the subsystems were defined to explore the challenges of introducing AGVs.

The first step in the analysis, the within-case analysis, resulted in the case descriptions presented in the paper. Each case was analysed individually in terms of human, technical, and organisational aspects. The human factor aspects of the employees working with AGVs were analysed. In the technical subsystem, the analysis focused on the technical design of the AGV system, such as the number of vehicles, navigation technology, and control. Finally, in the work organisational subsystem, aspects such as the organisation of training sessions and the organisational structure for managing errors were analysed.

The HTO model was used for the cross-case analysis. The analysis focused on the challenges of introducing AGVs related to the interactions between AGVs and humans (H–T interactions), AGVs and the organisation (T–O interactions), and all three subsystems simultaneously (H–T–O interactions).

Finally, actions to manage the challenges were suggested. These suggested actions were discussed with the interviewees from the case companies to obtain their input on them. Although the main interviewee in case 1, the reliability engineer, had left the company at this point, the individual who assumed the role had been well informed by their predecessor and was capable of answering the questions suitably.

3.3.4. Methods applied in the study for Paper IV

Paper IV explored requirements for the automation of loading and unloading. The paper address: which are the requirements for automated loading and unloading of autonomous trucks? Automated loading and unloading in this paper denote fully automated loading and unloading process. A multiple case study consisting of three cases was conducted.

Case selection

In Paper IV, the three cases examined demonstrate both similarities and differences, providing a basis for identifying requirements for automated loading and unloading. Cases 1 and 2 used similar loading and unloading solutions, involving trucks dedicated to the material flow with conveyors installed in the trailers. Matching conveyors were also installed in the sending and receiving facilities, and a truck driver was needed to operate the loading and unloading solution. Although cases 1 and 2 are not fully automated, the requirements for fully automating loading and unloading could be identified by observing them. By contrast, case 3 involved a pilot project using AGVs for the automated loading and unloading of an autonomous truck. There were no truck drivers or operators involved in the loading and unloading of the truck in this pilot project. Thus, two different loading and unloading solutions, which may entail different requirements for automated loading and unloading, are represented in the cases.

All three cases involved industrial material flows in which transports took place between warehouses and production facilities. Cases 1 and 3 involved palletised goods, while case 2 used racks. The sending and receiving facilities belonged to the same company in case 3, whereas in the other two cases, they belonged to different companies, which could affect interoperability requirements, such as those related to processes, legal aspects, and the IT systems used. In all three cases, transport providers were responsible for the transport between the sender and the recipient. In case 3, an autonomous truck was used. The cases also differed in terms of their operational setup, for example, in case 2, the goods had to be delivered in-sequence, and the case involved a return flow of empty unit loads.

Data collection

Data collection was conducted for each of the cases at both the sender and recipient facilities and largely consisted of direct observations of the material flows. The activities performed by the truck driver from arrival to departure, as well as those performed by the logistics operators in the inbound and outbound flows, were observed. During the observations, the operators and truck drivers explained each step they performed and their procedures when something did not operate as expected. The material flows from the sender to the recipient were also video recorded to allow for a later review of the activities performed in the flows. Interviews were conducted with managers and engineers who explained the setup for the collaboration between the sender, recipient, and transport provider.

The automated loading and unloading solution using AGVs in case 3 was not fully operational during data collection. Since there was no automated loading and unloading solution to begin with, this presented an excellent opportunity to identify requirements for automating the loading and unloading in the material flow together with the industrial participants, which aligned with the aim of paper. Tests using AGVs for loading and unloading were conducted. In cases 1 and 2, the automated loading and unloading had already been established. The collected data were compiled into case descriptions that were sent to the case companies for validation.

Analysis

A framework was developed in the paper to facilitate the identification of requirements for automated loading and unloading. The first dimension consisted of the four types of functions where automation can be applied based on the framework of Parasuraman et al. (2000). These functions consisted of information acquisition, information analysis, decision and action selection, and action implementation. The second dimension consisted of four interoperability layers, including organisational, legal, semantic, and technical interoperability (European Commission, 2017). A four-by-four matrix was created using the types of functions and layers of interoperability, and requirements were identified in each cell of the matrix.

First, a within-case analysis was conducted, in which all the activities involved in the loading and unloading were mapped and categorised into one of four functions where automation can be applied. All the activities, from when the truck arrives until it departs for the next destination, at the sender and at receiver facilities, were mapped. The within-case analysis also consisted of identifying the IT systems involved in the loading and unloading, the information flows between systems and between the sender, recipient, and transport provider, as well as the legal terms regarding loading and unloading.

Second, a cross-case analysis was conducted, in which the cases were compared along the four interoperability dimensions to identify requirements for automated loading and unloading. Since loading and unloading involves several different actors, interoperability between the actors is crucial, and requirements were identified in each layer. A comparison of the three cases revealed that although many requirements were similar across them, some requirements were unique, for example, requirements relating to the technical loading and unloading solution that was used.

3.3.5. Methods applied in the study for Paper V

Paper V has the purpose to develop an understanding for what is required of the work organisation to support AGV operations, in the implementation phase and in the post-implementation phase.

Case selection

Two cases were studied. Both cases were in production environments where AGVs move materials to, from, and between production cells. Case 1 consisted of three AGVs. The AGVs in this case had advanced navigational capabilities that did not require guidepaths and were capable of avoiding obstacles in their planned routes. The operational areas and load transfer positions could be redesigned without supplier involvement, influencing the organisation in making design changes. In Case 2, there were 17 AGVs, which were laser guided and followed predefined guidepaths in the environment. The technical capabilities of the AGVs could influence the work organisation in ensuring that the AGVs are operational. More advanced navigational capabilities may be more robust and function without manual interventions to a larger extent. The size of the AGV fleet can also influence the work organisation, as keeping 17 AGVs operational requires greater effort compared to managing three AGVs. The AGVs in case 2 cannot be redesigned without supplier involvement. Case 1 involved AGVs from two suppliers, requiring the company to have competencies to manage both types of AGVs.

Data collection

Data collection mainly consisted of interviews. Interviews were conducted with the key employees involved in the implementation and post-implementation phases of the AGV system, including the production manager, production technician, process engineers, reliability engineers, project managers, and AGV superusers. The interviews focused on the work organisation in the AGV system, how it was initially designed, how it evolved throughout implementation, and how it functioned in the post-implementation phase. The organisational structure, job dimensions, and competencies were explored in the interviews. In addition to the interviews, study visits were conducted for both cases. During the visits, a comprehensive understanding of AGV operations was achieved. The visits were led by the main contact person for each case, i.e. the project managers in case 1 and the reliability engineer for the AGV system in case 2.

Analysis

An analytical framework was derived from the literature, consisting of two aspects: three dimensions of a work organisation and two implementation phases. The three dimensions of a work organisation were organisational structure, competence and job. The two phases of the implementation considered were the implementation phase and the post-implementation phase (i.e. when the AGVs had been integrated into daily operations). The within-case analysis involved individually analysing the cases based on the work organisation in the two implementation phases. The cases were then compared along these dimensions to determine what is required of the work organisation in the two phases and to identify the similarities and differences between the cases in these dimensions.

3.4. Research quality

Many criteria can be used to assess research quality. Given that four case studies were conducted as part of the research, this thesis adopted Yin’s (2014) four research quality criteria for case studies: construct validity, internal validity, external validity, and reliability. Each of these quality criteria is addressed in the following subsections in relation to the research conducted. The research conducted in Paper II is also assessed in terms of these four criteria, even though it was a simulation study.

3.4.1. Construct validity

Yin (2014, p. 40) defines construct validity as ‘identifying correct operational measures for the concepts being studied’.

The convergence of multiple sources of evidence supports construct validity (Ellram, 1996; Yin, 2014). Triangulation involves using more than one source of data to study a phenomenon (Bell et al., 2022; Stake, 2005); it is a common strategy to improve the quality of qualitative research (Flick, 2009) and can strengthen construct validity (Voss et al., 2002). All the papers used multiple sources of evidence. Papers I and III were based on three sources of data, namely interviews, direct observation, and internal documents. In Papers IV and V, two data sources were used for triangulation: direct observations and interviews. Paper IV also involved video recordings of the activities performed in the loading and unloading, which allowed the activities to be reviewed at a later point in time. Paper II, used archival data from historical transport requests and layout drawings, including measurements and the localisation of pick-up and delivery points. To ensure a correct understanding of the material flow, interviews with the company's global logistics specialist and direct observations during a site visit (during which the logistics specialist answered questions) were conducted.

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 (Yin, 2014). In all the papers, a chain of evidence was established from the data collected from the cases and for the modelling in Paper II. The data collection was carefully documented in each study, including the sequence in which the data were collected.

Having key informants review draft case study reports also supports construct validity (Yin, 2014). In the four papers based on case studies, the key informants from the cases were asked to review the case descriptions developed from the collected data and to provide feedback on the descriptions if necessary. In the study for Paper II, the simulation model's development was discussed on several occasions with the global logistics specialist and industrial parties involved in the FAKTA project.

3.4.2. Internal validity

Internal validity refers to 'seeking to establish causal relationship, whereby certain conditions are believed to lead to other conditions, as distinguished from spurious relationships' (Yin, 2014, p. 40).

Whenever an event cannot be directly observed in case research, an inference is made, and those inferences must be correct to achieve internal validity (Yin, 2014). In the research for Papers I, III, and V, the processes of designing and implementing the AGV systems had already been completed by the time of data collection, meaning direct observation of either process was impossible. Thus, Papers I, III and V relied on inferences made about events that could not be directly observed. The data collection focused on interviewing people that had substantial knowledge about the AGV systems and that had been involved in the design. These interviewees could thus provide answers to the aspects which could not be observed. Site visits were conducted in all studies, were an understanding of the AGV systems could be achieved and design decisions mentioned in the interviews could be confirmed by observations. In Paper II, archival data on demand were collected i.e. how the demand was logged was not observed. A site visit was conducted to better understand how demand is generated and logged in the system, and the global logistics specialist explained the material flow in detail.

Paper IV was largely based on observations, particularly in cases 1 and 2. The loading and unloading processes were observed for full cycles in cases 1 and 2, and Paper IV thus relied less on inferences than the other case studies. In case 3, the pilot project for using AGVs for automated loading and unloading was conducted during data collection. However, inferences were also made in Paper IV regarding events that could not be observed during the study visits, including anomalies that could occur during loading and unloading and the requirements related to such events. Anomalies seldom occurred and not at fixed intervals, making them difficult to observe. The truck drivers explained the tasks performed when something malfunctions during loading and unloading. The truck drivers were the most knowledgeable about the malfunctions since they work with the loading and unloading solutions every day.

Voss et al. (2002) state that cross-case analysis can improve internal validity by countering conclusions made based on limited data. Cross-case analyses were performed in Papers I, III, IV, and V to highlight their differences and similarities. The analyses in these papers were guided by frameworks developed based on the literature. Matching the findings from the cases with the frameworks derived from the literature is considered to improve internal validity (Yin, 2014).

3.4.3. External validity

Yin (2014, p. 40) states that external validity refers to 'defining the domain to which a study's findings can be generalised'. Generalising from case studies can be challenging due to the typically small number of cases (Bell et al., 2022). However, external validity can be improved by studying multiple cases (Voss et al., 2002). Additionally, because case research relies on analytical generalisation rather than statistical generalisation, 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 (Yin, 2014). Accordingly, the research in Papers I, III, IV, and V involved multiple cases, cross-case analysis, and comparisons with previous research. In all five papers, the cases were also described in detail, which enabled comparisons with other contexts.

In Paper II, the modelled material flow had to be representative of similar settings and not only relevant to the specific material flow that inspired the model. The material flow was within the assembly line of a global automotive manufacturer with decades of industry experience. Similar material flows are likely to be found at other automotive manufacturers. Performance measures and the factors evaluated in the model were based on the literature. The levels of the factors in the simulation experiments were also identified in the literature to ensure that the factors were evaluated at relevant levels, making the study's results easier to generalise. Additionally, the material flow is described in detail, which can facilitate in making comparison to other material flows and assessing to which flows the results are applicable.

All the papers have been presented at conferences to knowledgeable researchers and practitioners. Paper I was presented at PLAN Forsknings- och tillämpningskonferens in 2020 a Swedish conference oriented towards practitioners. Paper II was presented at the 2023 Cluster Conference (Klusterkonferensen), a Swedish conference in which practitioners and researchers working with logistics and production participate and share ideas. Paper III was also presented at the Cluster Conference but a year earlier, in 2022, and later at the Assembly Conference (Monteringskonferensen). The Assembly Conference, similar to the Cluster Conference, involves both practitioners and researchers, with a focus on assembly and production-related topics. It is also a Swedish conference. A conference version of Paper IV was presented at the Annual EurOMA conference in 2023. EurOMA is a conference oriented towards researchers. Paper V was presented at the Annual EurOMA conference in 2024. Feedback on the papers was received at these conferences. Additionally, before the papers were finalised, the results of Papers I, II, and III were presented to the industrial parties involved in the FAKTA project.

3.4.4. Reliability

Yin (2014, p. 40) defines 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 (Ellram, 1996; Yin, 2014), as they allow careful documentation of the process and the collected data. For the research in Papers I, III, IV, and V, a database was created for each study to store all interview-related material, notes from direct observations, internal documents, and the case descriptions derived from the data. Voss et al. (2002) state that the reliability of data can be improved if multiple sources of data are used when studying a single phenomenon. Multiple sources of data were indeed used in all the papers. An overarching protocol for each case within the case studies of the papers was established, with a plan for the data collection for each case that included how and what kind of data to collect, such as potential roles at the case companies to interview. A database was created for the archival data and drawings of the material flow received from the company in Paper II.

When interviews are conducted, reliability can be improved by having multiple interviewers present, which increases the likelihood that a common approach is followed in all interviews across all cases (Voss et al., 2002). This is important when studying multiple cases. Having multiple interviewers can also reduce the risk of personal biases influencing data interpretation. In the research for Papers I, III, and IV, at least two co-authors were involved in the interviews and site visits, which improved the reliability of the research. Eisenhardt (1989) stated that there are two advantages to having multiple investigators in case research. First, creativity in the study may be enhanced by the investigators having different perspectives, which may result in complementary insights from the data. Second, converging observations from multiple investigators increases confidence in the findings.

4. Summaries of the appended papers

This chapter presents summaries of the five appended papers explaining the purpose, method, findings, and the contribution of each paper.

4.1. Paper I

Thylén, N., Hanson, R., and Johansson, M. I. "Requirements influencing the design of automated guided vehicle systems."

Updated version of the paper from PLAN Forsknings- och tillämpningskonferens, October 2020.

Purpose / RQ: To identify requirements in AGV system design and to develop an understanding of how the identified requirements influence that design.

Method: A multiple case study consisting of three cases of AGV systems in production environments was conducted. Data collection was based on interviews, direct observations, and documents.

Findings: A framework was developed consisting of two parts: sources of requirements and design areas for designing AGV systems. Four sources of requirements were derived from material handling equipment selection literature. Design areas for AGV systems were derived from literature on AGV system design. The framework was applied to identify requirements and understand how the requirements influence AGV system design. Several requirements were identified. Some relationships between requirements and design areas were expected, while others were novel; for example, work organisation was identified as an important part of the AGV system.

Contributions: The paper revealed a need for work organisation that previous research on AGV systems had not considered in technical design areas. In addition, it revealed that humans are also influenced by AGV systems, worries, changing work procedures and routines, which need to be taken into account in design. The results can assist both users and suppliers in clearly specifying the requirements to facilitate the design process and ensure a well-functioning AGV system.

4.2. Paper II

Thylén, N., Medbo, P., Fager, P., Frantzén, M., and Hanson, R. (Submitted) "AGV part feeding: The impact of load capacity and fleet size."

Purpose / RQ: How do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding?

Method: A discrete event simulation study, inspired by real-world industrial material flow in automotive mixed-model assembly, was conducted. The layout, demand data and locations of load transfer positions were collected from the industrial material flow.

Findings: The paper showed how the different combinations of load capacity and fleet size impact required inventory levels considering AGV speed, load transfer duration and single/multiple lane routes. For example, AGV speed strongly impacts combinations with small load capacity, since these combinations have the largest travel distances per transport request and thus benefit the most from increasing speed. By contrast, a large load capacity benefits most from short load transfer durations, since in each delivery round, all carried unit loads need to wait for the load transfer for all the other unit loads.

Contributions: In previous research on AGV system design, mostly AGVs with a load capacity of one have been considered. This paper provided further details on combinations of AGVs of different fleet sizes and load capacities and how they impact required inventory, thus contributing to the research on fleet sizing of AGV systems. The findings can be useful for practitioners involved in designing part feeding of mixed-model assembly lines.

4.3. Paper III

Thylén, N., Wänström, C., and Hanson, R. (2023). ”Challenges in introducing automated guided vehicles in a production facility – interactions between human, technology, and organisation.” *International Journal of Production Research*, 61(22), pp.7809-7829.

Purpose / RQ: What human- and organisation-related challenges arise in the introduction of AGVs in production facilities?

Method: A multiple case study consisting of two cases in which AGVs were introduced in production environments. Data collection was based on interviews, direct observations, and documents.

Findings: The HTO model was used to analyse the collected data and identify challenges. Several challenges were identified relating to human–technical, technical–organisation, and human–technical–organisation interactions. Human–technical challenges involved worry, stress and inexperience in relation to working with AGVs. In the technical–organisation interaction, decision about new routines and training had to be made to address the. In the interaction between all three dimensions, acceptance and understanding of the AGVs were crucial.

Contribution: The paper focused on human and organisational challenges, which had received limited attention in previous research. Overcoming these challenges is crucial for the operation of an AGV system, including the acceptance of AGVs among the employees on the shop floor, establishing routines and responsibilities for managing anomalies and errors in the AGV operations. Preliminary actions for how to deal with these challenges are discussed in the paper.

4.4. Paper IV

Thylén, N., Flodén, J., Johansson, M. I., and Hanson, R. (2025) “Requirements for the automated loading and unloading of autonomous trucks: An interoperability perspective.” Accepted for publication in *International Journal of Physical Distribution & Logistics Management*. (in press).

Purpose / RQ: The paper explores the requirements in the automation of loading and unloading by posing the research question: which are the requirements for automated loading and unloading of autonomous trucks?

Method: A multiple case study consisting of three cases of automated loading and unloading solutions in industrial material flows was conducted. Data collection was based on direct observations during site visits, interviews, and video recordings.

Findings: A framework for identifying requirements was developed consisting of four layers of interoperability and four types of functions where automation can be applied. The framework assisted in identifying requirements relating to organisational, semantic, legal, and technical interoperability. Many activities are manually operated today but would need to be eliminated or be performed automatically if an autonomous truck is used (organisational). Automating loading and unloading requires that several systems can communicate and understand each other (semantic), and several sensors are needed to monitor the activities performed (technical). Legal agreements need to be in place, and it is important to secure cargo on the truck or trailer (legal).

Contribution: Automated loading and unloading is an underexplored area in research, but its relevance is growing with the rising interest in applications of autonomous trucks when no truck driver is available to perform the loading and unloading. While previous research had suggested different technical solutions for automated loading and unloading, this paper showed that there are several requirements relating to, for example, the legal or organisational layers of interoperability. The findings can assist practitioners in designing automated loading and unloading systems.

4.5. Paper V

Thylén, N. (working paper). "Designing work organisations for supporting automated guided vehicles operations."

Updated version of the paper from the Annual Euroma conference, July 2024.

Purpose: to develop an understanding for what is required of the work organisation to support AGV operations, in the implementation phase and the post-implementation phase.

Method: A multiple case study consisting of two cases of AGV systems in production environments was conducted. Data collection was based on interviews and direct observations during site visits.

Findings: The work organisation focuses on establishing an awareness and understanding of the AGV system in the implementation phase. It is important to get employees working with AGVs to accept and support AGV implementation. In the implementation phase, the work organisation must also establish work tasks related to AGV system operation, e.g. error management responsibilities, and develop competence in working with the AGV system. In the post-implementation phase, managing design changes and maintaining competence levels are crucial.

Contribution: Previous research has identified barriers for the organisation when implementing technologies such as a lack of experience, a risk of resistance and low acceptance of new technologies. This paper revealed that such barriers must be overcome by the design of a work organisation in AGV system implementation. It also identified the efforts needed to maintain the work organisation for continued operation of the AGV system in the post-implementation phase. The work organisation needs to be adapted over time to best support the AGV system. Practitioners can use the findings in design situations and for managing AGV systems in the long term.

5. Results

The results of the thesis are presented in this chapter. The results are presented in relation to the three research questions. Section 5.1 reports the results in relation to RQ 1. Section 5.2 reports the results in relation RQ 2, and the results in relation RQ 3 are presented in Section 5.3. The chapter is concluded by presenting a summary of the results in Section 5.4.

5.1. RQ 1: Which are the requirements to consider in AGV system design?

In this section, results related to RQ 1 are presented, drawing from the findings from Papers I, III, and IV in the categorisation of requirements presented in Section 2.5.2: internal logistics environment, characteristics of transported loads, performance, and interactions within and between subsystems.

5.1.1. Internal logistics environment requirements

Concerning the internal logistics environment, physical restrictions of the environment such as walls, ceiling heights, racking, floor quality, gates, workstations, machines, and pillars create requirements that need to be considered in the guidepath design of AGV systems. Aisle width creates a requirement that can influence whether multiple lane traffic is possible in the environment, which in turn influences fleet sizing. Restrictions in the environment can create a requirement for the battery charging localisation. In the three cases in Paper I, frequent changes in the environments imposed requirements on the navigation technology of the AGV systems. For example, machines, racking, workstations and equipment were often moved to new locations, which influenced the navigation technology of the AGVs, and these changes needed to be addressed in the guidepath design. The navigation technology needed to be flexible to accommodate the changes in the environment.

The environment put requirements on the navigation of the AGV system where the navigation should be suitable for the environment, that the features of the environment are considered when choosing navigation as well as for the guidepath design. In case 2 in Paper I, there were some aisles which were not suitable for the navigational technology of the AGVs since the AGVs would sometimes lose track of its position and would not be able to continue. The guidepaths had to be adapted to avoid these aisles.

The travel distances in the environment and the location and number of pick-up and delivery locations, as well as the overall demands of material flow, impose requirements on the fleet size of an AGV system. The AGV system must be able to fulfil the demand. How demand for transport is distributed spatially imposes requirements on fleet sizing and traffic management and control. In case 3 in Paper I, several production cells near each other occasionally start or finish batches at the same time, meaning that many transport requests for the AGV system to the same area are created simultaneously. Several AGVs are then sent to the same area, causing traffic congestion and, in turn, delays for many transports, which risks delays in production. Thus, traffic management and control, as well as fleet sizing decisions, need to consider spatial demand distribution.

The internal logistics environment can create requirements for the load-carrying mechanism. In case 3 in Paper I, a few production cells were designed such that AGVs with longer forks were required to pick up and drop off pallets. As a result, three AGVs were dedicated to these production cells and could not be used in any other material flows in the facility. Another requirement from the environment that influences the load-carrying mechanism is whether goods need to be picked up or delivered at different heights. In cases 1 and 2 in Paper I, goods were only managed at the floor level, while in case 3, the racking had several levels.

5.1.2. Characteristics of transported loads

The characteristics of transported loads, such as the weight and dimensions of unit loads, impose requirements on the load-carrying mechanism of an AGV system, which was seen in all the cases in Paper I.

A requirement that needs to be considered is whether the AGV system has to handle a mix of unit loads. When there are mixed unit loads, it is important to consider the dimensions of the unit loads as well as the unit loads' design so that there is a fit between the AGV and all the unit loads. In case 3 in Paper I, the AGV system manages two pallets with the same dimensions but slight differences in design, which impacts pallet detection, and due to the location of a sensor on the AGV, the pallets might not be detected, which can cause errors and stops. A requirement is thus for the AGV system to be able to manage the mix of unit loads.

In case 2 in Paper I, the unit loads partially blocked some of the navigational sensors when loaded on the AGV, which occasionally caused navigational issues. An important requirement is that the unit load is compatible with the AGV, for example, that navigational sensors are not blocked.

The weight and height of the pallets impose requirements on the load securing of the cargo during loading and unloading of trucks in case 3 in Paper IV. The AGV performing the loading and unloading needs to get information on how many unit loads should be loaded or unloaded and how they should be placed on the truck to secure the cargo. The load securing together with the weight and height of the pallet thus influence the control of the AGV system.

5.1.3. Performance requirements

Performance requirements can be expressed in many ways where meeting the overall demand of the material flows is a central requirement for the AGV system. It is important to consider how the demand is distributed over time. High variations in demand may lead to having several idle AGVs during low demand while during peaks in demand, the AGV system may struggle to complete the transports on time, risking late deliveries. Designing the AGV system considering the variations in demand was difficult in all cases of Paper I, influencing the fleet size and traffic management and control, as well as the work organisational subsystems.

Ensuring high availability of the AGVs is an important requirement and managing failures and errors is a vital to keep the AGV systems in operational condition. The failure management involves requirements related to interactions within and between subsystems, as additions and changes in the work organisational subsystem are necessary. Quickly managing problems is of course important in loading and unloading as well since long downtimes can cause delays in the departure of the truck. In Paper IV, an AGV may encounter problems in the loading and unloading, and it is unlikely that the AGV itself will be able to solve the problems.

In case 3 in Paper IV, an important requirement for using AGVs for loading and unloading is that the unit loads need to be stacked before being loaded onto a truck, to improve the fill rate of the truck. The AGV thus needs to have capabilities to stack pallets, to reduce the number of trips of the truck as observed in case 3 in Paper IV.

Another performance requirement relates to the charging of the AGVs. Ensuring AGV availability is important also in terms of charging. The AGVs in the cases of Paper I are all battery-powered and thus require charging stations to be located at appropriate spots in the environment. There could be restrictions in the internal logistics environment which influence the localisation of the battery charging facilities.

5.1.4. Interactions within and between subsystems

In case 3 in Paper I, three generations of the same AGV model were used. Generational differences imposed interoperability requirements, since the AGVs detected the environment differently due the positions of their navigational sensors and the available features in the software. This influenced traffic management and control and AGV navigation. There were interoperability issues indicated in case 1 in paper V also concerning using AGVs from two suppliers. The AGVs had to separate navigational systems which were not interoperable.

Another interoperability requirement for the technical subsystem in case 3 in Paper I is that AGV control is interoperable with the IT systems of the facility to receive and confirm the completion of transport tasks. In cases 1 and 2 in Paper I, transport requests for the AGV system are created by operators pushing buttons, and the IT systems and the AGV control do not need to communicate. In Paper IV, a clear requirement for automated loading and unloading with AGVs is that when no humans are involved in loading and unloading, the AGV control needs to be able to communicate with the IT systems used in the facility. Transport requests need to be initiated for the AGV system, either by pushing buttons, through the IT systems or other means. Initiating transport requests for the AGV system is a requirement that influence both the work organisation and technical subsystems.

In case 3 in Paper IV, the AGVs need to be able to scan barcodes on the pallets to determine whether the correct pallets are managed during loading. Thus, the AGVs need to be equipped with barcode scanners, and the barcodes need to be placed in the right position on all pallets; otherwise, the AGVs will be unable to scan the barcodes, causing loading interruptions.

In the three cases in Paper I, there were requirements related to the interactions between the technical and human subsystems, which were further explored in Paper III. Drawing upon the challenges identified in Paper III, there was a lack of previous experience with working with AGVs among various roles on the shop floor (e.g. production and logistics operators, team leaders, and maintenance personnel) relating to the cognitive human factor aspects. Worry and higher stress levels among the operators on the shop floor were identified in cases 1 and 2 in Paper III, which relate to the psychosocial human factor aspects. For example, manually operated forklift or tugger train operators can establish eye contact with other operators, and their intentions can be communicated with gestures and glances. Such communication with AGVs is impossible, and it can sometimes be difficult to know what the AGVs are going to do. The operators also had concerns about safety when working with AGVs and were doubtful about their benefits, since they experienced frequent operational problems during their introduction, especially in case 1 in Paper III. The worry, stress, and doubts about the benefits of the AGVs contributed to low understanding and acceptance of the AGVs among operators on the shop floor early in the introduction phase, and negative views of the AGVs took time to overcome. Developing competencies and new skills, as well as overcoming worry and stress by developing an understanding and acceptance of the AGV system are crucial requirements. Training and informing employees were needed in the work organisational subsystem.

The work force at a company is constantly changing as employees might quit or get new positions within the company, and there is continuous employee hiring, making it important that new employees know what to do concerning the AGV system where safety routines are crucial. In case 2 in Paper III, the reliability engineer responsible for the operation of the AGV system changed their position, so their know-how had to be transferred to the new reliability engineer.

The operators were uncertain about how to act when encountering an AGV on the shop floor and how the safety features of the AGVs function, creating requirements for the work organisational subsystem. For example, in cases 1 and 2 in Paper III, before the AGV system's introduction, pallets and other equipment could be placed in the aisles, since the manually operated equipment could easily avoid them. When the AGVs were introduced, this was no longer possible, and it became critical to keep the aisles clear. New routines and work tasks needed to be developed, such as traffic rules and safety procedures, to ensure the safe and efficient operation of the AGV system.

In the cases in Paper III, the AGVs sound an alarm and use flashing lights to get the attention of operators in the vicinity when safety is particularly important or when encountering errors in operations. From a cognitive human factor aspect perspective, the alarm was stressful and frustrating for the operators, as it initially occurred frequently. The alarm signal had the opposite effect; instead of getting the attention of the operators in the vicinity, the operators started to ignore the alarm signals. To get the attention of the operators, the situations triggering an alarm signal had to be adapted.

Interactions with humans can influence the performance of AGV systems. Humans may interrupt the AGVs by moving in front of them or placing items in their paths, and the AGVs might interrupt or cause stress in the humans working in the same aisles. A requirement for guidepath design and fleet sizing is to consider where consider there are pedestrians or substantial manually operated traffic in the facility.

Successful load transferring is a requirement for AGV systems. In the cases in Paper I, the unit loads are managed manually by operators at some of the load transfer positions. For an AGV to be able to perform a load transfer, the unit loads need to be placed with sufficient accuracy at the predetermined load transfer spot, which is difficult for the operators to achieve. With more advanced navigational capabilities, as indicated in case 1 in paper V, less accuracy is required, since the AGVs are able to manage deviations in unit load placement while still being able to perform the load transfer.

As stated in Section 5.1.3, to achieve a well-functioning AGV system, managing and eliminating failures is of course important. This imposes requirements on the design of the work organisational subsystem related to efficiently managing errors. To prevent recurring failures or errors, redesigning the AGV system to eliminate the errors is vital. There needs to be an organisational structure, competencies, and work tasks to manage the design changes. It is also important to continuously improve the AGV system; there could be changes in the environment influencing the AGV system and requiring that parts of the system be redesigned.

5.2. RQ 2: How can the requirements influence the design of an AGV system?

In this section, results related to RQ 2 are presented, drawing from the findings of Papers I, III, and V. The results are presented in two sections, which pertain to how the requirements from RQ 1 can influence the design of the technical subsystem (Section 5.2.1) and the design of the work organisational subsystem (Section 5.2.2). As previously stated, the human subsystem is not designable.

5.2.1. Design of the technical subsystem

The technical design areas of an AGV system need to consider the requirements imposed by the physical restrictions in the internal logistics environment. In designing the AGV system, physical restrictions in the environment, such as walls, ceiling heights, racking, workstations, machines, and pillars, influence several technical design areas. As mentioned in Section 5.1.1, aisle width imposes requirements on guidepath design. If an aisle is wide enough to accommodate multiple-lane traffic, with one lane for each direction, its throughput can be increased. If not, bidirectional or unidirectional guidepaths are need, which reduces throughput. The use of bidirectional or multiple-lane guidepaths also influences the fleet size required. Traffic management and control also need to consider aisle width. In situations when an aisle is too narrow to accommodate traffic in both directions at the same time, for example, due to pillars, control zones might be necessary where only one AGV can be at the same time, to avoid the risk of a deadlock. The localisation of battery charging facilities can also be restricted by the environment. The battery recharging facility should be located to minimise the extra driving distance to the charging stations; however, due to physical restrictions, the recharging facility may have to be placed in less optimal locations, which was observed in case 3 in Paper I.

As mentioned in Section 5.1.1, the spatial distribution of demand for transports in the environment imposes requirements for traffic management and control, which must determine how to appropriately dispatch the AGVs. In case 3 in Paper I, the dispatching of the AGVs was important due to the many production cells located in the same area of the facility. If too many AGVs were sent to the production cells at the same time, traffic congestion could occur, delaying many transports. Fleet sizing is also affected by how the demand is distributed in the environment, as traffic congestion needs to be taken into account. Naturally, the overall distances in the environment and number of load transfer positions create requirements that need considered regarding fleet size.

In case 3 in Paper I, the design of the production cells required that AGVs with two different fork lengths were needed. AGVs with longer forks were necessary to deliver the unit loads to the correct spot within the production cell. These AGVs could only be used for these production cells, so there were two AGVs with different fork lengths in the fleet. The load carrying mechanism was thus influenced by a requirement imposed by the production cell design. When determining fleet size, the load transfer positions need to be considered. A requirement for the AGVs in Case 3 in Paper I is picking up and delivering goods on several levels of racking which influences the fleet size. The load transfer time is longer if unit loads need to be picked up above floor level and thus must be considered in fleet sizing. Additional AGVs may be needed if a large portion of the material flow goes through racking above the floor level.

Picking up and delivering unit loads from racking also imposes requirements on the load-carrying mechanism, as AGVs need to have lifting capabilities and additional sensors to handle unit loads at heights above floor level. The pallets needed to be stacked during loading and unloading in case 3 in Paper IV. The AGVs needed to have a load-carrying mechanism that could stack and unstack pallets when needed to improve the fill rate of the truck. To ensure that the correct pallets are loaded on to a truck, the AGVs also need to be equipped with a barcode scanner.

The internal logistics environment also imposes requirements for the navigation of the AGV system. Some of the aisles in case 2 in Paper I had few distinctive features upon which the AGVs could base their navigation, which sometimes caused them to lose track of their positions. The guidepath had to be redesigned with the features of the environment and the navigational limitations taken into account. The fit between the navigational capabilities of the AGVs and the environment in which the AGVs are to be used is an important requirement for the choice of navigation technology.

AGVs need to be suited to the characteristics of their transported loads, such as dimensions and weight, which impose requirements for their load-carrying mechanisms. In case 2 in Paper I, this was not fully considered, as the unit loads partially blocked the AGVs' sensors, influencing navigation. The AGV system is required to manage all unit loads that are part of the material flow. In case 3 in Paper I, since there were two unit loads with slightly different designs, the delivery locations where both pallets were managed had to have special designs to ensure the detection of the two pallet types.

The weight and height of the unit loads influence AGV system design in loading and unloading applications of AGVs as seen in case 3 in Paper IV as they influence traffic management and control. Load securing is crucial, and a requirement is that the unit loads should be placed on trucks such that the cargo is secured. A predetermined loading scheme is assigned to the AGVs based on how many unit loads should be loaded, the weight of the unit loads, and whether the unit loads are stacked. The AGV system then needs to follow this loading scheme to ensure the loads are secured during transport. Traffic management and control thus need to consider load securing when AGVs are used for loading and unloading.

The AGV fleet size needs to meet the demands of the assigned material flows, which is a central performance requirement. The cases in Paper I show that variations in demand over time make determining an appropriate fleet size difficult. In the cases in Paper I, there was an excess capacity of the AGV system to manage the peaks in demand. Occasionally, this excess capacity was insufficient, and operators needed to support the

AGV system by moving unit loads manually, influencing the work organisational subsystem.

Regarding battery management, the number of charging locations and their localisation need to be determined to ensure availability of the AGV system. Physical restrictions in the environment limits the placement of the charging facility. In the cases in Paper I, the charging of the AGVs was quick, and battery charging had a minor impact on the AGV system performance.

The design of the technical subsystem of an AGV system may need to be adapted when changes occur in the environment. A requirement needing consideration is the degree of flexibility in managing required design changes. When changes occur frequently in the environment, influencing the AGV system's guidepath, a navigation technology that allows easy adaptation of the guidepath can save considerable time for the designers. In cases 1 and 2 in Paper I, the AGVs navigated by detecting contours in the environment, and the guidepaths were easily adjustable in the AGV software. AGVs using laser guidance as were used in case 3 in paper I, require that reflectors be placed in the environment. These reflectors might have to be moved when the environment changes so that the AGVs do not lose track of their position, which entails more effort when redesigning guidepaths. In case 1 in Paper V, the AGVs had SLAM-based navigation, and no guidepaths were needed allowing for changing the operating area of the AGVs easily. The choice of navigation technology should consider how frequently changes in the environment occur. Making changes to the assigned area requires that competence are developed at the company, influencing the work organisational subsystem.

Traffic management and control need to consider interoperability requirements when operating an AGV system consisting of several generations of AGVs. As observed in case 3 in Paper I, three generations of AGVs needed to operate together. The software settings of the AGVs had to be set such that the three generations could operate in the same way in the environment, for example, disabling certain features in the newer AGV versions that were unavailable in the older version. The sensors were located at different spots on the AGVs, and there were differences in how the AGVs detected the environment, which also had to be considered, for example, during load transferring.

Interoperability between the IT systems in the facility and the AGV control was a requirement seen in case 3 in Paper I and case 3 in Paper IV. The IT systems and AGV control need to be interoperable so that they can send and receive signals, such as transport requests or requests to start loading or unloading. In automated loading and unloading with AGVs, it is important to meet this interoperability requirement so that loading and unloading can be performed without the need for human intervention.

To ensure a safe work environment with AGVs, operators and other personnel working in the same environment are required to pay close attention to AGV alarm signals. However, as mentioned in Section 5.1.4, alarm signals coming from the AGVs were ignored in both cases 1 and 2 in Paper III due to their excessive occurrence. The settings for the AGV alarm signals were changed so that only critical situations concerning safety resulted in an alarm signal. This improved safety, as the operators paid closer attention to AGV alarm signals.

In the cases in Paper I, unit loads had to be placed with high accuracy at their predetermined load transfer spots for the AGVs to be able to pick up the unit loads. Consistently placing unit loads with that level of accuracy is difficult for operators. To fulfil the requirement in the load transferring, guiding rails were installed at the load transfer positions to ensure that operators handling the unit loads manually always placed the loads in the correct spot, with the required level of accuracy. The guiding rails were needed at all load transfer spots. The guiding rails reduced the flexibility in changing the load transfer positions, as this would require more effort and impose installation costs. The more advanced AGVs in case 1 in Paper V did not require guiding rails, since they could adjust to slightly misplaced unit loads.

Interactions with humans in the environment create requirements that need to be considered in the design of guidepaths, fleet sizing, and traffic management and control. Guidepaths should be developed so that interactions are kept low. For example, in case 2 in Paper I, the guidepaths for the AGVs were initially in parts of the picking aisles, which caused many interruptions for both AGVs and operators and stressful situations for operators. The guidepaths were then designed so that the AGVs no longer travelled through the picking aisles. Regarding fleet sizing, it is important to consider potential interruptions of AGV operations due to pedestrians and manually operated equipment. Adding control zones that, for example, limit the speed of the AGVs in areas with many pedestrians can improve safety. Of course, AGVs also have to be equipped with several sensors and emergency brakes to avoid collisions and accidents with operators in the facility.

5.2.2. Design of the work organisational subsystem

The human subsystem influences the design of the work organisational subsystem in several ways. In Paper III, worry and stress related to the AGVs among employees on the shop floor was due to a lack of previous experience working with AGVs. The work organisational subsystem needs to overcome these to increase acceptance and understanding of the AGV system. Training sessions and information meetings early in the introduction were established to address operators' lack of experience of working with AGVs. Through training and experience, acceptance increased over time. What information to provide to different groups of employees, who should conduct the training, and how much training is needed were decided in the work organisational subsystem.

Paper V showed that training is important in the implementation and post-implementation phases. In the post-implementation phase, there is a lesser need for training sessions, but they are still necessary for new employees and to maintain an appropriate competence level in the shift teams. It was clear that the employees, after getting used to the AGVs, did not follow the prescribed traffic rules, or they trusted too much in the safety features of the AGVs, causing unnecessary emergency stops. Employees may not stay at their positions in a company, and it is crucial that the competencies regarding the AGV system are not lost when key personnel change positions, such as the reliability engineer in case 3 in Paper I which is another reason for the need for further training.

Production takes place in several shifts in the cases in Papers III and V, and a requirement for the work organisational subsystem is that all shifts are informed regarding the AGV system. A structure was established so that all shifts were informed and received training.

At first, informing and training were the responsibility of the project team implementing the AGVs in the cases in Paper V, but as the project teams were disbanded, the responsibility for training was shifted to the roles responsible for AGV operations in the post-implementation phase. To facilitate the training of new employees in case 1 in Paper III, an e-learning module was developed to cover the most vital safety aspects of the AGVs, reducing the need for conducting training sessions.

A safe work environment is a vital requirement when working with AGVs. The work organisation had to establish new and adapted work tasks relating to the job dimension, such as new traffic rules as evident in Paper V. AGVs stop for obstacles in their paths, making it highly important to place items and equipment in their designated spots as observed in Paper I. Instructions need to be created for restarting an AGV if it is stopped. In case 1 in Paper V, the AGVs can avoid obstacles, making this new work task less strict but still important, as the AGVs have to lower their speed to do so.

Training sessions were required not only to develop understanding and competencies but also to explain new work tasks. A requirement influencing the development of the training session was the competencies required by different roles in the operations. The different roles in the operations had different needs regarding what they needed to know about the AGVs, concerning safety considerations, understanding of the AGVs, and due to the degree of involvement in activities relating the AGVs. All employees must understand the safety aspects of the AGVs. In case 1 in Paper I, operators were given training on basic error management skills, such as resetting the AGV, whereas production technicians had more training and could manage more complicated issues. In case 1 in Paper V, it was decided that only the AGV superusers should have the skills and be allowed to change the programming of the AGV.

Transports for the AGV system must be initiated which can influence work tasks. Case 1 in Paper V highlighted multiple ways in which transports were initiated in the manually operated material flow, for example, by visually examining certain load transfer positions, by operators scanning barcodes, and automatically through the IT systems. Thus, the work organisational subsystem needed to be designed with the AGVs in mind when it came to the initiation of transport requests. In cases 1 and 2 in Paper I, the transport requests were initiated by pressing a button. In case 3, transport requests were automatically initiated by the IT system.

Error management is a crucial part of the design of a work organisational subsystem for managing anomalies and operational failures in AGV operations. An organisational structure with new roles is needed, competencies regarding how to manage errors need to be developed, and new work tasks must be added in the job dimension. Regarding organisational structure, it is important to clarify the responsibilities of different roles or teams, as well as how to escalate errors to the correct role, having the right competence to manage the errors. In case 1 in Paper III, all operators were initially responsible for managing errors; however, it was problematic to get the operators to feel accountable, as they sometimes ignored the AGVs. In case 1 in Paper V, a few operators in each shift were given more extensive AGV training and had additional responsibilities to restore AGVs to operation when errors occurred. Having operators with further AGV competence is needed in each shift to avoid AGVs being taken out of operations during production hours when, for instance, an AGV superuser is not present. Paper III showed that the work organisation needs to be suitable for the number of errors that occur. In the implementation phase, there can be many errors requiring a lot of resources from the work organisation, with many people involved. In the post-implementation phase, the most common errors have been removed through redesigning the system, and the work organisation needs to change and be adapted to the new situation. The work organisation of failure management can be influenced by the number of AGVs to monitor as well as how large the area is where the AGVs operate.

A requirement for the work organisational subsystem is to adapt the design of the AGV system to changes in the environment that influence the system. The AGV system in the cases in Papers III and V were in environments where changes occurred frequently, for example, changing or adding production cells, changing racking areas, and adding new load transfer positions. The design of the work organisational subsystem needs to include structure, competencies, and additions in the job dimensions to manage design changes. Additionally, the AGV system needs to be adapted when errors occur, to ensure that the errors do not happen again. In case 1 in Paper III, only one person was responsible for this, whereas in case 2 in Paper III, a team consisting of operators, team leaders, and production technicians was established to manage design changes. In Case 1 in Paper V, initially only one person was involved in improving the AGV system in the implementation phase. When the fleet size was increased, a new AGV superuser role was established, and a team of engineers also learned how to programme the AGVs to increase the number of people with the competencies needed to quickly implement necessary design changes.

In case 1 in Paper V, the case company could make any changes to the AGV system design without supplier involvement, which improved flexibility. In the cases studied in Paper I, the supplier needed to be involved in adjusting the design of the system, which limited flexibility. In case 1 in Paper V, competencies for making changes to the design of the AGV system had to be developed and maintained in the company. Since AGVs from two suppliers were used, competencies in designing AGV systems from both suppliers were needed.

Case 1 in Paper V showed that receiving materials delivered by AGVs can involve further work tasks. In the material flow before the introduction of AGVs, logistics operators moved containers of scrap metal from machines. The logistics operators had to first switch off the machines before replacing the container. When the AGVs were introduced, a new work task had to be designed; since the AGVs cannot turn off the machine, an operator in a nearby production cell is required.

A crucial requirement for managing design changes is getting input from the operators on the shop floor so that the technical or work organisational subsystems can be appropriately changed. An organisational structure and tasks in the job dimensions need to be established for this. The employees working with the design changes are not on the shop floor to the same extent as the operators, so it is important that the operators' observations are used as input for design changes. Since the operations take place in several shifts input from all shift teams is needed.

Paper V showed that there needs to be someone or a team responsible for the AGV system operations when the implementation project team is disbanded, and this needs to be established in the work organisational subsystem. During the implementation phase in the cases in Paper V, there was a project management team responsible for the AGV system operations. When the project management team was disbanded, the overall responsibility was transferred. In both cases in Paper V, this meant the establishment of new roles in their organisational structures: the AGV superuser in case 1 and the reliability engineer in case 2.

5.3. RQ 3: How do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding?

The answer to RQ 3 draws from Paper II, which focused on material deliveries to a mixed-model assembly line, where material is moved from central storage to replenish receiving stations along the assembly line. Space in the along the assembly line is often limited, and restricting the possibilities to keep inventory. Different combinations of fleet size and load capacity influence the required inventory levels at the receiving stations. The required inventory level is the inventory required to avoid shortages of materials at the assembly line. Thus, combinations of fleet size and load capacity are important aspects of the design of the part feeding of the mixed-model assembly line.

Fleet sizing is a central technical design area of AGV system design, as the load capacity of AGVs is a crucial factor to consider in decision-making, and various combinations of fleet sizes and load capacities can be used. Three factors that interact with the fleet size and load capacity of AGVs were investigated in the simulation experiments of Paper II: AGV speed, load transfer duration, and limitations regarding the routes (whether there are multiple lanes, i.e. one lane in each direction, or a single unidirectional lane).

Figures 5.1 and 5.2 show results from the simulation model and highlight the relative importance of AGV speed and load transfer duration for two AGV options as well as how multiple lane versus single lane routes interact with these combinations. These options were selected based on previous experiments in the simulation model of Paper II. The options represent the largest fleet size when the load capacity is fixed to one and the smallest fleet size when the load capacity is fixed to nine while meeting the demands of the material flow. The colours of the contours in the figures highlight different levels of required inventory at the receiving stations. Figure 5.1 shows the option with a fixed fleet size of one and a load capacity of nine. Figure 5.2 shows the option of fixed load capacity of one, with the fleet size fixed to three AGVs in multiple lane routes and fixed to four AGVs in the single lane routes. The multiple lane routes allow the fleet size to be reduced by one while still managing the most challenging combinations of speed and load transfer duration. The contour plots highlight the interaction of AGV speed and load transfer duration and how they impact the required inventory levels.

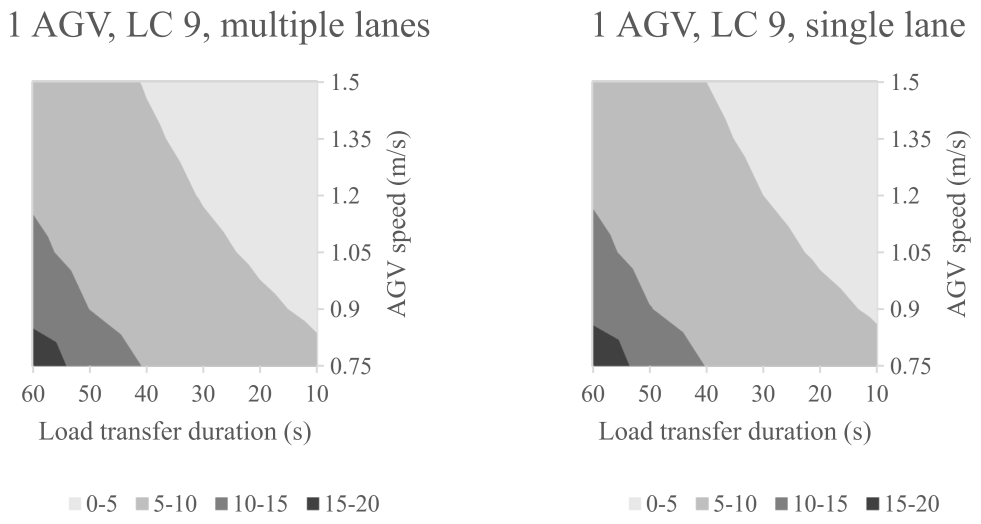

Figure 5.1. *Contour plots for varying AGV speed and load transfer duration simultaneously for the 1 AGV option in multiple and single lane routes.*

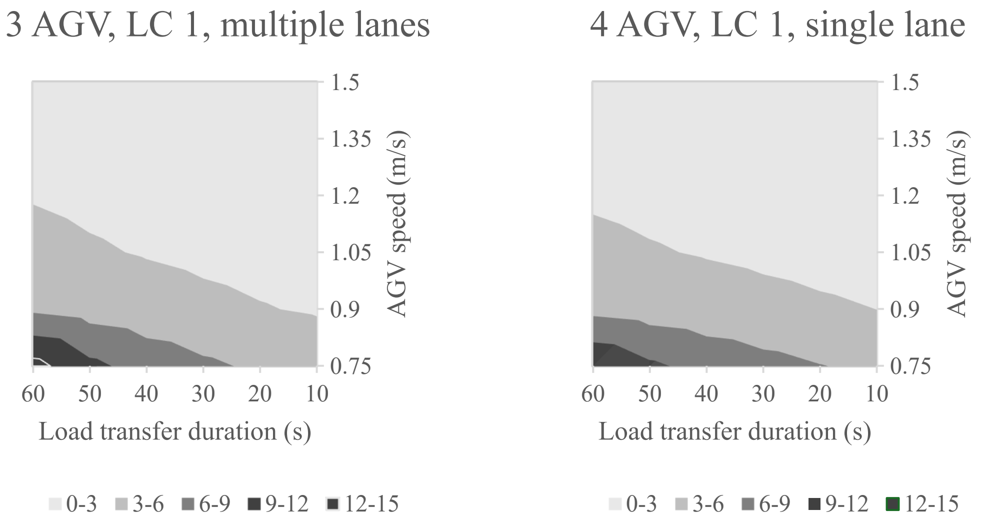

Figure 5.2. *Contour plots for varying AGV speed and load transfer duration simultaneously for the 1 LC (load capacity) option in multiple and single lane routes.*

It is clear from Figures 5.1 and 5.2 that speed and load transfer duration impact the required inventory levels differently for the two options. The contour lines are more vertical in Figure 5.1 when the fleet size is fixed to one AGV, whereas in Figure 5.2, they are more horizontal when the load capacity is fixed to one. These results show that a small reduction in load transfer duration requires a much larger increase in AGV speed to achieve the same inventory level as in Figure 5.1. By contrast, in Figure 5.2, a slight increase in speed substantially impacts the required inventory level, requiring a greater reduction in load transfer duration to achieve a comparable inventory level. This suggests that load transfer duration is relatively more important when using a large load capacity and that speed is more important when using a small load capacity.

Using AGVs with a small load capacity involves longer average travel distances for each completed transport request compared to AGVs with large load capacity. An improvement in speed thus results in a larger positive impact for the small load capacity AGVs, as the time spent traversing the layout can be reduced, thereby decreasing the required inventory to a greater extent. The importance of load transfer duration for the option with a large load capacity can be explained by that each carried unit load must wait for the load transfer duration of the other unit loads. Thus, the load transfer duration has a smaller impact when the load capacity is one, in comparison to Figure 5.1, where as many as nine unit loads can be carried simultaneously in one delivery.

Figure 5.2 shows that multiple-lane routes enable a reduction in fleet size by one compared with single-lane routes. By contrast, Figure 5.1 shows that single- and multiple-lane routes do not influence the load capacity for this option; a load capacity of nine is necessary to meet the most challenging conditions in both routes. Furthermore, the interaction between AGV speed and load transfer duration with respect to the required inventory levels are observed to be unaffected by whether the routes have single lanes or multiple lanes. The same pattern is observed in the contour plots for the single- and multiple-lane routes in Figures 5.1 and 5.2.

The results from Paper II highlight that the different options of load capacity and fleet size perform differently with respect to the required inventory level. Using a small fleet size and a large load capacity can be beneficial from an investment costs perspective, but as Paper II shows, this option requires a larger inventory at the receiving stations to avoid the risk of shortages of materials at the assembly line. By contrast, whereas a larger fleet size in which each AGV has a small load capacity can often reduce the required inventory by frequent deliveries, a large fleet size involves high investment costs, since the AGVs themselves usually comprise a major part of the investment costs. Furthermore, there are often restrictions on how much inventory can be kept near the assembly line due to limited available space. Some combinations of load capacity and fleet size might not be viable due to the need to keep a prohibitively large inventory. Finding a suitable option of fleet size and load capacity is crucial for well-functioning part feeding to mixed-model assembly lines, influencing required inventory as well as investment costs.

5.4. Summary of findings in relation to the RQ 1 and RQ 2

Table 5.1 summarises the requirements from 5.1, the influences on design presented in 5.2, and the results in relation to the fleet sizing and load capacity in 5.3. The third column, AGV system design area includes not only the technical design areas presented in Section 2.3, but also suggestions for the work organisation subsystem.

Table 5.1. *Summary of the results.*

Category of requirements	Requirement	Design area	Influence of the identified requirements on the AGV system design
Internal logistics environment	Accommodating the physical restrictions in the environment	Guidepaths and navigation	Guidepath design needs to consider the restrictions in the environment to create a suitable guidepath network. The fit between navigation technology and the environment can also impact the choice of guidance technology and the guidepath design. Aisle width is important for deciding on potential multiple-lane traffic, unidirectional or bidirectional traffic.
	Dealing with frequent changes in the environment		Environments where changes occur frequently make a flexible navigation technology suitable to easily accommodate the changes. Flexibility is constrained when AGV suppliers have exclusive control of potential modifications to the guidepath and load transfer positions.
	Accommodating physical restrictions in the environment	Fleet sizing	The overall distances that the AGVs need to cover, aisle widths, and the localisation of load transfer positions influence fleet sizing. Paper II showed the influence of multiple versus single (unidirectional) lane traffic on fleet sizing. It also showed that a higher speed naturally has a positive impact on the fleet size and the required inventory; however, the AGV speed that can be safely applied in the facility could be limited by restrictions in the environment as stipulated in the ISO standard for driverless industrial trucks (ISO, 2023).
	Managing pick-ups and deliveries above floor level		The height from which the AGVs need to pick-up or deliver goods influences fleet sizing as seen in case 3 in Paper I. Paper II showed that load transfer duration impacts the fleet size and load capacity and the inventory levels
	Capability of handling the distribution of transport requests in the layout.		How the demand is distributed spatially in the layout influences fleet sizing due the risk of traffic congestions. Production cells near each other may require AGV transport at the same time, causing congestion. Excess capacity helps managing variation but does not reduce the cause of the variation. Manual transport can be used to support the AGV system.
	Accommodating restrictions of load transfer positions	Load-carrying mechanism	Restrictions in the environment could require the introduction of AGVs with several different load-carrying mechanisms, e.g., longer forks in case 3 in Paper I.
	Capability of handling goods above floor level		The load transfer positions regarding whether the AGVs need to pick up unit loads from different heights on racking or from the floor influence load-carrying mechanism.
	Ensuring deadlock free operations	Traffic management and control	In narrow parts of aisles where two AGVs cannot meet, control zones can be used to avoid deadlocks and collisions.
	Capability of handling the distribution of transport requests in the layout		Dispatching of AGVs to available transport request should avoid sending too many AGVs to the same area, as seen in case 3 in Paper I.
	Accommodating physical restrictions in the environment	Battery management	Limited free space can restrict the placement of charging facilities causing extra driving for the AGVs.
Characteristics of transported loads	Suitable AGV for the unit loads	Load-carrying mechanism	The weight and dimensions of the unit load must be considered when choosing the load-carrying mechanism.
	Assuring compatibility between unit loads and AGVs		Compatibility between the AGVs and unit loads can impact AGV navigation. In case 2 in Paper I, sensors were blocked by the size of the unit load which caused navigational issues.
	Managing a mix of unit loads		AGVs need to manage all the unit loads that are part of the material flow. Case 3 in Paper I had a mix of unit loads which influenced the design of the load transfer positions.
	Ensuring load securing. Need to stack unit loads	Traffic management and control	The characteristics of the unit loads needs to be considered when securing the loads during loading and unloading, e.g. stacking of unit loads. In case 3 in Paper IV, a predetermined load schedule in the cargo hold was needed.
Performance	Fulfilling the demand of transport requests	Fleet sizing	The required performance in terms of number of transport requests per hour impact fleet sizing. It is important to understand how transports are distributed over time.
	Achieving suitable inventory levels		Fleet size and load capacity of the AGV impact the inventory levels at the receiving stations as shown in Paper II. These factors need to be determined.
	Ensuring high AGV availability	Battery management	Performance demands together with restrictions in the environment may influence the location and number of charging facilities.
		Failure management	Efficient failure management is crucial for ensuring high AGV availability. This has implications for the work organisation.

	Capability of handling stacking of pallets	Load carrying mechanism	To increase the fill rate of a truck, stacking unit loads is important. The load carrying type need to be able to stack unit loads. The choice of load carrying mechanism needs to consider different heights of at the load transfer positions.
Interactions within and between subsystems	Accommodating human and AGV interactions	Guidepaths and navigation	The presences of pedestrians, forklifts, tugger trains, and other traffic needs to be considered in the guidepath design in order to improve the traffic for both manual drivers and AGVs.
		Fleet sizing	Interactions with manual traffic cause variations in performance and influence the required fleet size in addition to influencing the humans also operating in the environment.
	Ensuring interoperability between the AGV system and IT system	Traffic management and control	Interoperability and connection to internal IT systems are needed to communicate with the AGVs and transfer transport requests to and from them. In smaller AGV systems, pressing buttons can be used to initiate orders for the system as in cases 1 and 2 in Paper I. This is an important requirement in loading and unloading when the AGV system needs to send and receive signals from the IT systems in the facility to start and finalise loading or unloading.
	Accommodating human and interactions, safety considerations		The AGVs need to operate in a predictable way in the interaction with humans. Safety is vital when the AGVs work in the same environment as humans and influences the use of control zones.
	Ensuring interoperability between AGVs		The interoperability between AGVs influences the design of AGV systems. Generational differences between AGVs need to be considered, and adjustments to safety features may be needed as exemplified in case 3 in Paper I.
	Capability for scanning barcodes on unit loads		In loading and unloading the AGV system needs information on how many pallets there are to load and unload. The AGVs need to have barcode scanners installed to ensure that the correct pallets are managed.
	Overcoming worry and stress, and developing acceptance and understanding	Work organisation	To facilitate the interaction between AGVs and manual operators, training is needed overcome worry and stress and to improve acceptance and understanding. All shift teams need to be informed about the AGV system and receive training. Performing the training involves additions in the job dimension as well as in the organisational structure for how the training should be performed.
	Ensuring correct competencies		All employees need to have a base competence regarding how the safety features of the AGVs function and how to work with them. Some employees may need further competencies since they are involved in further work tasks related to the AGV system., for example regarding failure management, and redesign of the AGV system.
	Ensuring competencies to operate the AGV system over time		Training is important in the post-implementation phase to maintain the competence level in the organisation. Training is also needed when new employees are recruited.
	Ensuring safe and efficient AGV operations		New work tasks need to be established in the job dimensions for the safety of the employees working with the AGVs as well as for an efficient AGV system operations concerning traffic rules, item placement routines, ordering material, receiving material, and failure management, and reporting of errors.
	Ensuring capability to manage design changes and continuous improvement		An AGV system that operates in an environment that changes often may have to be adjusted over time to accommodate the changing environment. Additionally, it is important to adapt the design to avoid reoccurring errors. It is suitable to create an organisational structure to support making changes in the system's design as well as the competencies necessary adjust the system design.
	Ensuring AGV operations		Initially, a project team is responsible that the AGV system operates as it should, but the competence and responsibility need to be assigned to a new role when the project team is disbanded.
	Accommodating for the limitations of operators in accuracy in load transferring		The cases in Paper I showed that guiding rails are needed at load transfer positions since high accuracy in unit load placement is required by the AGVs. The guiding rails assists the operators in placing the unit load correctly. This is not needed in case 1 in paper V due to the navigational capabilities of the AGVs. In this case the operators place the unit loads within marked areas. The limits of the AGVs and the operators both influence the load transferring

6. Discussion

In this chapter, the results of the thesis are discussed. Sections 6.1, 6.2, and 6.3 address the answers to the three RQs. Section 6.4 presents a discussion of the results in relation to the purpose of the thesis and its contributions to theory and practice. Section 6.5 follows with a discussion of the generalisability of the findings. Finally, Section 6.6 concludes the discussion by detailing suggestions for future research based on the limitations and results of the thesis.

6.1. Discussion of results related to RQ 1

RQ 1 is formulated as: Which are the requirements to consider in AGV system design? The first step in a design process is analysis and specification of requirements and objectives (e.g. Granlund, 2014; Johansson, 2007). Several requirements were identified in the studies conducted for this thesis. The first step in a design process is Some of these requirements have already been acknowledged in previous research with a technical focus, and this thesis also found support for them. Other requirements have received limited attention. These requirements are discussed in the following subsections. Requirements stemming from interactions within and between subsystems are discussed in Section 6.1.1. In Section 6.1.2, interoperability requirements are discussed. The thesis compiles requirements that have been considered in previous research, confirms them and identifies requirements that have received limited attention. By bringing all these requirements together, the thesis provides a comprehensive overview of requirements for AGV system design, which is discussed in Section 6.1.3.

6.1.1. Interactions within and between subsystems

There has been limited attention concerning humans in AGV system design. Previous research has considered the requirements stemming from the human subsystem in relation to the development of the technical capabilities of AGVs. Humans have been taken into account in the development of, for example, navigational capabilities (Indri et al., 2020; Rey et al., 2019), safety capabilities (Babić et al., 2022; Reich et al., 2022; Zamora-Cadenas et al., 2021), sensors (Indri et al., 2019), signalling of AGVs (Bergman et al., 2020), and gesture control (Zhang et al., 2019). Less attention has been given to considering humans in the design of AGV systems beyond their technical capabilities. AGV systems are often used in the same environment as humans, and they interact and work together (Oleari et al., 2014; Sabattini et al., 2017; Zuin et al., 2020). Compared with other automation, such as robots within fenced-off production cells, AGVs work closely with humans, making considerations of the human subsystem central.

Paper III highlighted many challenges connected to the human factor aspects that result in requirements for the design of the technical and work organisational subsystems. If human factors are not considered, there is a risk that the anticipated profits are not achieved due to negative consequences such as high rates of sick leave, injuries, and poor work environments (Sgarbossa et al., 2020). As indicated by Neumann and Village (2012), if human factors are not considered in the initial steps of the design process, it is unlikely that human factors will be considered at all. A lack of attention to human factors can lead to discomfort among humans and can negatively affect well-being (Vijayakumar et al., 2021). This thesis contributes previous research on AGV system design by highlighting the need to consider requirements that stem from the human subsystem to develop an AGV system wherein operators are not worried and do not work against the AGV system. In Paper III, various physical, cognitive, and psychosocial human factor aspects clearly influenced the introduction of an AGV system. Paper III for example highlighted that acceptance and understanding, worry and stress, and getting employees to perform new work tasks, such as error management and reporting, were challenging to address but crucial when introducing AGVs.

Some research that has given attention to humans in AGV systems has focused on aspects other than their technical capabilities. Kopp et al. (2023) highlighted how crucial acceptance is when implementing an AGV system through a survey. Lee and Leonard (1990) showed that many roles in manufacturing are influenced by the introduction of an AGV system, as some roles have their work pace controlled by the AGVs to a greater extent than before their introduction, indicating the need for considering human factors. This thesis found support for the findings of Kopp et al. (2023) and Lee and Leonard (1990) but also highlights further aspects concerning the human subsystem.

6.1.2. Interoperability requirements

Interoperability requirements influence the design of AGV systems in several ways, which is shown in Papers I and IV, as well as V.

Interoperability between AGV systems and IT systems is a requirement when the AGV system needs to send and receive information from the IT systems in the facility. In case 3 in Paper I, the IT system in the manufacturing facility automatically creates transport requests for the AGV system, making interoperability between the IT system and AGV systems a requirement. In cases 1 and 2 in Paper I, on the other hand, transport requests are created by operators pushing buttons, and the AGV system is not connected to the IT system in production; thus, there is no interoperability requirement for system communication in these cases. Interoperability with IT systems is also crucial when an AGV system is used for automated loading and unloading without human intervention as observed in Paper IV. The AGVs need information on when to start and end the loading or unloading, how to place the goods on the truck, and confirm that the correct goods are managed. That the AGV system needs to communicate with IT systems and other machines has been identified in previous research (e.g. Bechtsis et al., 2017; Vlachos et al., 2024) and the thesis also find support for the interoperability between AGVs and IT systems.

Interoperability between different generations of AGVs was identified in Paper I as a requirement when several generations are used in the same AGV system. The generational differences between the AGVs in case 3 in Paper I concerned hardware updates regarding the location of sensors on the AGV and updates in software features and how the AGVs operated. For safety reasons, the different AGV generations had to be adapted to ensure that they all operated in the same way. Thus, interoperability requirements must be considered when several AGVs are used, even if they are from the same supplier. Scholz et al. (2019) found that AGVs from different suppliers often have different standards and are therefore seldom interoperable. In case 1 in Paper V, there were AGVs from two suppliers, which led to interoperability issues concerning navigation. Competence to manage and update the navigation of both AGVs had to be developed in the work organisational subsystem. Previous research has not address interoperability in AGV system design concerning AGV to AGV interoperability, and the thesis contributes by showing that interoperability requirements should not be neglected as it can influence many design areas as well as which AGVs to purchase. There are many AGV suppliers on the market today, and newly developed technologies influence AGV features, leading to new models and generations. Future AGV systems may more frequently involve AGVs of different models, generations or from different suppliers, making interoperability requirements increasingly relevant to consider in the design.

The German Association of Automotive Industry (2022) has launched an initiative driven that focuses on interoperability in AGV systems, indicating that it is a significant issue in the industry. A specification was developed for AGV suppliers, VDA 5050, which, if followed, would allow AGVs from various suppliers to work together. Future research could focus on interoperability requirements and how to manage them (see Section 6.6 for further elaboration).

6.1.3. Comprehensive overview of requirements

Many studies on AGV system design have focused on individual technical design areas, such as scheduling (e.g. Dang et al., 2021), fleet sizing (e.g. Choobineh et al., 2012; Ferrara et al., 2014), dispatching (e.g. Singh et al., 2023) and, battery management (e.g. Kabir & Suzuki, 2018; Kabir & Suzuki, 2019), in which these design areas have been analysed in detail. Previous review papers on AGV system design (Bechtsis et al., 2017; Dolgui et al., 2022; Fragapane et al., 2021a; Le-Anh & de Koster, 2006; Vis, 2006) have reported the results of research on technical design areas, highlighting methods that have been used to address the technical design areas. Such review studies and studies focusing on individual design areas provide an indication of relevant requirements for the technical subsystem but there is no comprehensive overview of requirements. For example, Vis (2006) and Le-Anh and de Koster (2006) argued for requirements such as material flow demand, facility layout restrictions, number and location of transport requests, unit loads, and meeting various performance measures. This thesis confirms the findings of previous studies in that these requirements need to be considered in AGV system design. Requirements such as restrictions in the environment affecting navigation and guidepaths, the characteristics of the unit loads influencing the selection of the load-carrying mechanism, and meeting the demands of material flow have been identified in Paper I.

The first step of a design process is to obtain a comprehensive overview of requirements (Granlund & Wiktorsson, 2014), and by combining the results from Papers I, III, and IV, this thesis contributes to this design step, creating a solid starting point for the design of an AGV system. An overview of requirements including both technical and requirements due to the human and work organisational subsystem is lacking in previous research and this thesis contributes to previous research on AGV system design with a comprehensive overview of requirements. As discussed in Sections 6.1.1 and 6.1.2, the thesis highlights requirements relating to interactions within and between subsystems and interoperability. The thesis thus expands the perspective on AGV system design, beyond the technical requirements. A categorisation of requirements was created in Paper I and was used to identify the requirements in the cases it presented. The four categories – internal logistics environment, characteristics of transported loads, performance requirements, and interactions within and between subsystems – facilitated a comprehensive overview of requirements.

6.2. Discussion of results related to RQ 2

RQ 2 was formulated as follows: How can the requirements influence AGV system design? Following the specification of requirements and objectives phase, the design process proceeds to conceptual and detailed design (Johansson, 2007). In this thesis, the technical subsystem and the work organisational subsystems are considered to be designable. Sections 6.2.1 and 6.2.2 discuss the findings in relation to the design of the technical subsystem and the work organisational subsystem, respectively.

6.2.1. Design of the technical subsystem

Previous research addressing the design of AGV systems has largely had a technical focus (Benzidia et al., 2019; Fragapane et al., 2021a; Hrušecká et al., 2019; Zuin et al., 2020), with technical design areas receiving substantial attention. As discussed in Section 6.1.3, some of the requirements identified in the appended papers have an expected influence on AGV system design and confirm the results of previous research. For example, Paper I showed that guidepaths need to be designed in consideration of physical restrictions in the environment and the locations of load transfer positions, fleet sizing should be suitable for the demands of material flow, and the characteristics of the transported loads affect decisions on the load-carrying mechanism.

The human subsystem needs further attention in the design of the technical subsystem. In Section 6.1.1, requirements coming from the interactions within and between subsystems were discussed. For example, the design of the technical subsystem is influenced by humans in how the guidepaths should be created. In previous research, guidepath design focused on minimising total AGV travel distance, and interactions with humans were not considered (Le-Anh & de Koster, 2006). Zuin et al. (2020) suggested that AGVs and human should have separate paths in the environment. Paper I similarly showed that the guidepaths were designed to reduce interactions with humans, to benefit the humans working in the aisles by removing stressful interactions and to improve AGV system performance. Additionally, the load transfer positions were designed taking into account the limits of the operators in placing unit loads with high precision and the technical limits of the AGVs. The alarm signals of the AGVs were changed to not be irritating for the operators as shown in Paper III. Safety is crucial, which has also been shown in previous research (Sabattini et al., 2017; Zuin et al., 2020). The thesis contributes by showing that the technical design areas are influenced by the human subsystem, and the human subsystem should be considered.

Interoperability requirements were mentioned in Section 6.1.2, and they influence the technical subsystem. In Paper III, the different generations of AGVs caused interoperability issues due to the different placements of the navigational sensors of the AGVs. The design of the AGV system had to be adapted, and the setting of the AGVs had to be changed to ensure that the AGVs behave in approximately the same way. In Paper V, there were AGVs from two suppliers, and they had separate navigation systems. The navigational areas and guidepaths of the AGVs have to be designed separately. The two navigational systems occasionally caused stops in the aisles when the AGVs encountered each other. Interoperability requirements need to be considered in the design of the technical subsystem of an AGV system, but this has scarcely been addressed in previous research. The industry-driven VDA 5050 initiative indicates that interoperability is an important issues in the design of AGV systems (German Association of Automotive

Industry, 2022). Interoperability requirements become increasingly important as the number of suppliers increases and AGV systems expand over time. Interoperability requirements could be considered when purchasing AGVs to avoid having to, for example, design and maintain two navigational systems as in case 1 in Paper V.

Making changes and continuously improving the technical and work organisational subsystems of an AGV system over time were identified in Papers I, III, and Moeuf et al. (2020) and Brodeur et al. (2023) indicate that continuous improvements are crucial for new technologies. In case 1 in Paper V, the supplier allowed the users to make almost any changes to the technical subsystem without their involvement. In the other AGV systems studied in Papers I, III, and V, suppliers had to be involved when changes were made. The thesis contributes by highlighting that the ability to redesign the technical subsystem independently without needing supplier involvement is important when choosing a suitable AGV. Redesigning the AGV system, as in case 1 in Paper V, requires that the right technical competencies are present within the company, influencing the design of the work organisational subsystem. By being able to redesign the AGV system, the case company also become less reliant on the AGV supplier.

6.2.2. Design of the work organisational subsystem

Previous research has shown that companies often underestimate the costs and difficulties of changing the organisation for new technologies (Cimini et al., 2021). Work organisation is crucial for successful implementation of technologies; only focusing on the technologies increases the risk of failure (Marcon et al., 2022). The work organisational subsystem has received limited attention in research on AGV systems but this thesis shows that the work organisational subsystem in an AGV system is crucial.

Implementing an AGV system involves making changes, such as adding and removing roles. Benzidia et al. (2019) found that new roles and competencies are needed when an AGV system is introduced to manage transports compared to the manually performed transports. Lee and Leonard (1990) found that several roles, from supervisors and team leaders to operators in production and logistics, need to be changed when implementing an AGV system. This thesis supports the findings of Benzidia et al. (2019) and Lee and Leonard (1990) by also identifying that roles need to be changed and competencies that need to be developed. The thesis also contributes with further details concerning the design of the work organisational subsystem. Papers III and V provided indications for the design of the work organisational subsystem for AGV systems concerning developing acceptance and understanding, educating employees on how to work with the AGVs, managing operational issues and failures, introducing new roles (e.g. superuser and reliability engineer), and managing design changes over time. Managing failures quickly to avoid using too many resources is also important in the design of the work organisational subsystem.

A lack of knowledge or skills has been identified as a barrier to the implementation of new technologies (Kamble et al., 2018; Senna et al., 2022; Stentoft et al., 2021). Employees must be informed and educated to overcome a lack of knowledge (Brodeur et al., 2023; Pozzi et al., 2023). Clear communication and training are important acceptance factors when an AGV system is implemented (Kopp et al., 2023). The findings of this thesis also confirm the importance of and the need for training and informing employees when an AGV system is implemented and designed. The thesis shows that employees need to be taught new routines, safety rules and, in general, how to behave when working with AGVs. The knowledge required in various employee roles differs depending on the level of engagement in activities such as error management. Overcoming worry and stress about working with automated equipment is important. As previously stated, AGVs, in comparison to many other forms of automation, are not separated from the work environment of humans, which means that training and informing employees is crucial to fostering an adequate work environment. Additionally, the thesis contributes by showing that training and informing should not only occur in the implementation phase but must also continue in the post-implementation phase. Operators may become overconfident and place undue trust in the safety features of AGVs, causing interruptions to operations or violations of traffic rules, which can result in unsafe manoeuvring of manually operated forklifts. Determining and maintaining an appropriate knowledge level is crucial for ensuring a safe and well-functioning AGV system, and this extends beyond the implementation phase.

Moeuf et al. (2020) found that a strategy for continuous improvement is a critical success factor for Industry 4.0. According to Brodeur et al. (2023), continuous improvements of technologies are important, and their case study showed that establishing a superuser role to provide technical support can facilitate the management of operational issues. This thesis finds support for the need for continuous improvements for AGV systems. Paper III showed that when changes in the environment influence an AGV system, its design must be adapted. There is a need to establish work tasks, competence, and structures for how to improve the AGV system over time. In continuous improvement, input from employees on the shop floor is important, since they interact with and observe the problems occurring in their daily work, unlike the reliability engineer or superusers in Paper V, for example. The continuous improvement fine-tunes the AGV system design as observed in Paper V, solving problems and improving AGV operations over time. A contribution from the thesis is the input to the structure, competence, and job dimensions for continuous improvement of an AGV system.

Error management was important in all the studied cases. Soltani et al. (2019) suggest developing an expert system that summarises previous knowledge on errors occurring in operations, which helps operators manage errors more quickly. Similar methods were used in the cases to quickly teach employees about the most common operational issues and how to solve them. In case 3 in Paper I, a e-learning application was developed which included basic error management for new employees.

6.3. Discussion of results related to RQ 3

RQ 3 was formulated as follows: How do different combinations of load capacity and fleet size impact the required inventory levels at the receiving stations in part feeding? This is part of the detailed design for an AGV system.

The findings of Paper II showed that a large load capacity means that a smaller fleet size can be used at the cost of requiring a larger inventory at the receiving stations to avoid a shortage at the receiving stations due to the more infrequent transports. By contrast, a small load capacity, for example, a load capacity of one unit load, results in a larger fleet being needed, but the inventory can be kept lower. There are, of course, combinations between minimising the load capacity and minimising the fleet size that are possible, and Paper II provided insights into the relation between the fleet size, load capacity, and required inventory. Fleet sizing is a central design area for AGV systems because fleet size is usually the main determinant of investment costs. As previous research has shown, an appropriate number of AGVs is important: too many vehicles and the costs become unnecessarily high, and performance may be reduced due to traffic congestion (e.g. Vis, 2006). Conversely, having too few AGVs results in a system that cannot keep up during peaks in demand, risking delays in subsequent processes.

The combinations of fleet size and load capacity interact in different ways with factors such as AGV speed, load transfer duration, and single versus multiple lane routes, and Paper II elucidated these interactions. For example, load transfer duration has a stronger interaction with AGVs with large load capacities, while AGV speed more strongly interacts with AGVs with small load capacities. The thesis contributes to the literature on AGV fleet sizing, where most attention is paid to single-load AGVs (Dang et al., 2021; Yan et al., 2020), and highlights the interactions between fleet size and load capacity and their impact on the required inventory levels at the receiving stations. The results presented in Figures 5.1 and 5.2 can facilitate in determining a suitable combination of load capacity and fleet size, showing that the impact of speed and load transfer duration is not the same for different options, providing guidance on what to focus on.

The answer to RQ 3 provides knowledge to one part of AGV system design, fleet sizing. To design an AGV system, fleet sizing together with the other technical design areas need to be considered jointly with the other subsystems. AGV speed is varied in Paper II to reveal how it interacts with fleet size, load capacity, and inventory. It is discussed in Paper II that the AGV speed that can be achieved in the facility is restricted by the interactions with humans. There could be for safety reasons for limiting the speed as well as a very fast AGV might be perceived as more threatening by employees working in the environment. Focusing on one technical design area in particular, as the fleet sizing in this case, could reveal aspects related to the human or work organisational subsystems that need to be addressed in the design of the AGV system as a whole.

6.4. Discussion of results in relation to purpose

The purpose of the thesis is to develop knowledge to support the design of AGV systems considering the human, technical, and work organisational subsystems. First, theoretical contributions are discussed, followed by a discussion concerning practical contributions.

6.4.1. Theoretical contribution

The thesis contributes to the design process for AGV system design. A design process begins with a formulation and evaluation of the requirements that the design should meet (e.g. Granlund, 2014; Johansson, 2007; Tompkins et al., 2010). Developing a well-formulated requirements specification is a vital step in a design process, not least when considering automation (Granlund & Wiktorsson, 2014). Without a proper understanding of the requirements, there is a risk that the design will not perform well. As a design process progresses, making changes becomes more costly (Slack et al., 2013), highlighting the need for a comprehensive overview of requirements from the beginning to avoid costly redesigns later. This thesis provides support for the design of AGV systems at this early stage of the design process. The next step in a design process, after the requirements specification has been produced, is to develop conceptual design and, following that, more detailed design suggestions (Johansson, 2007; Tompkins et al., 2010). The thesis contributes with knowledge to the design of the technical and work organisational subsystems in these design phases.

Previous research has had a strong focus on the technical design areas in AGV system design (Benzidia et al., 2019; Fragapane et al., 2021a; Hrušecká et al., 2019; Zuin et al., 2020), as repeated several times in the thesis. However, designing an AGV system is not only a technical undertaking. By combining the answers to the RQs, the thesis supports the design process for an AGV system with knowledge to different phases in the process. Figure 6.1 shows the contributions of the thesis in relation to the three design phases presented in Figure 2.3. The thesis contributes to all the three phases: specification of requirements and objectives, conceptual design, and detailed design.

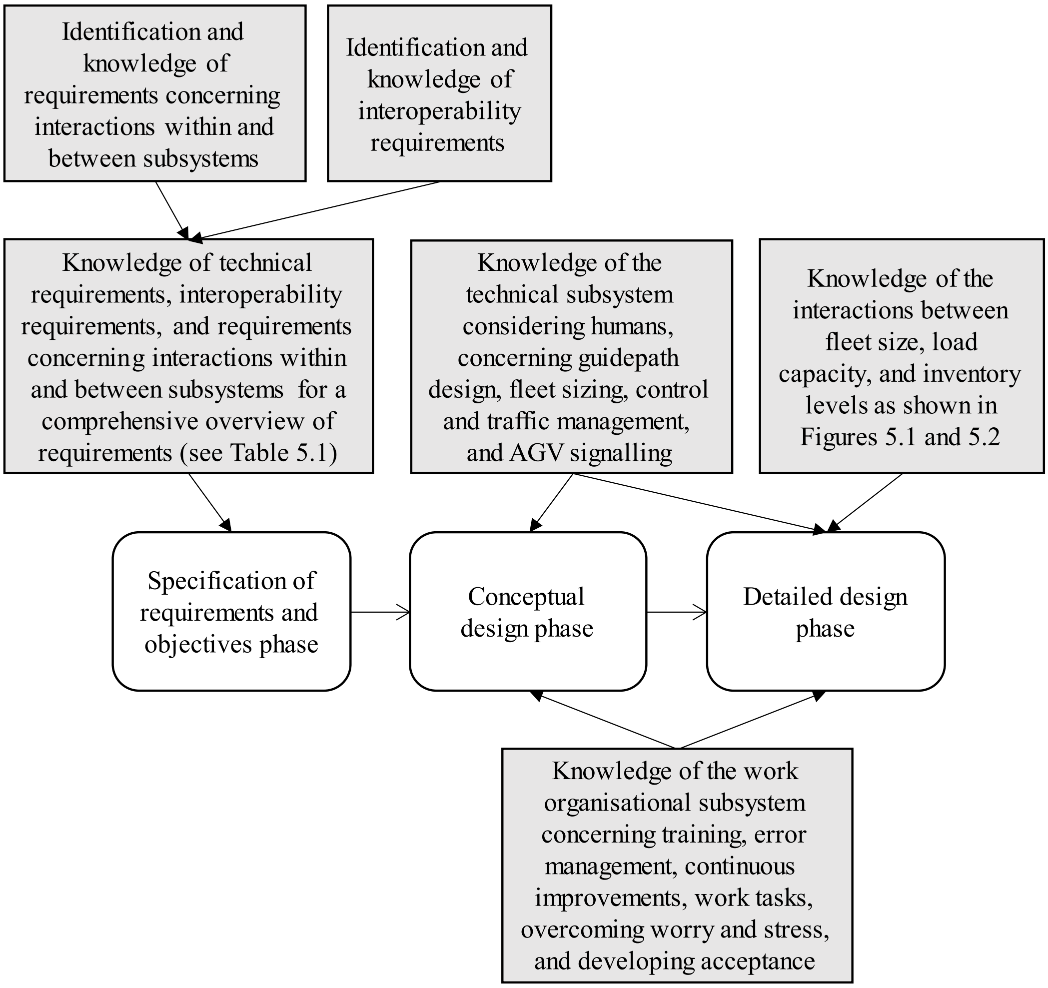

Figure 6.1. *The thesis contribution in relation to the three design process phases.*

The thesis contributes to the specification of requirements and objectives phase. Previous research has shown that there are many requirements to consider for the technical subsystem in an AGV system such as, pick-up and delivery locations, unit loads, number of units to be transported at what times (Le-Anh & de Koster, 2006; Vis, 2006), and layout restrictions (Zuin et al., 2020). Safety is also crucial (Hrušecká et al., 2019). This thesis also confirms these requirements as presented in Table 5.1. The thesis contributes to the technical requirements by highlighting interoperability requirements when there are different AGV generations or AGVs from different suppliers that need to operate together (see Section 6.1.2). In addition to the technical requirements, the thesis contributes by identifying requirements stemming from the interaction within and between subsystems. Previous research has shown that human factors are crucial in the design and implementation of technologies (Kadir & Broberg, 2021; Neumann et al., 2021; Vijayakumar et al., 2021). Considering human factors can result in improved employee well-being and reduced sick-leave (Reiman et al., 2023), and 'phantom profits' can be avoided (Sgarbossa et al., 2020). Previous research on AGV systems has mostly considered safety when humans are concerned (Tubis et al., 2024) or when improving technical capabilities of the AGVs (e.g. Babić et al., 2022; Bergman et al., 2020; Indri et al., 2019). The thesis contributes by identifying requirements relating to the human factors in the design of AGV systems. For example, overcoming employee worry and stress when working with the AGV in the same environment, developing necessary competence, and new work tasks (see Section 6.1.1). The thesis unites technical and non-technical requirements providing a comprehensive overview (see Section 6.1.3) and the findings of the thesis can contribute to making AGV system design human-centric and to improve the wellbeing of employees.

The thesis contributes to the conceptual and detailed design phase of an AGV system regarding the design of the technical subsystem. The design of the technical subsystem has been thoroughly examined in previous research as stated, and the findings of the thesis concerning the design of this subsystem aligns with previous research as discussed in 6.2.1. However, the thesis shows that humans need to be considered in the technical design areas, for example so that aisles for AGVs and humans are separated in guidepath design, control of the AGVs for a safe traffic situation, designing the load transfer positions considering the limitations of the operators, and adjusting AGV signalling. In these aspects, less attention has been paid in previous research, but they are important for AGV system operations and the well-being of the employees. The thesis contributes to one of technical design areas in particular, the fleet sizing considering the load capacity of each AGV as discussed in 6.3. The interactions between fleet size and load capacity have not been thoroughly addressed in previous research where most attention is directed towards AGVs with a load capacity of one (Dang et al., 2021; Yan et al., 2022). The fleet size and load capacity can have substantial impact on the required inventory levels at the receiving stations.

The thesis contributes to the conceptual and detailed design phase for an AGV system regarding the design of the work organisational subsystem. Reiman et al. (2021) stated that humans should not only be considered on an individual level but also on an organisational level, and previous research has shown the importance of the work organisation when technologies are designed and implemented. There are several difficulties associated with adapting the organisation to new technologies, and the costs involved in adapting the organisation are often underestimated (Cimini et al., 2021). Marcon et al. (2022) stated that the work organisation is important for the successful implementation of new technology and showed that companies which only focus on technologies risk failing but they tend to focus on productivity and labour costs. Cagliano et al. (2019) identified that introducing technologies strongly influence the work organisation. Research on AGV systems provides limited guidance on the design of the work organisational subsystem. In relation to AGV systems, acceptance factors (Kopp et al., 2023) and changes in roles and competencies (Benzidia et al., 2019; Lee et al., 1990) have been addressed to some extent. Considering the relevance of the work organisation when technologies are introduced as shown in previous research, the thesis contributes with insights to the design of the work organisational subsystem in an AGV system. As discussed in Section 6.2.2 these insights refer to designing training and competence, new and adapted work tasks, error management, and continuous improvements.

As stipulated in socio-technical systems theory, the risk of suboptimising arises when focusing solely on one subsystem (Grosse et al., 2023) and a joint consideration is needed (Hendrick & Kleiner, 2002). The joint consideration of technical and social systems is not new, it has been a core aspect of socio-technical systems theory since its conception (e.g. Fox, 1995; Mumford, 2006; Trist, 1981). However, in relation to the design of AGV systems, a socio-technical perspective jointly considering all subsystems is novel. The thesis has had a socio-technical perspective inspired by the HTO-model which was useful in expanding the focus beyond the technical aspects. The thesis contributes to research on AGV system design by showing aspects that need to be considered concerning the human subsystem as well as the design of the technical and work organisational subsystems, as discussed in the previous paragraphs in Section 6.4.1. This knowledge is relevant considering that there is research that indicates that humans will not be replaced in the warehouses or production, they will remain a central part in internal logistics (Grosse et al., 2023; Winkelhaus et al., 2022). Additionally, the Industry 5.0 concept introduced in 2021 highlights human centric design as crucial (Breque et al., 2021). The thesis is timely and aligned with human centric design when it comes to the design of AGV systems.

6.4.2. Practical contribution

The findings from the thesis could assist practitioners such as project managers and engineers at different stages in the design process of AGV systems, by providing insights into the design of both the technical and work organisational subsystems.

The results of the thesis provide knowledge that is important in the early stages of the design process regarding an overview of requirements for AGV systems as discussed in Section 6.1. Knowledge about requirements could assist practitioners in knowing what to assess in their context and operations before contacting potential AGV suppliers. The thesis presented four categories of requirements, internal logistics environment, characteristics of transported loads, performance requirements, and interactions within and between subsystems, each containing several requirements which would need to be assessed in a design situation.

Knowledge regarding requirements could facilitate interaction between buyers and suppliers of AGV systems. Grover and Ashraf (2024) state that end users often lack AGV expertise internally and rely on the supplier in the implementation phase. This thesis could provide buying companies with more knowledge when interacting with AGV suppliers. Based on the findings in this thesis, the buying company could develop a better requirements specification. A better understanding of requirements and how they influence the design of the AGV system in the buying company could facilitate the interaction between the buying company and the supplier. With a well-prepared requirements specification for the intended AGV system, suppliers could generate more accurate design suggestions for the buying company. The buyer could be more prepared and ask the supplied the ‘right’ questions. The buying company would also not be as dependent on the supplier when it comes to AGV system design. The buying company could conclude that an AGV system is not the most suitable way forward.

The requirements identified concerning the interactions within and between subsystem show to both buyers and suppliers that humans need to be considered in design. Work organisation subsystem also needs to be designed, and this thesis provides guidance on what the work organisational subsystem needs to include and how it may need to change throughout the implementation and post-implementation phases. The AGV suppliers are likely very knowledgeable about their AGV technology, how it functions and where it is suitable to use. For the suppliers, the findings concerning the design of the work organisational subsystem presented in this thesis may be more novel for them. The supplier could, with input from this thesis, provide recommendations regarding the work organisation and how to best manage and ensure that their specific AGV models are kept in operational condition. Thus, the answers to RQ 1 and RQ 2 provide input for engineers and project managers involved in the design of AGV systems and can facilitate the design, for both AGV suppliers and buyers.

The answer to RQ3 provides both suppliers and buyers with information that can facilitate fleet sizing. When AGVs with different load capacities can be used, the answer to RQ 3 provides information that can facilitate decisions regarding load capacity of individual AGVs and how that decision could influence the inventory levels at receiving stations.

It was stated in Chapter 3 that the results of the research have been presented to practitioners on several occasions, such as at conferences and within the research projects. These practitioners found the results to be useful and relevant. This indicates that the results of the thesis are practically relevant.

6.5. Generalisability

In this section, the generalisability of the findings from the thesis is discussed.

The cases studied in this thesis have focused on industrial material flows, often in manufacturing environments. Paper IV focused on the loading and unloading to and from manufacturing and warehouse facilities. The findings are likely generalisable to similar industrial contexts like warehousing. Warehousing is similar in that it often involves several employees working in the same environment with order picking or operating forklifts and tugger trains. The warehousing context would likely be similar to the contexts studied in the research for this thesis. AGV systems are also applied in non-industrial contexts like in hospital logistics. Findings from the thesis showing the need for new competencies and responsibilities for the AGV systems are applicable in this context as well, as indicated by (Benzidia et al., 2019; Fragapane, 2021) who study AGVs in hospital logistics. However, there could new types of interactions between the AGVs and with people that may not have any experience of automation such as patients and visitors resulting in additional requirements for the design of AGV systems. This is further discussed in 6.6.1.

In section 1.6, it was stated that AGV is used as an umbrella term encompassing other terms used in research and industry for automated vehicles. The findings of the thesis are considered to be applicable for the design of other automated vehicle systems. Autonomous mobile robots for instance have become popular in current research. Based on the definition of autonomous mobile robots (e.g. Fragapane et al., 2021a), the AGVs in case 1 in Paper V were autonomous mobile robots since they navigate freely in the environment. There were some differences in the design of the technical and work organisational subsystem compared to the other cases due to the advanced capabilities of the AGVs in case 1 in Paper V, for example, no guidepath design was needed, load transferring could be performed without guiding rails, and the system could be redesigned without supplier involvement. Besides these examples, similar considerations to the human subsystem were observed in case 1 in Paper V as in the other cases with AGVs not having these advanced capabilities. The design of the work organisational subsystem was also similar concerning training, error management, and work tasks. This indicates that the findings of the thesis are generalisable when designing AGV systems with more advanced functionality.

The thesis focused on the design of AGV systems; the only other automation technology considered was conveyor-based automated loading and unloading in Paper IV. Findings concerning requirements and technical design areas that are unique to AGV system are not generalisable to other automation technologies. For example, findings concerning guidance technologies and guidepath design are not applicable beyond AGV system design. However, findings concerning the design of the work organisational subsystem could be useful for other automation technologies. For example, findings concerning what kind of competencies are needed for different roles, how error management could be performed, and how humans influence and are influenced by the technical subsystem could be applicable.

Paper IV consisted of two additional cases that have not been presented in the cover paper because they involve the use of conveyors for loading and unloading rather than AGVs. The cases highlighted many similar requirements for automated loading and unloading. There were similar requirements related to technical infrastructure in these cases (e.g. communication between the loading and unloading equipment and the IT systems with correct semantics). The identified requirements are similar in the cases despite the use of two different types of loading and unloading equipment. This indicates that the findings from Paper IV are generalisable beyond AGV systems in loading and unloading and include these conveyor-based loading and unloading applications.

Analytical frameworks were developed and used in the papers. The framework in Paper IV combines interoperability layers and types of functions and could be applied for identifying requirements for other types of automation or when actors need to interoperate in the supply chain, for example, regarding implementing a joint IT system. When multiple actors are involved, the framework can provide guidance regarding what to consider in the interoperation between the actors as shown in the loading and unloading application in Paper IV. The framework from Paper IV could be applicable beyond loading and unloading applications. In Paper IV it was clear that the framework was applicable not only for loading and unloading using AGVs but also for the conveyor-based solutions.

6.6. Suggestions for future research

Future research is suggested in this section based on the limitations and the findings of the thesis.

6.6.1. Context of the AGV system

The research in this thesis focused on AGV systems within industrial material flows, mostly in manufacturing environments. Additional cases could be studied in other environments to assess whether the findings from this thesis are generalisable to them and to add to the findings of this thesis. AGV systems have been used in container terminals, warehousing, and hospital logistics. In the industrial environments studied in this thesis, it is possible to provide training to employees working in the same environment as the AGV system. In hospital logistics, by contrast, AGVs can be used to perform transports in wards where employees, patients, and visitors are moving (e.g. Fragapane, 2021; Fragapane et al., 2020), so the potential to provide training to all people who come in contact with the AGVs would be more limited, for example, visitors or patients who might not have encountered an AGV before. This could entail the consideration of further human factor when designing an AGV system in hospital logistics. In container terminals, AGVs operate outdoors, and the payloads are much larger, which influences the technical subsystem. There could be more interactions between manually operated vehicles and AGVs, while in a manufacturing environment, there are often interactions between AGVs and pedestrians in the environment, which could be an important aspect of the human subsystem. Weather conditions also need to be taken into account, for example snow may make it more difficult to navigate and influence the sensors of the AGVs. Other contexts, like hospital logistics, container ports, or warehousing in which AGV systems are applied could be studied in future research.

6.6.2. AGV system applications

Two main applications of AGV systems were studied in this thesis: AGV systems as a means for transporting goods and one case wherein AGVs were used for automated loading and unloading. There are other applications of AGV systems, such as supporting order picking (Glock et al., 2024) and supporting assembly, for example, AGVs equipped with a robot manipulator (e.g. Fragapane et al., 2021a). An AGV system could support order picking by moving material to the pickers, allowing the order picker to focus on the picking of parts. Alternatively, an AGV could follow an order picker in the environment and automatically deliver finished picking assignments to a depot, reducing transport time. AGVs equipped with manipulators could entail several safety requirements and the potential collaboration with humans need to be planned. Future research could thus focus on these other applications of AGV systems to determine whether the findings of this thesis apply and for identifying for example further aspects in the technical, human, or work organisational subsystems.

6.6.3. Economic assessment of AGV systems

The research conducted in this thesis was principally qualitative. Limited attention was given to quantitative aspects. However, Paper II was a discrete event simulation study that focused on AGV combinations of different fleet sizes and load capacities. Future research could focus on conducting an economical assessment of the total costs involved, building upon the findings of Paper II. There are investment costs associated with purchasing AGVs that are influenced by load capacity and the fleet size. As seen in Paper II, the required inventory at the receiving stations is influenced by the number of AGVs and their load capacity. The inventory carrying cost is therefore important to consider in the total cost assessment. This thesis shows that the work organisational subsystem is important in AGV systems in which employees carry out maintenance activities, manage errors, and make design changes, which entails operational costs that need to be assessed and included in the total costs. Thus, an economic model, including investment costs, inventory costs, and operational costs, is suggested as an avenue for future research.

6.6.4. Refining the framework

In section 6.5, the potential applicability of the framework of Paper IV for the implementation of other automation solutions than automated loading and unloading is discussed. The framework was useful in the study for identifying requirements for loading and unloading when multiple different organisations need to interoperate. The framework could, for example be applied in supply chains when multiple actors need to operate together regarding some activity or in the implementation of some type of common equipment such as automated loading and unloading as in Paper IV. Applying the framework in new contexts could lead to developing it further, adding more details and expanding the scope of applications. New dimensions may be added to the framework that are important in a specific context or for a specific technology.

6.6.5. Interoperability issues

In Section 6.1.3, interoperability was discussed, and the ongoing initiative of the German Association of Automotive Industry (2022) involving the VDA 5050 standard was presented. VDA 5050 is an interface for communication between AGVs and a master control, which facilitates interoperability between AGVs from several suppliers. The VDA 5050 standard is an industry driven initiative, and research efforts into interoperability relating to AGV systems have been limited, but this thesis showed that there are potential interoperability issues in AGV system design. Paper I revealed the interoperability issues that arise when an existing AGV system is expanded with additional AGVs at a later point in time. The AGVs, although of the same model, were not completely the same, which influenced the design of the AGV system. Future research could study how to manage interoperability issues in AGV system design, potentially regarding how to apply the VDA 5050 standard.

7. Conclusion

AGV system design was the focus of this thesis. This chapter presents the conclusions of the thesis, presenting the main findings as well as suggestions for future research based on these findings.

Current trends are driving increased interest in automation in general and, together with the improving technical capabilities of the AGVs, have led to a growing number of AGV system applications. Whereas previous research on AGV systems has had a predominantly technical focus, this thesis applied a socio-technical systems perspective inspired by the HTO model. By focusing only on technical aspects there is a risk that the system is suboptimized and does not achieve the intended performance outcome and results in poor employee well-being, highlighting the need for a broader perspective. AGV systems in this thesis have been viewed as consisting of three subsystems – human, technical, and work organisational. The thesis addressed three research questions that focused on developing knowledge to support AGV system design. The research conducted to answer these questions was based on case studies, with the exception of one study, which was based on discrete event simulation. The first research question focused on the requirements for AGV system design. The second research question concerned how the requirements can influence the design of AGV systems. The third and final research question focused on fleet sizing.

The socio-technical perspective in the thesis facilitated the identification of requirements in relation to RQ 1 and an understanding of how the requirements influence the design of AGV systems in relation to RQ 2. It is clear that the design of AGV systems should not only focus on the technical subsystem but must also consider the human subsystem regarding, for example, acceptance and understanding, and the design of the work organisational subsystem with new work tasks, roles and competencies to develop. The findings of the thesis align with the concept of Industry 5.0, which underscores the need for human-centric design.

In relation to RQ 3, the thesis focused on one of the detailed technical design areas of AGV systems, namely fleet sizing, considering different combinations of fleet size and load capacity. The results show the interactions between fleet size and load capacity and their impacts on required inventory levels considering AGV speed, load transfer duration, and routes in the environment.

The thesis shows that the socio-technical perspective with a human and work organisational subsystem together with the technical subsystem is relevant for designing an AGV system. The thesis can facilitate the design process of an AGV system by providing input for the requirements and objectives specification phase early in the process and the conceptual and detailed design stages, encompassing the design of both the technical and work organisational subsystems. The findings could be useful for both suppliers and users of AGV systems when designing these systems.

Suggestions for future research were provided in the thesis. Future research could focus on other contexts and applications of AGV system. The main context of this thesis was industrial material flows, largely in manufacturing environments. Studying other contexts and applications of AGV systems could establish whether the findings are also applicable to them. Interoperability was shown to impose requirements on AGV system design, and designing AGV systems in the future may involve additional interoperability considerations due to the increasing number of AGV suppliers, new models, and new technologies that would need to operate together. Thus, the exploration of interoperability issues constitutes another potential area for future research. An economic model based on the answer to the third research question is also suggested. Finally, while the conceptual framework applied in Paper IV was useful for identifying interoperability requirements, the applicability of the framework could be explored in future research.

References

Anand, G., Kodali, R., & Kumar, B. S. (2011). Development of analytic network process for the selection of material handling systems in the design of flexible manufacturing systems (FMS). *Journal of Advances in Management Research*, *8*(1), pp.123-147. https://doi.org/10.1108/09727981111129336

Andreasson, H., Bouguerra, A., Cirillo, M., Dimitrov, D. N., Driankov, D., Karlsson, L., Lilienthal, A. J., Pecora, F., Saarinen, J. P., Sherikov, A., & Stoyanov, T. (2015). Autonomous Transport Vehicles: Where We Are and What Is Missing. *IEEE Robotics & Automation Magazine*, *22*(1), pp.64. https://doi.org/10.1109/MRA.2014.2381357

Arlbjørn, J. S., & Mikkelsen, O. S. (2014). Backshoring manufacturing: Notes on an important but under-researched theme. *Journal of Purchasing and Supply Management*, *20*(1), pp.60-62. https://doi.org/10.1016/j.pursup.2014.02.003

Asef-Vaziri, A., & Goetschalckx, M. (2008). Dual track and segmented single track bidirectional loop guidepath layout for AGV systems. *European Journal of Operational Research*, *186*(3), pp.972-989. https://doi.org/10.1016/j.ejor.2007.02.049

Babić, J., Bilić, M., & Kovač, I. (2022). Safety Vest System for Human-Robot Collaboration. In: *2022 45th Jubilee International Convention on Information, Communication and Electronic Technology (MIPRO)*, pp.12-17. https://doi.org/10.23919/MIPRO55190.2022.9803318

Banks, J. (2010). *Discrete-event system simulation* (5. ed., International edition ed.). Pearson Education.

Battini, D., Boysen, N., & Emde, S. (2013). Just-in-Time supermarkets for part supply in the automobile industry. *Journal of Management Control*, *24*(2), pp.209-217. https://doi.org/10.1007/s00187-012-0154-y

Battini, D., Gamberi, M., Persona, A., & Sgarbossa, F. (2015). Part-feeding with supermarket in assembly systems: Transportation mode selection model and multi-scenario analysis. *Assembly Automation*, *35*(1), pp.149-159. https://doi.org/10.1108/AA-06-2014-053

Bechtsis, D., Tsolakis, N., Vlachos, D., & Iakovou, E. (2017). Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles. *Journal of Cleaner Production*, *142*(4), pp.3970-3984. https://doi.org/10.1016/j.jclepro.2016.10.057

Beier, G., Ullrich, A., Niehoff, S., Reißig, M., & Habich, M. (2020). Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review. *Journal of Cleaner Production*, *259*. https://doi.org/10.1016/j.jclepro.2020.120856

Bell, E., Bryman, A., & Harley, B. (2022). *Business research methods*. Oxford university press.

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

Berglund, M., & Karltun, J. (2007). Human, technological and organizational aspects influencing the production scheduling process. *International Journal of Production Economics*, *110*(1), pp.160-174. https://doi.org/10.1016/j.ijpe.2007.02.024

Bergman, M., Bedaf, S., van Heel, G., & Sturm, J. (2020). Can I Just Pass by? Testing Design Principles for Industrial Transport Robots. In: *CHIRA 2020 - Proceedings of the 4th International Conference on Computer-Human Interaction Research and Applications*, pp.178-187. https://doi.org/10.5220/0010144301780187

Berx, N., Pintelon, L., & Decré, W. (2021). Psychosocial Impact of Collaborating with an Autonomous Mobile Robot: Results of an Exploratory Case Study. In: *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction*, pp.280–282. https://doi.org/10.1145/3434074.3447176

Bilge, Ü., & Tanchoco, J. M. A. (1997). AGV Systems with Multi-Load Carriers: Basic Issues and Potential Benefits. *Journal of Manufacturing Systems*, *16*(3), pp.159-174. https://doi.org/10.1016/S0278-6125(97)88885-1

Bloss, R. (2008). Simultaneous sensing of location and mapping for autonomous robots. *Sensor Review*, *28*(2), pp.102-107. https://doi.org/10.1108/02602280810856651

Bouh, M. A., & Riopel, D. (2015). Material handling equipment selection: New classifications of equipments and attributes. In: *2015 International Conference on Industrial Engineering and Systems Management (IESM)*, pp.461-468. https://doi.org/10.1109/IESM.2015.7380198

Breque, M., De Nul, L., & Petridis, A. (2021). *Industry 5.0 : towards a sustainable, human-centric and resilient European industry*. Publications Office. https://data.europa.eu/doi/10.2777/308407

Brodeur, J., Deschamps, I., & Pellerin, R. (2023). Organizational changes approaches to facilitate the management of Industry 4.0 transformation in manufacturing SMEs. *Journal of Manufacturing Technology Management*, *34*(7), pp.1098-1119. https://doi.org/10.1108/JMTM-10-2022-0359

Caccavale, R., & Finzi, A. (2019). An Automated Guided Vehicle for Flexible and Interactive Task Execution in Hospital Scenarios. In: *AIRO@AI*IA*,

Cagliano, R., Canterino, F., Longoni, A., & Bartezzaghi, E. (2019). The interplay between smart manufacturing technologies and work organization. *International Journal of Operations & Production Management*, *39*(6/7/8), pp.913-934. https://doi.org/10.1108/IJOPM-01-2019-0093

Calzavara, M., Battini, D., Bogataj, D., Sgarbossa, F., & Zennaro, I. (2020). Ageing workforce management in manufacturing systems: state of the art and future research agenda. *International Journal of Production Research*, *58*(3), pp.729-747. https://doi.org/10.1080/00207543.2019.1600759

Campion, M. A. (1988). Interdisciplinary approaches to job design: A constructive replication with extensions. *Journal of applied psychology*, *73*(3), pp.467–481. https://doi.org/10.1037/0021-9010.73.3.467

Carayon, P., Hancock, P., Leveson, N., Noy, I., Sznelwar, L., & van Hootegem, G. (2015). Advancing a sociotechnical systems approach to workplace safety – developing the conceptual framework. *Ergonomics*, *58*(4), pp.548-564. https://doi.org/10.1080/00140139.2015.1015623

Chakrabarti, A., Morgenstern, S., & Knaab, H. (2004). Identification and application of requirements and their impact on the design process: a protocol study. *Research in Engineering Design*, *15*(1), pp.22-39. https://doi.org/10.1007/s00163-003-0033-5

Chen, C., Xi, L.-f., Zhou, B.-h., & Zhou, S.-s. (2011). A multiple-criteria real-time scheduling approach for multiple-load carriers subject to LIFO loading constraints. *International Journal of Production Research*, *49*(16), pp.4787-4806. https://doi.org/10.1080/00207543.2010.510486

Chen, C., Xia, B., Zhou, B.-h., & Xi, L. (2015). A reinforcement learning based approach for a multiple-load carrier scheduling problem. *Journal of Intelligent Manufacturing*, *26*(6), pp.1233-1245. https://doi.org/10.1007/s10845-013-0852-9

Chen, D., Doumeingts, G., & Vernadat, F. (2008). Architectures for enterprise integration and interoperability: Past, present and future. *Computers in Industry*, *59*(7), pp.647-659. https://doi.org/10.1016/j.compind.2007.12.016

Chivilò, M., & Meneghetti, A. (2023). An Industry 5.0 Perspective on Feeding Production Lines. *Sustainability*, *15*(22), pp.16088. https://doi.org/10.3390/su152216088

Cho, C., & Egbelu, P. J. (2005). Design of a web-based integrated material handling system for manufacturing applications. *International Journal of Production Research*, *43*(2), pp.375-403. https://doi.org/10.1080/0020754042000268866

Choobineh, F. F., Asef-Vaziri, A., & Huang, X. (2012). Fleet sizing of automated guided vehicles: a linear programming approach based on closed queuing networks. *International Journal of Production Research*, *50*(12), pp.3222-3235. https://doi.org/10.1080/00207543.2011.562560

Chung, C. A. (2003). *Simulation modeling handbook: a practical approach*. CRC press.

Cilekoglu, A. A., Moreno, R., & Ramos, R. (2024). The impact of robot adoption on global sourcing. *Research Policy*, *53*(3), pp.104953. https://doi.org/10.1016/j.respol.2024.104953

Cimini, C., Boffelli, A., Lagorio, A., Kalchschmidt, M., & Pinto, R. (2021). How do industry 4.0 technologies influence organisational change? An empirical analysis of Italian SMEs. *Journal of Manufacturing Technology Management*, *32*(3), pp.695-721. https://doi.org/10.1108/JMTM-04-2019-0135

Confessore, G., Liotta, G., & Fabiano, M. (2013). A network flow based heuristic approach for optimising AGV movements. *Journal of Intelligent Manufacturing*, *24*(2), pp.405-419. https://doi.org/10.1007/s10845-011-0612-7

Cugno, M., Castagnoli, R., & Büchi, G. (2021). Openness to Industry 4.0 and performance: The impact of barriers and incentives. *Technological Forecasting and Social Change*, *168*, pp.120756. https://doi.org/10.1016/j.techfore.2021.120756

Dang, Q.-V., Singh, N., Adan, I., Martagan, T., & van de Sande, D. (2021). Scheduling heterogeneous multi-load AGVs with battery constraints. *Computers and Operations Research*, *136*, pp.105517. https://doi.org/10.1016/j.cor.2021.105517

Daniellou, F. (2006). Epistemological issues about ergonomics and human factors. In W. Karwowski (Ed.), *International encyclopedia of ergonomics and human factors* (2 ed., pp. 43-46). CRC Press. https://doi.org/10.1201/9780849375477

De Ryck, M., Versteyhe, M., & Debrouwere, F. (2020). Automated guided vehicle systems, state-of-the-art control algorithms and techniques. *Journal of Manufacturing Systems*, *54*, pp.152-173. https://doi.org/10.1016/j.jmsy.2019.12.002

Dolgui, A., Sgarbossa, F., & Simonetto, M. (2022). Design and management of assembly systems 4.0: systematic literature review and research agenda. *International Journal of Production Research*, *60*(1), pp.184-210. https://doi.org/10.1080/00207543.2021.1990433

Draganjac, I., Petrović, T., Miklić, D., Kovačić, Z., & Oršulić, J. (2020). Highly-scalable traffic management of autonomous industrial transportation systems. *Robotics and Computer-Integrated Manufacturing*, *63*, pp.101915. https://doi.org/10.1016/j.rcim.2019.101915

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review*, *14*(4), pp.532-550. https://doi.org/10.2307/258557

Eisenhardt, K. M. (2021). What is the Eisenhardt Method, really? *Strategic Organization*, *19*(1), pp.147-160. https://doi.org/10.1177/1476127020982866

Ellithy, K., Salah, M., Fahim, I. S., & Shalaby, R. (2024). AGV and Industry 4.0 in warehouses: a comprehensive analysis of existing literature and an innovative framework for flexible automation. *The International Journal of Advanced Manufacturing Technology*, *134*(1), pp.15-38. https://doi.org/10.1007/s00170-024-14127-0

Ellram, L. M. (1996). The use of the case study method in logistics research. *Journal of Business Logistics*, *17*(2), pp.93.

Emde, S., Fliedner, M., & Boysen, N. (2012). Optimally loading tow trains for just-in-time supply of mixed-model assembly lines. *IIE Transactions*, *44*(2), pp.121-135. https://doi.org/10.1080/0740817X.2011.575442

Emde, S., & Gendreau, M. (2017). Scheduling in-house transport vehicles to feed parts to automotive assembly lines. *European Journal of Operational Research*, *260*(1), pp.255-267. https://doi.org/10.1016/j.ejor.2016.12.012

Esmaeilian, B., Behdad, S., & Wang, B. (2016). The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, *39*, pp.79-100. https://doi.org/10.1016/j.jmsy.2016.03.001

European Commission. (2017). *New European Interoperability Framework - Promoting seamless services and data flows for European public administrations*. Publications Office of the European Union. https://doi.org/10.2799/78681

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

Fletcher, S. R., Johnson, T., Adlon, T., Larreina, J., Casla, P., Parigot, L., Alfaro, P. J., & Otero, M. d. M. (2020). Adaptive automation assembly: Identifying system requirements for technical efficiency and worker satisfaction. *Computers and Industrial Engineering*, *139*, pp.105772. https://doi.org/10.1016/j.cie.2019.03.036

Flick, U. (2009). *An introduction to qualitative research* (4 ed. ed.). SAGE.

Fox, W. M. (1995). Sociotechnical System Principles and Guidelines: Past and Present. *The Journal of Applied Behavioral Science*, *31*(1), pp.91-105. https://doi.org/10.1177/0021886395311009

Fragapane, G. (2021). *Autonomous material transportation in hospital intralogistics* [PhD thesis, Norwegian University of Science and Technology].

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

Fragapane, G., Hvolby, H.-H., Sgarbossa, F., & Strandhagen, J. O. (2021b). Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework. *Production Planning and Control*, pp.53-67. https://doi.org/10.1080/09537287.2021.1884914

Fragapane, G., Peron, M., Sgarbossa, F., Strandhagen, J. O., & Ivanov, D. (2020). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research*, *308*, pp.125-143. https://doi.org/10.1007/s10479-020-03526-7

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, pp.15-26. https://doi.org/10.1016/j.ijpe.2019.01.004

Galati, F., & Bigliardi, B. (2019). Industry 4.0: Emerging themes and future research avenues using a text mining approach. *Computers in Industry*, *109*, pp.100-113. https://doi.org/10.1016/j.compind.2019.04.018

German Association of Automotive Industry. (2022). *Interface for the communication between automated guided vehicles (AGV) and a master control*. V. d. Automobilindustrie. https://github.com/VDA5050/VDA5050/blob/main/VDA5050_EN.md

Glock, C. H., Grosse, E. H., & Winkelhaus, S. (2024). Warehousing 5.0: Conceptual Background. In C. H. Glock & E. H. Grosse (Eds.), *Warehousing 5.0 Managing the transition from techno-focused to human-value-centric intralogistics*. Amazon Fulfilment.

Goli, A., Tirkolaee, E. B., & Aydın, N. S. (2021). Fuzzy Integrated Cell Formation and Production Scheduling Considering Automated Guided Vehicles and Human Factors. *IEEE Transactions on Fuzzy Systems*, *29*(12), pp.3686-3695. https://doi.org/10.1109/TFUZZ.2021.3053838

Granlund, A. (2014). *Facilitating automation development in internal logistics systems* [PhD Thesis, Mälardalen University].

Granlund, A., & Wiktorsson, M. (2014). Automation in internal logistics: Strategic and operational challenges. *International Journal of Logistics Systems and Management*, *18*(4), pp.538-558. https://doi.org/10.1504/IJLSM.2014.063984

Groover, M. P. (2016). *Automation, production systems, and computer-integrated manufacturing*. Pearson Education India.

Grosse, E. H., Sgarbossa, F., Berlin, C., & Neumann, W. P. (2023). Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0. *International Journal of Production Research*, *61*(22), pp.7749-7759. https://doi.org/10.1080/00207543.2023.2246783

Grover, A. K., & Ashraf, M. H. (2024). Leveraging autonomous mobile robots for Industry 4.0 warehouses: a multiple case study analysis. *The International Journal of Logistics Management*, *35*(4), pp.1168-1199. https://doi.org/10.1108/IJLM-09-2022-0362

Hackman, J. R., & Oldham, G. R. (1976). Motivation through the Design of Work: Test of a Theory. *Organizational Behavior and Human Performance*, *16*(2), pp.250-279. https://doi.org/10.1016/0030-5073(76)90016-7

Hassan, M. M. D. (2010). A framework for selection of material handling equipment in manufacturing and logistics facilities. *Journal of Manufacturing Technology Management*, *21*(2), pp.246-268. https://doi.org/10.1108/17410381011014396

Hellmann, W., Marino, D., Megahed, M., Suggs, M., Borowski, J., & Negahban, A. (2019). Human, AGV or AIV? An integrated framework for material handling system selection with real-world application in an injection molding facility. *International Journal of Advanced Manufacturing Technology*, *101*(1-4), pp.815-824. https://doi.org/10.1007/s00170-018-2958-x

Hendrick, H. W., & Kleiner, B. M. (2002). *Macroergonomics: Theory, methods, and applications*.

Ho, Y.-C., & Liu, H.-C. (2009). The performance of load-selection rules and pickup-dispatching rules for multiple-load AGVs. *Journal of Manufacturing Systems*, *28*(1), pp.1-10. https://doi.org/10.1016/j.jmsy.2009.06.001

Ho, Y. C., & Chien, S. H. (2006). A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs. *International Journal of Production Research*, *44*(20), pp.4193-4222. https://doi.org/10.1080/00207540500442401

Ho, Y. C., Liu, H. C., & Yih, Y. (2012). A multiple-attribute method for concurrently solving the pickup-dispatching problem and the load-selection problem of multiple-load AGVs. *Journal of Manufacturing Systems*, *31*(3), pp.288-300. https://doi.org/10.1016/j.jmsy.2012.03.002

Hollnagel, E. (1997). Cognitive ergonomics: it's all in the mind. *Ergonomics*, *40*(10), pp.1170-1182. https://doi.org/10.1080/001401397187685

Hrušecká, D., Borges Lopes, R., & Juřičková, E. (2019). CHALLENGES IN THE INTRODUCTION OF AGVS IN PRODUCTION LINES: CASE STUDIES IN THE AUTOMOTIVE INDUSTRY. *Serbian Journal of Management*, *14*(1), pp.233-247. https://doi.org/10.5937/sjm14-18064

Hu, H., Jia, X., He, Q., Fu, S., & Liu, K. (2020). Deep reinforcement learning based AGVs real-time scheduling with mixed rule for flexible shop floor in industry 4.0. *Computers and Industrial Engineering*, *149*, pp.106749. https://doi.org/10.1016/j.cie.2020.106749

Humphrey, S. E., Nahrgang, J. D., & Morgeson, F. P. (2007). Integrating motivational, social, and contextual work design features: a meta-analytic summary and theoretical extension of the work design literature. *Journal of applied psychology*, *92*(5), pp.1332. https://doi.org/10.1037/0021-9010.92.5.1332

IEA. (2024). *What is Ergonomics*. Retrieved 2024-04-04 from https://iea.cc/what-is-ergonomics/

Indri, M., Sibona, F., & Cheng, P. D. C. (2019). Sensor data fusion for smart AMRs in human-shared industrial workspaces. In: *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, pp.738-743. https://doi.org/10.1109/IECON.2019.8927622

Indri, M., Sibona, F., Cheng, P. D. C., & Possieri, C. (2020). Online supervised global path planning for AMRs with human-obstacle avoidance. In: *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, pp.1473-1479. https://doi.org/10.1109/ETFA46521.2020.9212151

ISO. (2023). ISO 3691-4:2023 Industrial trucks — Safety requirements and verification — Part 4: Driverless industrial trucks and their systems. In: International Organization for Standardization.

Ivanov, D. (2023). The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. *International Journal of Production Research*, *61*(5), pp.1683-1695. https://doi.org/10.1080/00207543.2022.2118892

Ivanov, D., Tang, C. S., Dolgui, A., Battini, D., & Das, A. (2021). Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management.

International Journal of Production Research, 59(7), pp.2055-2078. https://doi.org/10.1080/00207543.2020.1798035

Johansson, E. (2007). Towards a design process for materials supply systems. *International Journal of Operations and Production Management*, 27(4), pp.388-408. https://doi.org/10.1108/01443570710736976

Jun, S., Lee, S., & Yih, Y. (2021). Pickup and delivery problem with recharging for material handling systems utilising autonomous mobile robots. *European Journal of Operational Research*, 289(3), pp.1153-1168. https://doi.org/10.1016/j.ejor.2020.07.049

Kabir, Q. S., & Suzuki, Y. (2018). Increasing manufacturing flexibility through battery management of automated guided vehicles. *Computers and Industrial Engineering*, 117, pp.225-236. https://doi.org/10.1016/j.cie.2018.01.026

Kabir, Q. S., & Suzuki, Y. (2019). Comparative analysis of different routing heuristics for the battery management of automated guided vehicles. *International Journal of Production Research*, 57(2), pp.624-641. https://doi.org/10.1080/00207543.2018.1475761

Kadir, B. A., & Broberg, O. (2021). Human-centered design of work systems in the transition to industry 4.0. *Applied Ergonomics*, 92, pp.103334. https://doi.org/10.1016/j.apergo.2020.103334

Kadir, B. A., Broberg, O., & Conceição, C. S. d. (2019). Current research and future perspectives on human factors and ergonomics in Industry 4.0. *Computers and Industrial Engineering*, 137, pp.106004. https://doi.org/10.1016/j.cie.2019.106004

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion.

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018). Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. *Computers in Industry*, 101, pp.107-119. https://doi.org/10.1016/j.compind.2018.06.004

Karasek, R. A. (1979). Job Demands, Job Decision Latitude, and Mental Strain: Implications for Job Redesign. *Administrative Science Quarterly*, 24(2), pp.285-308. https://doi.org/10.2307/2392498

Karltun, A., Karltun, J., Berglund, M., & Eklund, J. (2017). HTO – A complementary ergonomics approach. *Applied Ergonomics*, 59, pp.182-190. https://doi.org/10.1016/j.apergo.2016.08.024

Katzenbach, J. R., & Smith, D. K. (2015). *The wisdom of teams: Creating the high-performance organization*. Harvard Business Review Press.

Kirks, T., Jost, J., Finke, J., & Hoose, S. (2020). Modelling Proxemics for Human-Technology-Interaction in Decentralized Social-Robot-Systems. In: *Intelligent Human Systems Integration 2020*, pp.153-158. https://doi.org/10.1007/978-3-030-39512-4_24

Klumpp, M. (2018). Automation and artificial intelligence in business logistics systems: human reactions and collaboration requirements. *International Journal of Logistics: Research and Applications*, 21(3), pp.224-242. https://doi.org/10.1080/13675567.2017.1384451

Klumpp, M., & Ruiner, C. (2022). Artificial intelligence, robotics, and logistics employment: The human factor in digital logistics. *Journal of Business Logistics*, 43(3), pp.297-301. https://doi.org/10.1111/jbl.12314

Kopp, T., Baumgartner, M., & Kinkel, S. (2021). Success factors for introducing industrial human-robot interaction in practice: an empirically driven framework. *The International Journal of Advanced Manufacturing Technology*, 112(3), pp.685-704. https://doi.org/10.1007/s00170-020-06398-0

Kopp, T., Baumgartner, M., Seeger, M., & Kinkel, S. (2023). Perspectives of managers and workers on the implementation of automated-guided vehicles (AGVs)—a quantitative survey. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-023-11294-4

Kumbhar, S. G., Thombare, R. B., & Salunkhe, A. B. (2018). Automated Guided Vehicles for Small Manufacturing Enterprises: A Review. *SAE International Journal of Materials and Manufacturing*(3), pp.253. https://doi.org/10.4271/05-11-03-0024

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

Lee, J., Choi, R. H.-G., & Khaksar, M. (1990). Evaluation of automated guided vehicle systems by simulation. *Computers & Industrial Engineering*, *19*(1), pp.318-321. https://doi.org/10.1016/0360-8352(90)90130-E

Lee, J., & Srisawat, T. (2006). Effect of manufacturing system constructs on pick-up and drop-off strategies of multiple-load AGVs. *International Journal of Production Research*, *44*(4), pp.653-673. https://doi.org/10.1080/00207540500251646

Lee, R. J. V., & Leonard, R. (1990). Changing role of humans within an integrated automated guided vehicle system. *Computer Integrated Manufacturing Systems*, *3*(2), pp.115-120. https://doi.org/10.1016/0951-5240(90)90114-T

Liao, Y., Deschamps, F., Loures, E. d. F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), pp.3609-3629. https://doi.org/10.1080/00207543.2017.1308576

Liu, F.-H., & Hung, P.-C. (2001). Real-time deadlock-free control strategy for single multi-load automated guided vehicle on a job shop manufacturing system. *International Journal of Production Research*, *39*(7), pp.1323-1342. https://doi.org/10.1080/00207540010005105

Liu, J., Li, M., & Wang, Z. (2022a). AGV Variable Speed Control for Human Body Adaptability. In: *2022 IEEE 5th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, pp.1473-1478. https://doi.org/10.1109/IMCEC55388.2022.10019990

Liu, L., Qu, T., Thürer, M., Ma, L., Zhang, Z., & Yuan, M. (2022b). A new knowledge-guided multi-objective optimisation for the multi-AGV dispatching problem in dynamic production environments. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2022.2122619

Longo, F., Nicoletti, L., & Padovano, A. (2019). Modeling workers' behavior: A human factors taxonomy and a fuzzy analysis in the case of industrial accidents. *International Journal of Industrial Ergonomics*, *69*, pp.29-47. https://doi.org/10.1016/j.ergon.2018.09.002

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, *6*, pp.1-10. https://doi.org/10.1016/j.jii.2017.04.005

Löcklin, A., Artelt, M., Ruppert, T., Vietz, H., Jazdi, N., & Weyrich, M. (2022). Trajectory Prediction of Moving Workers for Autonomous Mobile Robots on the Shop Floor. In: *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, pp.1-8. https://doi.org/10.1109/ETFA52439.2022.9921493

Małopolski, W. (2018). A sustainable and conflict-free operation of AGVs in a square topology. *Computers & Industrial Engineering*, *126*, pp.472-481. https://doi.org/10.1016/j.cie.2018.10.002

Maniya, K. D., & Bhatt, M. G. (2011). A multi-attribute selection of automated guided vehicle using the AHP/M-GRA technique. *International Journal of Production Research*, *49*(20), pp.6107-6124. https://doi.org/10.1080/00207543.2010.518988

Marcon, É., Soliman, M., Gerstlberger, W., & Frank, A. G. (2022). Sociotechnical factors and Industry 4.0: an integrative perspective for the adoption of smart manufacturing technologies. *Journal of Manufacturing Technology Management*, *33*(2), pp.259-286. https://doi.org/10.1108/JMTM-01-2021-0017

Marković, S. (2023). *Robotics: market data & analysis*. Statista Market Analysis.

Martin, L., González-Romo, M., Sahnoun, M., Bettayeb, B., He, N., & Gao, J. (2021). Effect of Human-Robot Interaction on the Fleet Size of AIV Transporters in FMS. In: *2021 1st International Conference On Cyber Management And Engineering (CyMaEn)*, pp.1-5. https://doi.org/10.1109/CyMaEn50288.2021.9497273

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management*, *16*(4), pp.441-454. https://doi.org/10.1016/S0272-6963(98)00023-0

Mirhosseyni, S. H. L., & Webb, P. (2009). A Hybrid Fuzzy Knowledge-Based Expert System and Genetic Algorithm for efficient selection and assignment of Material Handling Equipment. *Expert Systems with Applications*, *36*(9), pp.11875-11887. https://doi.org/10.1016/j.eswa.2009.04.014

Miyamoto, T., & Inoue, K. (2016). Local and random searches for dispatch and conflict-free routing problem of capacitated AGV systems. *Computers and Industrial Engineering*, *91*, pp.1-9. https://doi.org/10.1016/j.cie.2015.10.017

Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E., & Eburdy, R. (2020). Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. *International Journal of Production Research*, *58*(5), pp.1384-1400. https://doi.org/10.1080/00207543.2019.1636323

Mohsin, S., Khan, I. A., & Ali, M. (2019). Ergonomics-based working flexibility for automated guided vehicle (AGV) operators. *The International Journal of Advanced Manufacturing Technology*, *103*(1), pp.529-547. https://doi.org/10.1007/s00170-019-03542-3

Morgeson, F. P., & Humphrey, S. E. (2006). The Work Design Questionnaire (WDQ): developing and validating a comprehensive measure for assessing job design and the nature of work. *Journal of applied psychology*, *91*(6), pp.1321-1339. https://doi.org/10.1037/0021-9010.91.6.1321

Mumford, E. (2006). The story of socio-technical design: reflections on its successes, failures and potential. *Information Systems Journal*, *16*(4), pp.317-342. https://doi.org/10.1111/j.1365-2575.2006.00221.x

Mumtaz, J., Minhas, K. A., Rauf, M., Yue, L., & Chen, Y. (2024). Solving line balancing and AGV scheduling problems for intelligent decisions using a Genetic-Artificial bee colony algorithm. *Computers & Industrial Engineering*, *189*, pp.109976. https://doi.org/10.1016/j.cie.2024.109976

Nayernia, H., Bahemia, H., & Papagiannidis, S. (2021). A systematic review of the implementation of industry 4.0 from the organisational perspective. *International Journal of Production Research*, *60*(14), pp.4365-4396. https://doi.org/10.1080/00207543.2021.2002964

Netterstrøm, B., Conrad, N., Bech, P., Fink, P., Olsen, O., Rugulies, R., & Stansfeld, S. (2008). The Relation between Work-related Psychosocial Factors and the Development of Depression. *Epidemiologic Reviews*, *30*(1), pp.118-132. https://doi.org/10.1093/epirev/mxn004

Neumann, W. P., & Village, J. (2012). Ergonomics action research II: a framework for integrating HF into work system design. *Ergonomics*, *55*(10), pp.1140-1156. https://doi.org/10.1080/00140139.2012.706714

Neumann, W. P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S. E. (2006). Production system design elements influencing productivity and ergonomics. *International Journal of Operations and Production Management*, *26*(8), pp.904-923. https://doi.org/10.1108/01443570610678666

Neumann, W. P., Winkelhaus, S., Grosse, E. H., & Glock, C. H. (2021). Industry 4.0 and the human factor – A systems framework and analysis methodology for successful development. *International Journal of Production Economics*, *233*, pp.107992. https://doi.org/10.1016/j.ijpe.2020.107992

Oleari, F., Magnani, M., Ronzoni, D., & Sabattini, L. (2014). Industrial AGVs: Toward a pervasive diffusion in modern factory warehouses. In: *2014 IEEE 10th International Conference on Intelligent Computer Communication and Processing (ICCP)*, pp.233-238. https://doi.org/10.1109/ICCP.2014.6937002

Oyekanlu, E., Smith, A., Thomas, W., Mulroy, G., Hitesh, D., Ramsey, M., Kuhn, D., McGhinnis, J., Buonavita, S., Looper, N., Ng, M., Ng'oma, A., Liu, W., McBride, P., Shultz, M., Cerasi, C., & Sun, D. (2020). A Review of Recent Advances in Automated Guided Vehicle Technologies: Integration Challenges and Research Areas for 5G-Based

Smart Manufacturing Applications. *IEEE Access*, *8*, pp.202312-202353. https://doi.org/10.1109/ACCESS.2020.3035729

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *30*(3), pp.286-297. https://doi.org/10.1109/3468.844354

Parker, S. K., Wall, T. D., & Cordery, J. L. (2001). Future work design research and practice: Towards an elaborated model of work design. *Journal of occupational and organizational psychology*, *74*(4), pp.413-440. https://doi.org/10.1348/096317901167460

Pinheiro, A., Sochirca, E., Afonso, O., & Neves, P. C. (2023). Automation and off(re)shoring: A meta-regression analysis. *International Journal of Production Economics*, *264*, pp.108980. https://doi.org/10.1016/j.ijpe.2023.108980

Pozzi, R., Rossi, T., & Secchi, R. (2023). Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies. *Production Planning & Control*, *34*(2), pp.139-158. https://doi.org/10.1080/09537287.2021.1891481

Prati, E., Peruzzini, M., Pellicciari, M., & Raffaeli, R. (2021). How to include User eXperience in the design of Human-Robot Interaction. *Robotics and Computer-Integrated Manufacturing*, *68*, pp.102072. https://doi.org/10.1016/j.rcim.2020.102072

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A. B., & Rajak, S. (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *International Journal of Production Economics*, *224*, pp.107546. https://doi.org/10.1016/j.ijpe.2019.107546

Ranasinghe, T., Grosse, E. H., Glock, C. H., & Jaber, M. Y. (2024). Never too late to learn: Unlocking the potential of aging workforce in manufacturing and service industries. *International Journal of Production Economics*, *270*, pp.109193. https://doi.org/10.1016/j.ijpe.2024.109193

Reich, J., Gerber, P., Laxman, N., Schneider, D., Ogata, T., Otsuka, S., & Ishigooka, T. (2022). Engineering Dynamic Risk and Capability Models to Improve Cooperation Efficiency Between Human Workers and Autonomous Mobile Robots in Shared Spaces. In: *Model-Based Safety and Assessment*, pp.237-251. https://doi.org/10.1007/978-3-031-15842-1_17

Reiman, A., Kaivo-oja, J., Parviainen, E., Takala, E.-P., & Lauraeus, T. (2021). Human factors and ergonomics in manufacturing in the industry 4.0 context – A scoping review. *Technology in Society*, *65*, pp.101572. https://doi.org/10.1016/j.techsoc.2021.101572

Reiman, A., Kaivo-oja, J., Parviainen, E., Takala, E.-P., & Lauraeus, T. (2023). Human work in the shift to Industry 4.0: a road map to the management of technological changes in manufacturing. *International Journal of Production Research*, pp.1-18. https://doi.org/10.1080/00207543.2023.2291814

Rey, R., Corzetto, M., Cobano, J. A., Merino, L., & Caballero, F. (2019). Human-robot co-working system for warehouse automation. In: *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, pp.578-585. https://doi.org/10.1109/ETFA.2019.8869178

Rezapour, S., Zanjirani-Farahani, R., & Miandoabchi, E. (2011). A machine-to-loop assignment and layout design methodology for tandem AGV systems with single-load vehicles. *International Journal of Production Research*, *49*(12), pp.3605-3633. https://doi.org/10.1080/00207543.2010.489056

Sabattini, L., Aikio, M., Beinschob, P., Boehning, M., Cardarelli, E., Digani, V., Krengel, A., Magnani, M., Mandici, S., & Oleari, F. (2017). The pan-robots project: Advanced automated guided vehicle systems for industrial logistics. *IEEE Robotics and Automation Magazine*, *25*(1), pp.55-64. https://doi.org/10.1109/MRA.2017.2700325

Saputro, T. E., Masudin, I., & Daneshvar Rouyendegh, B. (2015). A literature review on MHE selection problem: levels, contexts, and approaches. *International Journal of Production Research*, *53*(17), pp.5139-5152. https://doi.org/10.1080/00207543.2015.1005254

Scholz, M., Zwingel, M., Schuderer, P., & Franke, J. (2019). Sustainable Intralogistics due to Uniform Software and Modular Transport Entities. *Procedia CIRP*, *80*, pp.239-244. https://doi.org/10.1016/j.procir.2019.01.033

Schulze, L., & Wullner, A. (2006). The approach of automated guided vehicle systems. In: *2006 IEEE international conference on service operations and logistics, and informatics*, pp.522-527. https://doi.org/10.1109/SOLI.2006.328941

Senna, P. P., Ferreira, L. M. D. F., Barros, A. C., Bonnín Roca, J., & Magalhães, V. (2022). Prioritizing barriers for the adoption of Industry 4.0 technologies. *Computers and Industrial Engineering*, *171*, pp.108428. https://doi.org/10.1016/j.cie.2022.108428

Sgarbossa, F., Grosse, E. H., Neumann, W. P., Battini, D., & Glock, C. H. (2020). Human factors in production and logistics systems of the future. *Annual Reviews in Control*, *49*, pp.295-305. https://doi.org/10.1016/j.arcontrol.2020.04.007

Singh, N., Akcay, A., Dang, Q.-V., Martagan, T., & Adan, I. (2023). Dispatching AGVs with battery constraints using deep reinforcement learning. *Computers & Industrial Engineering*, pp.109678. https://doi.org/10.1016/j.cie.2023.109678

Slack, N., Brandon-Jones, A., & Johnston, R. (2013). *Operations management [electronic resource]* (7th ed.). Pearson.

Soltani, A., Stonis, M., & Overmeyer, L. (2019). Development of a Case-Based Reasoning expert system for the disturbance management in automated guided vehicle systems. *Logistics Journal: Proceedings*, *2019*(12). https://doi.org/10.2195/lj_Proc_soltani_en_201912_01

Song, K. T., Chiu, C. W., Kang, L. R., Sun, Y. X., & Meng, C. H. (2020). Autonomous Docking in a Human-Robot Collaborative Environment of Automated Guided Vehicles. In: *2020 International Automatic Control Conference (CACS)*, pp.1-6. https://doi.org/10.1109/CACS50047.2020.9289713

Sony, M., & Naik, S. (2020a). Critical factors for the successful implementation of Industry 4.0: a review and future research direction. *Production Planning & Control*, *31*(10), pp.799-815. https://doi.org/10.1080/09537287.2019.1691278

Sony, M., & Naik, S. (2020b). Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model. *Technology in Society*, *61*, pp.101248. https://doi.org/10.1016/j.techsoc.2020.101248

Soufi, Z., David, P., & Yahouni, Z. (2021). A methodology for the selection of Material Handling Equipment in manufacturing systems. *IFAC-PapersOnLine*, *54*(1), pp.122-127. https://doi.org/10.1016/j.ifacol.2021.08.193

Soufi, Z., David, P., & Yahouni, Z. (2024). Generation of material handling system alternatives: A constraints satisfaction problem approach. *Computers in Industry*, *155*, pp.104045. https://doi.org/10.1016/j.compind.2023.104045

Stake, R. E. (2005). Qualitative Case Studies. In N. K. Denzin & Y. S. Lincoln (Eds.), *The Sage handbook of qualitative research, 3rd ed.* (3rd ed., pp. 443-466). Sage Publications Ltd.

Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., & Haug, A. (2021). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. *Production Planning & Control*, *32*(10), pp.811-828. https://doi.org/10.1080/09537287.2020.1768318

Stentoft, J., & Rajkumar, C. (2020). The relevance of Industry 4.0 and its relationship with moving manufacturing out, back and staying at home. *International Journal of Production Research*, *58*(10), pp.2953-2973. https://doi.org/10.1080/00207543.2019.1660823

Swedish Radiation Safety Authority. (2014, 2017). *Man-Technology-Organisation*. Retrieved 2021-10-02 from https://www.stralsakerhetsmyndigheten.se/en/areas/nuclear-power/our-regulatory-supervision/man-technology-organisation/

Thormundsson, B. (2023). *Size of the global market for autonomous mobile robots (AMR) from 2016 to 2021, with a forecast through 2028*. Statista. https://www.statista.com/statistics/1285835/worldwide-autonomous-robots-market-size/#:~:text=The%20global%20market%20for%20autonomous,billion%20U.S.%20dollars%20by%202028

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities planning* (4 th ed.). John Wiley & Sons.

Tortorella, G., Fogliatto, F. S., Kumar, M., Gonzalez, V., & Pepper, M. (2023). Effect of Industry 4.0 on the relationship between socio-technical practices and workers' performance. *Journal of Manufacturing Technology Management*, *34*(1), pp.44-66. https://doi.org/10.1108/JMTM-04-2022-0173

Trist, E. L. (1981). *The evolution of socio-technical systems* (Vol. 2). Ontario Quality of Working Life Centre Toronto.

Trist, E. L., & Bamforth, K. W. (1951). Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System. *Human Relations*, *4*(1), pp.3-38. https://doi.org/10.1177/001872675100400101

Tubis, A. A., Poturaj, H., & Smok, A. (2024). Interaction between a Human and an AGV System in a Shared Workspace—A Literature Review Identifying Research Areas. *Sustainability*, *16*(3), pp.974. https://doi.org/10.3390/su16030974

Ullrich, G. (2015). *Automated Guided Vehicle Systems. [electronic resource]: A Primer with Practical Applications* (1st ed. 2015. ed.). Springer Berlin Heidelberg.

Ventura, J. A., Pazhani, S., & Mendoza, A. (2015). Finding optimal dwell points for automated guided vehicles in general guide-path layouts. *International Journal of Production Economics*, *170*, pp.850-861. https://doi.org/10.1016/j.ijpe.2015.03.007

Vijayakumar, V., Sgarbossa, F., Neumann, W. P., & Sobhani, A. (2021). Framework for incorporating human factors into production and logistics systems. *International Journal of Production Research*, *60*(2), pp.402-419. https://doi.org/10.1080/00207543.2021.1983225

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

Vlachos, I., Pascazzi, R. M., Ntotis, M., Spanaki, K., Despoudi, S., & Repoussis, P. (2024). Smart and flexible manufacturing systems using Autonomous Guided Vehicles (AGVs) and the Internet of Things (IoT). *International Journal of Production Research*, *62*(15), pp.5574-5595. https://doi.org/10.1080/00207543.2022.2136282

Vogel, K., Karltun, J., Eklund, J., & Engkvist, I. L. (2013). Improving meat cutters' work: Changes and effects following an intervention. *Applied Ergonomics*, *44*(6), pp.996-1003. https://doi.org/10.1016/j.apergo.2013.03.016

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations and Production Management*, *22*(2), pp.195-219. https://doi.org/10.1108/01443570210414329

Winkelhaus, S., & Grosse, E. H. (2020). Logistics 4.0: a systematic review towards a new logistics system. *International Journal of Production Research*, *58*(1), pp.18-43. https://doi.org/10.1080/00207543.2019.1612964

Winkelhaus, S., Grosse, E. H., & Glock, C. H. (2022). Job satisfaction: An explorative study on work characteristics changes of employees in Intralogistics 4.0. *Journal of Business Logistics*, *43*, pp.343-367. https://doi.org/10.1111/jbl.12296

Wu, B. (1994). *Manufacturing systems design and analysis : context and techniques* (2. ed. ed.). Chapman & Hall.

Yan, R., Dunnett, S. J., & Jackson, L. M. (2018). Novel methodology for optimising the design, operation and maintenance of a multi-AGV system. *Reliability Engineering and System Safety*, *178*, pp.130-139. https://doi.org/10.1016/j.ress.2018.06.003

Yan, R., Dunnett, S. J., & Jackson, L. M. (2022). Model-Based Research for Aiding Decision-Making During the Design and Operation of Multi-Load Automated Guided Vehicle Systems. *Reliability Engineering and System Safety*, *219*, pp.108264. https://doi.org/10.1016/j.ress.2021.108264

Yan, R., Jackson, L. M., & Dunnett, S. J. (2020). A study for further exploring the advantages of using multi-load automated guided vehicles. *Journal of Manufacturing Systems*, *57*, pp.19-30. https://doi.org/10.1016/j.jmsy.2020.08.005

Yin, R. K. (2014). *Case Study Research: Design and Methods* (5th ed.). SAGE Publications.

Zamora-Cadenas, L., Velez, I., & Sierra-Garcia, J. E. (2021). UWB-Based Safety System for Autonomous Guided Vehicles Without Hardware on the Infrastructure. *IEEE Access*, *9*, pp.96430-96443. https://doi.org/10.1109/ACCESS.2021.3094279

Zeid, A., Sundaram, S., Moghaddam, M., Kamarthi, S., & Marion, T. (2019). Interoperability in Smart Manufacturing: Research Challenges. *Machines*, *7*(21). https://doi.org/10.3390/machines7020021

Zhan, M., & Yu, K. (2018). Wireless communication technologies in automated guided vehicles: Survey and analysis. In: *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, pp.4155-4161. https://doi.org/10.1109/IECON.2018.8592782

Zhang, J., Peng, L., Feng, W., Ju, Z., & Liu, H. (2019). Human-AGV Interaction: Real-Time Gesture Detection Using Deep Learning. In: *Intelligent Robotics and Applications*, pp.231-242. https://doi.org/10.1007/978-3-030-27541-9_20

Zhang, M., Wang, L., Qiu, F., & Liu, X. (2023). Dynamic scheduling for flexible job shop with insufficient transportation resources via graph neural network and deep reinforcement learning. *Computers & Industrial Engineering*, *186*, pp.109718. https://doi.org/10.1016/j.cie.2023.109718

Zhang, Z., Wu, L., Zhang, W., Peng, T., & Zheng, J. (2021). Energy-efficient path planning for a single-load automated guided vehicle in a manufacturing workshop. *Computers and Industrial Engineering*, *158*, pp.107397. https://doi.org/10.1016/j.cie.2021.107397

Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. *International Journal of Production Research*, *59*(6), pp.1922-1954. https://doi.org/10.1080/00207543.2020.1824085

Zhou, B., & He, Z. (2021). A novel hybrid-load AGV for JIT-based sustainable material handling scheduling with time window in mixed-model assembly line. *International Journal of Production Research*, *61*(3), pp.796-817. https://doi.org/10.1080/00207543.2021.2017056

Zou, B., Xu, X., Gong, Y., & De Koster, R. (2018). Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system. *European Journal of Operational Research*, *267*(2), pp.733-753. https://doi.org/10.1016/j.ejor.2017.12.008

Zuin, S., Hanson, R., Battini, D., & Persona, A. (2020). Design of AGV systems in working environments shared with humans: a multi case study. *IFAC-PapersOnLine*, *53*(2), pp.10603-10608. https://doi.org/10.1016/j.ifacol.2020.12.2814