Doctoral theses at NTNU, 2021:247

Giuseppe Ismael Fragapane

# Autonomous material transportation in hospital intralogistics

Doctoral thesis

**NTNU**
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Mechanical and Industrial
Engineering

NTNU
Norwegian University of
Science and Technology

Giuseppe Ismael Fragapane

# Autonomous material transportation in hospital intralogistics

Thesis for the Degree of Philosophiae Doctor

Trondheim, April 2021

Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

NTNU
Norwegian University of
Science and Technology

**NTNU**
Norwegian University of Science and Technology

Thesis for the Degree of Philosophiae Doctor

Faculty of Engineering
Department of Mechanical and Industrial Engineering



ISBN 978-82-326-6821-2 (printed ver.)
ISBN 978-82-326-6122-0 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

Doctoral theses at NTNU, 2021:247

Printed by NTNU Grafisk senter

# Acknowledgments

During the past four years, I was lucky to be surrounded by many great people who inspired, criticized, and enlightened me, laughed with me, and pushed me going beyond my limits. Thank you to you all. I would also like to take the opportunity to say some words about several people and institutions that deserve more than just a thank you.

First, I would like to thank NTNU and the Department of Mechanical and Industrial Engineering for financing this research study. The opportunity to work full-time in research has been a unique experience. I have benefited significantly from the many opportunities of presenting my research nationally and internationally along the way. I was fortunate to have been given resources and opportunities to develop and foster my research competence.

Furthermore, I would like to thank NTNU's strategic research area—NTNU Health—which initiated this research study and facilitated collaboration with many research partners and hospitals. Many thanks to Unni Dahl, Lilian Leistad, and Bjørn Bakken from Sykehusbygg for supporting research in hospital logistics and opening many doors to case hospitals. I would also like to express my gratitude to the St. Olavs and Akershus hospitals, which allowed several long visits to collect data and discuss my research with multiple hospital employees.

This journey would have never started if, five years ago, my supervisor had not seen my potential and interest in pursuing a Ph.D. I wish to express my greatest gratitude to Jan Ola Strandhagen for getting me this research project and believing that I could manage it. I am further thankful to him for allowing me to follow my research interests and for his great guidance, especially in the last months and weeks of the project.

I was blessed to have many co-supervisors who helped during different stages of my Ph.D. Thank you, Marco Semini, for supporting me at the beginning of the research process in defining the research project with our research partners. To Hans-Henrik Hvolby, I am thankful for all our discussions that forced me to work harder, all the feedback on articles, and for accompanying me in visiting several hospitals. I was lucky that Fabio Sgarbossa joined our research group and my supervisor team. I want to thank you for your encouragement, guidance, patience, and comments. I learned an incredible amount about scientific writing.

I would like to express my gratitude to my family, friends, colleagues and my fellow Ph.D. students who always showed interest in my research study and supported me. Special thanks go to Sven-Vegard Buer, Aili Biriita Bertnum, and Jo Wessel Strandhagen. I will never forget our nights in Shanghai, Edinburgh, Brussels, Aalborg, San Marino, Bergamo, Stresa, Bologna, Seoul, Gothenburg, and Trondheim.

I dedicate this dissertation to my parents, Rosa and Silvestre, my wife, Charlotte, and daughter, Mathilde. To my parents, your hard work of educating me paid off, and thank you for everything. To my wife, this research project would have ended on day two without your encouragement and support. I love you. Finally, to Mathilde, who kept me up at night and made me smile during the day, you made this journey exceptional.

Ranheim, April 2021<br>Giuseppe-Ismael Fragapane

# Summary

Hospital intralogistics, which focus on the management, operation, and development of a hospital's internal flows, are one of the strongest levers to improve hospital performance (Moons et al., 2019). There is great potential in improving the hospital logistics of materials because they consume on average 30–40% of a hospital's budget (Poulin, 2003; Ozcan, 2005). Therefore, hospital intralogistics require advanced planning and control methods to transport materials to the right place, in the right quantity, with the right quality, and at the right time and price (Volland et al., 2017).

Material handling can support the detailed planning and execution of material transportation throughout a facility (MHI, 2021). Various manual, semi-automated, and automated material handling equipment and systems are currently used in hospital intralogistics. While many light and short deliveries of medical equipment, medicine, and so forth are transported manually by nurses or porters, heavy and long deliveries can be performed by automated guided vehicles (AGVs). However, the high demand for material transportation in hospital intralogistics challenges material handling systems to achieve higher performance. For instance, high flexibility is needed for handling a variety of material flows, high productivity for reducing personnel involvement in material transportation, high quality for performing safe and reliable transportation, high service for ensuring high responsiveness for material transportation and delivery accuracy, and lower costs for performing material transportation.

Hospital planners struggle to find appropriate material handling systems and automation for hospital intralogistics (Granlund & Wiktorsson, 2014). Hospital intralogistics require more highly tailored material handling systems that can adapt to their demands. The recent technological advances of stronger batteries, ubiquitous sensors, powerful onboard computers, artificial intelligence, and simultaneous location and mapping technology have facilitated the introduction of autonomous mobile robots (AMRs). Unlike other material handling systems applied in hospitals, AMRs utilize artificial intelligence for decision-making, which significantly increases their flexibility in indoor mobility and in performing material handling activities in hospitals. The integration of AMRs in hospitals allows for a rethinking of intralogistics and material handling activities.

Therefore, this study investigates hospital intralogistics and material handling systems to analyze the characteristics, requirements, and challenges of material transportation and to provide insights into which decision-making methods can be built on. Furthermore, it provides decision support for planning and controlling AMRs in intralogistics to improve material transportation performance with regard to flexibility,

productivity, service, quality, and cost performance. To achieve this, a threefold research approach was applied.

First, case research and simulation modeling supported the investigation of material transportation in several hospitals. Analyzing the movement patterns allowed for a characterization of material transportation. Thereby, the environmental and operational characteristics had a strong impact on material transportation. The key performance indicators (KPIs) for material transportation allowed establishing a comprehensive overview of the requirements and to work toward them achieving high performance. Material transportation and current applied material handling systems face a variety of problems, such as standardization of transportation, handling several material flows, and a dynamic environment. Hospital planners invest many hours to satisfy all the needs of the material flows and to reach high performance. Hence, more autonomous material handling systems in hospital intralogistics are needed.

Second, explaining the technological advances of AMRs compared with other material handling systems allowed us to understand the potential of AMRs in hospital intralogistics. Besides transporting materials, AMRs can collaborate with hospital staff and take over repetitive material handling tasks. Furthermore, decentralized control allows the AMR to react dynamically to changes and continuously optimize itself. To identify the application area of AMRs in hospital intralogistics, a multiple case study was applied. The developed strategic framework indicates that AMRs can provide highly flexible and cost-efficient material transportation. However, hospital planners need support in planning and controlling AMRs in material transportation.

Third, AGV planning and control frameworks are less suitable for vehicles with decentralized control. A systematic literature review supported the development of a planning and control framework for AMRs in intralogistics, providing methods for the different decision areas. However, only a few methods included the crucial characteristics of hospital intralogistics and material transportation. Therefore, a semi-open queuing network model was introduced to plan AMRs for material transportation in hospital intralogistics. The modeling and simulation approach supported hospital planners in determining the number of vehicles and understanding hospital layout configurations to achieve high performance.

In conclusion, AMRs in intralogistics can support the move from manual over automated to autonomous material transportation. Decentralized control supported by artificial intelligence can help keep the intralogistics at an optimum and allow hospital staff to focus on patient care.

# Sammendrag

Sykehusintralogistikk, som fokuserer på styring, drift og utvikling av sykehusets interne materialstrømmer, er en av de viktigste faktorene for å forbedre ytelsen til et sykehus (Moons et al., 2019). Det er et stort potensial i å forbedre materiallogistikken fordi den i gjennomsnitt representerer 30-40% av sykehusets budsjett (Poulin, 2003; Ozcan, 2005). Derfor krever sykehusintralogistikk avanserte planleggings- og styringsmetoder for å transportere materialer til riktig sted, i riktig mengde, med riktig kvalitet og til riktig tid og pris (Volland et al., 2017).

Materialhåndteringssystemer kan støtte detaljert planlegging og gjennomføring av materialtransport gjennom et anlegg (MHI, 2021). Forskjellige typer manuelle, halvautomatiske og automatiserte materialhåndteringsverktøy og -systemer brukes for tiden i sykehusintralogistikk. Mens mange av de lette og korte leveransene av for eksempel medisinsk utstyr og medisin transporteres manuelt av sykepleiere eller portører, kan tunge og lengre leveranser utføres av førerløse transportsystemer (AGV). Imidlertid påvirker de høye kravene til materialtransport i sykehusintralogistikk ytelsen til materialhåndteringssystemene. For eksempel er det behov for høy fleksibilitet for å håndtere flere materialstrømmer, høy produktivitet er nødvendig for å redusere menneskelig involvering i materialtransport, høy kvalitet er nødvendig for å sørge for sikker og pålitelig transport, høy servicegrad er nødvendig for å sikre rask respons for materialtransport, leveringsnøyaktighet og redusere kostnadene som trengs for å utføre materialtransport.

Sykehusplanleggere sliter med å finne passende materialhåndteringssystemer og automatiseringsnivå for sykehusintralogistikk (Granlund & Wiktorsson, 2014). Sykehusintralogistikk krever skreddersydde materialhåndteringssystemer som er tilpasset sine krav. Nylige teknologiske fremskritt slik som større batterikapasitet, billigere og mer utbredte sensorer, kraftigere maskinvare, kunstig intelligens og samtidig plasserings- og kartleggingsteknologi har gjort det mer aktuelt å innføre autonome mobile roboter (AMR) i intralogistikk. I motsetning til andre materialhåndteringssystemer som brukes på sykehus, bruker AMR kunstig intelligens i sin beslutningstaking, noe som øker deres fleksibilitet betydelig. Implementering av AMR på sykehus gir mulighet for å tenke nytt på intralogistikk og materialhåndteringsaktiviteter.

På bakgrunn av dette undersøker denne studien intralogistikk- og materialhåndteringssystemer på sykehus for å analysere deres egenskaper, krav og utfordringer ved materialtransport og for å gi innsikt i hvilke beslutningsmetoder man kan bygge videre på. Videre vil avhandlingen gi beslutningsstøtte for planlegging og styring av AMR innen intralogistikk for å forbedre ytelsen til materialtransportssystemene med hensyn til fleksibilitet, produktivitet, service, kvalitet og kostnad. For å oppnå dette ble det brukt en tredelt forskningstilnærming.

Først ble det benyttet caseforskning, simulering og modellering i undersøkelsen av materialtransport på flere sykehus. Analyse av bevegelsesmønstrene tillot oss å karakterisere materialtransporten. Det ble funnet at kontekst- og driftskarakteristikker har sterk innvirkning på materialtransporten. Ved å definere de viktigste prestasjonsindikatorene for materialtransport fikk man en omfattende oversikt over hvilke krav man må ta hensyn til og oppfylle for å oppnå høy ytelse. Materialtransport og dagens materialhåndteringssystemer står overfor en rekke utfordringer, slik som standardisering av transport, håndtering av flere materialstrømmer og et dynamisk miljø. Sykehusplanleggere bruker mange timer for å tilfredsstille alle behovene til materialstrømmene og å oppnå høy ytelse. Derfor er det behov for mer autonome materialhåndteringssystemer i sykehusintralogistikk.

Deretter, ved å kartlegge de teknologiske fremskrittene forbundet med AMR sammenlignet med andre materialhåndteringssystemer kunne man forstå potensialet og mulighetene til AMR i sykehusintralogistikk. Foruten å transportere materialer, kan AMR samarbeide tettere med sykehuspersonalet og overta repeterende materialhåndteringsoppgaver. Desentralisert styring gjør AMR i stand til å reagere dynamisk på endringer og kontinuerlig optimalisere egen drift. For å identifisere bruksområdene for AMR i sykehusintralogistikk ble det brukt en multippel casestudie. Det strategiske rammeverket utviklet gjennom casestudien indikerer at AMR kan gi svært fleksibel og kostnadseffektiv materialtransport. Likevel trenger sykehusplanleggere støtte i planlegging og styring av AMR for materialtransport.

Planleggings- og styringsrammeverk utviklet for AGV er mindre egnet for kjøretøy med desentralisert styring, slik som AMR. En systematisk litteraturgjennomgang støttet utviklingen av et planleggings- og styringsrammeverk for AMR i intralogistikk, og identifiserte eksisterende metoder for de forskjellige beslutningsområdene. Imidlertid inkluderte bare noen få av de identifiserte metodene de viktige karakteristikkene til sykehusintralogistikk og -materialtransport. Derfor ble en semi-åpen kø-nettverksmodell utviklet for å planlegge AMR for materialtransport i sykehusintralogistikk. Modellerings- og simuleringstilnærmingen støtter sykehusplanleggere i å bestemme antall kjøretøy og å forstå forskjellige typer planløsninger for å oppnå høy ytelse.

Studien konkluderer med at AMR i intralogistikk kan støtte overgangen fra manuell, via automatisert, og til autonom materialtransport. Den desentraliserte styringen støttet av kunstig intelligens kan bidra til å holde intralogistikken optimal og tillate sykehuspersonalet å fokusere på pasientbehandling.

# Abbreviations

| | |
|---|---|
| AGV | Automated guided vehicle |
| AI | Artificial intelligence |
| AMR | Autonomous mobile robot |
| KPI | Key performance indicator |
| RQ | Research question |
| SLR | Systematic literature review |
| SOQN | Semi-open queuing network |

# List of Appended Papers and Declaration of Authorship

| Paper | Title | Declaration of authorship |
| --- | --- | --- |
| 1 | Fragapane, G. I., Bertnum, A. B., Hvolby, H. H., & Strandhagen, J. O. (2018). Material distribution and transportation in a Norwegian hospital: a case study. *IFAC-papersonline*, 51(11), 352-357. | Fragapane conceptualized the paper and collected the data with Bertnum. Fragapane wrote the paper with feedback from Bertnum, Hvolby, and Strandhagen. |
| 2 | Fragapane, G. I., Zhang, C., Sgarbossa, F., & Strandhagen, J. O. (2019). An agent-based simulation approach to model hospital logistics. *Int J Simul Model*, 18(4), 654-665. | Fragapane conceptualized the paper. Fragapane and Zhang developed the simulation model. Fragapane wrote the paper with input from Zhang, Sgarbossa, and Strandhagen. |
| 3 | Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2020). Autonomous Mobile Robots in Hospital Logistics. In *IFIP International Conference on Advances in Production Management Systems* (pp. 672-679). Springer, Cham. | Fragapane conceptualized the paper. Fragapane wrote the paper with feedback from Hvolby, Sgarbossa, and Strandhagen. |
| 4 | Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2021). Autonomous mobile robots in sterile instrument logistics: An evaluation of the material handling system for a strategic fit framework. *Production planning & control.* | Fragapane conceptualized the paper and collected the data with Hvolby. Fragapane wrote the paper with feedback from Hvolby, Sgarbossa, and Strandhagen. |
| 5 | Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. *European Journal of Operational Research.* | Fragapane conceptualized the paper and conducted the literature review. Fragapane wrote the paper with feedback from de Koster, Sgarbossa, and Strandhagen. |
| 6 | Fragapane, G., Roy, D., Sgarbossa, F., & Strandhagen (under review). Planning autonomous material transportation in hospitals. In *IFIP International Conference on Advances in Production Management Systems.* Springer, Cham. | Fragapane conceptualized the paper. Fragapane wrote the paper with feedback from Debjit, Sgarbossa, and Strandhagen. |

# Contents

# Introduction 1

This chapter introduces the research study of autonomous material transportation in hospital intralogistics. First, the background of the research study and the problems faced in practices are described. Second, the motivation for research and the personal interest to conduct the research study are explained. Next, the research objectives and questions are presented to guide the research activities. The scope of this study clarifies and positions the research study within the existent literature streams and terminology. Lastly, the structure of the research study is elaborated on.

## 1.1. Background

Today's hospitals face a variety of overall challenges, such as an ever-increasing volume of sick patients due to ageing populations (Wittenberg et al., 2017), increasing complexity of healthcare pathways due to chronic diseases (Brunner-La Rocca et al., 2020), reinforced infection control in times of epidemic outbreaks (Grasselli et al., 2020), and rising medical service costs due to high labor costs (Dieleman et al., 2017). All these challenges affect hospital logistics, forcing hospital planners to seek new methods to increase flexibility, productivity, quality, service, and reduce costs.

Great potential lies in improving hospital logistics of materials since they consume, on average, 30%–40% of a hospital's budget (Poulin, 2003; Ozcan, 2005). According to a survey conducted by Nachtmann & Pohl (2009), the distribution of logistics costs is 21% inventory management, 32% order management, 28% transportation, receiving and shipment, and 21% “other”. Improving logistics can potentially halve costs and reduce hospital staff's time spent on logistics activities (Poulin, 2003). For instance, a case study of 19 hospitals revealed that professional nurses spend on average 6% of their time doing simple tasks, such as laundry and waste disposal (Kudo et al., 2012). In a 40-hour week, 2.4 hours are allocated to these simple tasks. Hospitals should create environments where professional nurses can concentrate on patient care and utilize their expertise to their fullest extent for patient flow. Freeing up a hospital staff’s time is the key solution to improving patient flow and quality, and for addressing hospitals' overall challenges.

However, most literature in this field has focused on supporting the external supply chain, while the internal supply chain and internal logistics are the weak links in the entire chain (Landry & Philippe, 2004). Granlund and Wiktorsson (2014) argue that the performance of internal logistics significantly impacts the organization's overall performance and emphasize the importance of continuous improvement of this segment for achieving high performance.

The field of hospital intralogistics focuses on the management, operation, and development of the hospital's internal flows. The characteristics of the material flows come with different requirements. For instance, sterile instruments must always be of high quality and available for emergency and planned surgeries (Chobin & Swanson, 2012). Up to 46% of delays in operating rooms can be traced back to the unavailability of sterile instruments (Wubben et al., 2010). These delays cause longer working hours for doctors and staff and can have a serious negative impact on the quality of care. Food must be distributed cold or warm and on time to avoid delaying planned surgeries and keep patients in great condition (Fatimah et al., 2011). Clean linens must be available for all patients and staff throughout the hospital to hinder the transmission of germs from one person to another (Yajuan et al., 2015). Residual and hazardous waste and cardboard must be collected and transported through the hospital without cross-contamination (Baveja et al., 2000; Chaerul et al., 2008). Extraordinary measures for waste transportation are often applied in the pandemic environment to increase the safety and quality of health of hospital staff and patients. Waste transportation paths avoid people and crowds as much as possible, and transportation trips rarely occur in the morning and evening rush hours (Peng et al., 2020). Both forward and reverse logistics have a significant impact on patient care outcomes and quality. Furthermore, hospitals circulate a wide range of instruments and equipment, often several times per day. The setup of both forward and reverse logistics must be reliable and robust to avoid bottlenecks and excessive inventory (Landry et al., 2004; Ozturk et al., 2014). The information flow that comes along with material flow plays a significant role. Different material management and material handling systems must communicate with each other to have seamless transportation. Managing material flows in a way that ensures they do not interfere with each other and are transported to the right place in the correct quantity, quality, time, and costs requires advanced planning and control methods.

Material handling refers to logistics activities focused on the detailed planning of transportation throughout a facility, and it incorporates a wide range of manual, semi-automated, and automated equipment and systems (MHI, 2021). The associated operations and activities include more than just the physical aspect. Transportation *per se* does not add value to hospital intralogistics and thus only increases costs. Therefore, it is crucial to keep transportation and material handling processes to a minimum (Tompkins et al., 2010). Planning and control frameworks for transportation support the decision-making process at various times, ensuring that transportation, including material handling equipment and systems, provides the desired results (Le-Anh & De Koster, 2006; Vis, 2006; Tompkins et al., 2010).

Depending on the material flow characteristics, material handling equipment and systems are assigned to perform transportation. For instance, blood samples are mainly sent through pneumatic tube systems due to time and size constraints, while linen is transported in wagons by Automated Guided Vehicles (AGVs) due to weight and volume constraints (Fernandes et al., 2006; Chikul et al., 2017). Material handling equipment and systems play a crucial role in the execution of hospital intralogistics, and they should come with:

- High flexibility: handling a variety of material flows, and adapting dynamically to changes in transportation demand;
- High productivity: increasing transportation capacity and reducing the personnel time involved in transportation;
- High quality: performing safe and reliable transportation;
- High service: ensuring high responsiveness for transportation and delivery accuracy; and
- Low costs: reducing implementation, adjustment, transportation, and maintenance costs.

Different manual, semi-automated, and automated material handling equipment and systems are applied in hospitals and can satisfy these requirements to some extent. Manual material handling is still, to a wide extent, used in hospitals since it allows for handling a variety of materials and for reacting quickly to changes in demand. However, individual human decision-making processes in material handling can lead to inefficient routing, poor transportation sequencing, and excess transportation (Moons et al., 2019). Automating the material flow in hospitals merely for its own sake will not necessarily bring a positive return on investment or achieve better performance than a manual approach (Chikul et al., 2017). Many automated material handling systems applied in hospitals derive from manufacturing or warehousing and must therefore be thoroughly planned in hospitals. Today, many hospitals use AGVs to transport several material flows with high productivity (Benzidia et al., 2019). However, the performance of AGVs in hospitals is vulnerable because of the dynamic environment of hospitals. Interacting with people and obstacles in narrow hallways can hinder an AGV's performance. They cannot avoid obstacles and depend on support personnel to address these limitations. Multiple automated material handling equipment and systems are still mostly dependent on human interaction for preparing, loading, unloading, and sending items. Due to safety issues, the automated material handling equipment and systems are either stationary and fixed in the departments or not allowed to travel inside the department. Therefore, manual transportation is still high inside departments.

Hospital intralogistics require more highly-tailored material handling equipment and systems to adapt to the hospital's dynamic environment and could benefit from robotics (Hichri et al., 2019). Recent technological advances have positively impacted robot indoor mobility, allowing for the development and implementation of mobile robots.

More powerful batteries, high-quality cameras for environmental recognition, and increased onboard computational power enable greater autonomy of mobile robot navigation. These changes have led to the introduction of autonomous mobile robots (AMRs) that can navigate freely within a predefined area and provide material handling services (Fragapane et al., 2020). Because of their obstacle avoidance, dynamic pathfinding, and smaller vehicle dimensions, AMRs can be used in busy environments, such as areas with patients present. This attribute allows AMRs to access more areas in hospitals and so be integrated more deeply within departments. Compared with an AGV, no physical reference points need to be preinstalled to guide an AMR through a hospital, and implementation time and costs can be greatly reduced. User-friendly controls enable employees to send, receive, and track each transportation with ease. AMRs offer an opportunity to reduce the involvement and responsibilities of people in material handling activities.

All in all, hospitals are continuously seeking methods to reduce the responsibilities of hospital staff and the time connected to material transportation. Freeing up hospital staff time can increase patient care and lower costs. The integration of AMRs as transportation, collaboration, or assistant robots allows for a rethinking of intralogistics and material handling activities in hospitals. However, previous studies are lacking in the analysis of material transportation in hospital intralogistics from a material handling perspective. Furthermore, hospital planners need support in decision-making processes to plan and control material transportation in hospital intralogistics.

Therefore, this study will investigate hospital intralogistics and material handling systems to analyze the characteristics, requirements, and challenges of material transportation and provide insights on which decision-making methods can be built on. Furthermore, it will provide decision support for planning and controlling AMRs in intralogistics to improve the material transportation performance of flexibility, productivity, service, quality, and costs. Finally, it will support moving from manual over automated to autonomous material transportation and keep the intralogistics at an optimal level, which will allow hospital staff to focus on patient care.

## 1.2. Research motivation

Hospital intralogistics has been identified as one of the key containment levers for improving hospital performance (Volland et al., 2017). A crucial intralogistics activity is material handling, which plays a vital role in the planning and execution of material transportation.

To plan material transportation, only a few studies provide methods for decision support (Volland et al., 2017; Moons et al., 2019). The materials of sterile instruments, pharmaceuticals, laundry, medical supplies, beds, and waste were studied mainly and provided support for the transportation decisions of routing and scheduling (Michelon et al., 1994; Banerjea-Brodeur et al., 1998; Lapierre & Ruiz, 2007; van de Klundert et al., 2008; Augusto & Xie, 2009). Thereby, analytical models combined with mixed-integer linear programming and simulation modeling are the preferred methodologies to provide the necessary decision support to optimize work routes, workloads, and costs. Due to the high variety of materials and material handling systems in hospitals, standards and best practices of how to transport materials in hospitals hardly exist (Volland et al., 2017). Benzidia et al. (2019) argue that more in-depth case studies are needed to identify the challenges and key factors of automating the transportation of materials in hospitals before optimizing them. Analyzing the drivers of high performance and examining the conditions under which specific practices, resources, or setups are used are all vital for planning and controlling material transportation in hospital intralogistics (Ketokivi & Schroeder, 2004; Böhme et al., 2016). More studies are needed to identify the characteristics, requirements, and challenges of material transportation in hospital intralogistics to provide insights on which decision-making methods can be built on.

The introduction of AMRs has opened new possibilities for performing services and activities, which might address some current hospital intralogistics requirements and challenges. Unlike other material handling equipment and systems applied in hospitals, AMRs utilize artificial intelligence (AI) to decentralize a wide range of decision-making processes for navigation and material handling activities. The AMR's capability of decentralized control has shown great potential in the automotive, warehousing, and process industries in increasing production flexibility and productivity (Fragapane et al., 2020). The potential of AMRs' high flexibility in navigation and providing services has not investigated in hospital environments. Studies analyzing the impact of AMR's decentralized control on hospital intralogistics and material handling are lacking. It is unsurprising that hospital planners still struggle to find appropriate material handling equipment and systems and the level of automation for material transportation in hospital intralogistics (Granlund et al., 2014). Most material handling equipment and systems originate and are operated in industrial settings, but to ensure long-term performance benefits, technologies must be aligned with material flows and hospital characteristics (Tortorella et al., 2020). Hospital planners need guidance to achieve high performance when applying advanced technologies such as AMRs. More studies are needed to identify the ideal states of material handling equipment and systems, especially the application of AMRs, and to provide decision support when applied at the strategic level.

Most literature on AMRs is fragmented and has a strong technological focus. The lack of a unified and accepted definition among practitioners and researchers has also hampered research in this field. AGVs have dominated the literature on vehicle planning and control systems in intralogistics. The planning and control frameworks developed by Le-Anh et al. (2006) and Vis (2006) are still the primary guidance in managing and operating AGVs. The greater degrees of autonomy, applicability, and flexibility provided by AMRs result in many different decisions that must be taken on the strategic, tactical, and operational levels, and this number continues to grow. Decision areas and methods must be identified and developed to successfully implement and manage AMRs in hospital intralogistics to achieve high performance.

Finally, the thematic research area called NTNU Health initiated a commitment to develop and improve knowledge and competence among patients and material flows in the Norwegian healthcare system. This research was conducted in close collaboration with European hospitals and the Production Management group with its Logisctis4.0Lab at the Department of Mechanical and Industrial Engineering at NTNU. Sykehusbygg, a competence center for planning and building new hospitals, was also invited as a research partner. The fundamental idea was to use the expertise of logistics and production management to analyze, model, and improve patient, material, and information flow in hospitals. Lastly, developing knowledge to enhance hospital intralogistics and thus increase patient care has motivated me to conduct this research study.

## 1.3. Research objectives and questions

Motivated by the challenges and research problem outlined above, this study aims to support hospital planners in applying AMRs in hospital intralogistics and moving towards autonomous material transportation in hospital intralogistics.

The research study can be broken down into the following research questions (RQs) to guide research activities:

**RQ1: What are the characteristics, requirements, and challenges of material transportation in hospital intralogistics?**

The first research question aims to map the characteristics, requirements, and challenges of material transportation in hospital intralogistics and provide insights on which decision support methods can build on.

**RQ2: How can AMRs support hospital intralogistics, and when should they be applied to material transportation in hospital intralogistics?**

The second research question aims to identify the technological advances of AMRs supporting material handling in hospital intralogistics and investigate the applicability of AMRs in material transportation in hospital intralogistics. It will allow the identification of ideal states to achieve high performance by analyzing the relationships between material handling equipment and systems and hospital characteristics.

**RQ3: How should AMRs be planned and controlled for material transportation in hospital intralogistics?**

The third research question aims to introduce an AMR planning and control framework to guide hospital planners in the decision-making process to achieve optimal performance in flexibility, productivity, service, quality, and costs. Furthermore, it will provide methods for the decision-making process to apply AMRs in hospital intralogistics.

## 1.4. Research scope

This section will briefly explain this research study's scope and clarify its position within the existing literature streams and terminology. The research study lies within the research area of logistics, and it can be narrowed down to the domains of hospital intralogistics, material handling, and AMRs.

Hospital logistics can be defined as the management, operation, and development of the flows of people, materials, and information in a hospital. Intralogistics refers to the organization, control, implementation, and optimization of internal flow of materials, flow of information, and handling of goods in industry, retail, and public facilities. It is distinct from “logistics,” which cover the same flow of materials and information inside and outside an organization (e.g., freight transportation) (VDMA, 2021). In this research study, hospital intralogistics focus on the management, operation, and development of internal flows of materials.

Material handling is one of the logistics activities focused on the movement, protection, storage, and control of materials and products throughout manufacturing, warehousing, distribution, consumption, and disposal (MHI, 2021). Since the focus lies in hospital intralogistics and transportation is its main material handling activity, in this research study, material handling is defined as a logistics activity focused on the detailed planning and control of transportation throughout a facility.

AMRs are an evolution of AGVs. While AGVs are computer-controlled wheel-based load carriers that travel along markers or wires on the floor or use vision or lasers to move within a facility without an onboard operator or driver (Le-Anh et al., 2006; Vis, 2006), technological developments allow AMRs to move autonomously and provide a wide range of material handling activities. In this study, AMRs are defined as industrial robots that use a decentralized decision-making process for collision-free navigation to provide a platform for material handling, collaborative activities, and full services within a bounded area (Fragapane et al., 2021).

The entire domain will not be investigated since that would exceed the timeframe of this research project and muddy its focus. Therefore, this research study will focus on and add knowledge in the overlapping areas of hospital intralogistics, material handling, and AMRs (Figure 1).

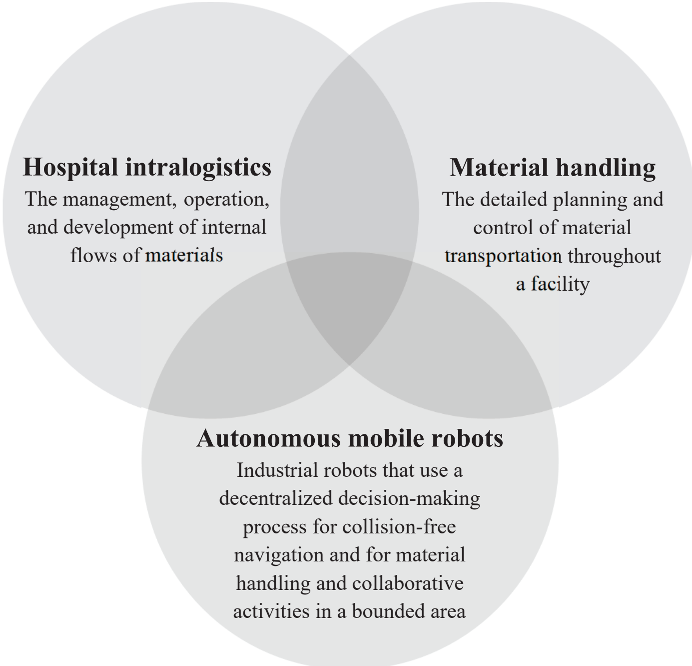



**Figure 1**: Research scope

## 1.5. Thesis outline

The thesis is divided into two parts. The first (I) contains the main report, while the second (II) includes the collection of published papers. The main report is based on research that has been conducted and documented in the appended papers. It gives an overview of the research process and synthesizes the independent papers' contributions into a coherent argument.

**Part I** is organized as follows.

**Chapter 1** is the introduction. It explains the problems faced in practice and motivation for research in this area. Furthermore, it describes the research problem investigated and defines the research objectives and questions addressed through this research study. The chapter concludes by presenting the study's scope and structure.

**Chapter 2** presents the theoretical background of the three domains of hospital intralogistics, material handling, and AMRs relevant to this research study.

**Chapter 3** begins with an overview of the research study, showing the connection between different parts of the research. Furthermore, it introduces the research design of this study and describes the applied research methods. Finally, the research quality is discussed using the four prevalent criteria.

**Chapter 4** presents the results and findings of the research study. It presents key outcomes addressing the research questions. Lastly, the findings are discussed.

**Chapter 5** summarizes the research study and provides concluding remarks. Furthermore, the research limitations are highlighted and recommendations for future research are presented.

**Part II** consists of the papers that were written to disseminate the results of this research study. It contains the following five published papers. An additional one is under review:

1. Fragapane, G. I., Bertnum, A. B., Hvolby, H. H., & Strandhagen, J. O. (2018). Material distribution and transportation in a Norwegian hospital: a case study. *IFAC-papersonline,* 51(11), 352-357.
2. Fragapane, G. I., Zhang, C., Sgarbossa, F., & Strandhagen, J. O. (2019). An agent-based simulation approach to model hospital logistics*. Int J Simul Model,* 18(4), 654-665.
3. Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2020). Autonomous Mobile Robots in Hospital Logistics. In *IFIP International Conference on Advances in Production Management Systems* (pp. 672-679). Springer, Cham.
4. Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2021). Autonomous mobile robots in sterile instrument logistics: An evaluation of the material handling system for a strategic fit framework. *Production Planning & Control.*
5. Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. *European Journal of Operational Research.*
6. Fragapane, G., Roy, D., Sgarbossa, F., & Strandhagen (under review) Planning autonomous material transportation in hospitals. In *IFIP International Conference on Advances in Production Management Systems*. Springer, Cham.

# Theoretical Background 2

This chapter presents the theoretical background of the three domains of hospital intralogistics, material handling, and AMRs relevant to this research study (A more detailed review on the different domains can be found in the papers).

## 2.1. Hospital intralogistics

The demands of hospital logistics are handling different materials flows and enabling planned and *ad hoc* healthcare provision to a clientele with strong variability and a low predictable profile (Bourlakis et al., 2011; Wieser, 2011). Developing productive and cost-efficient logistics is challenging since the hospital supply chain is usually characterized as highly complex (Rivard-Royer et al., 2002; Volland et al., 2017). The complexity arises from the involvement of multiple stakeholders, the multitude of different supplies and distribution channels, and the synchronization of the internal and external supply chains to supply materials to the point-of-use, the patient, and the end customer (Rivard-Royer et al., 2002; Byrnes, 2004; Schneller et al., 2006) (Figure 2).

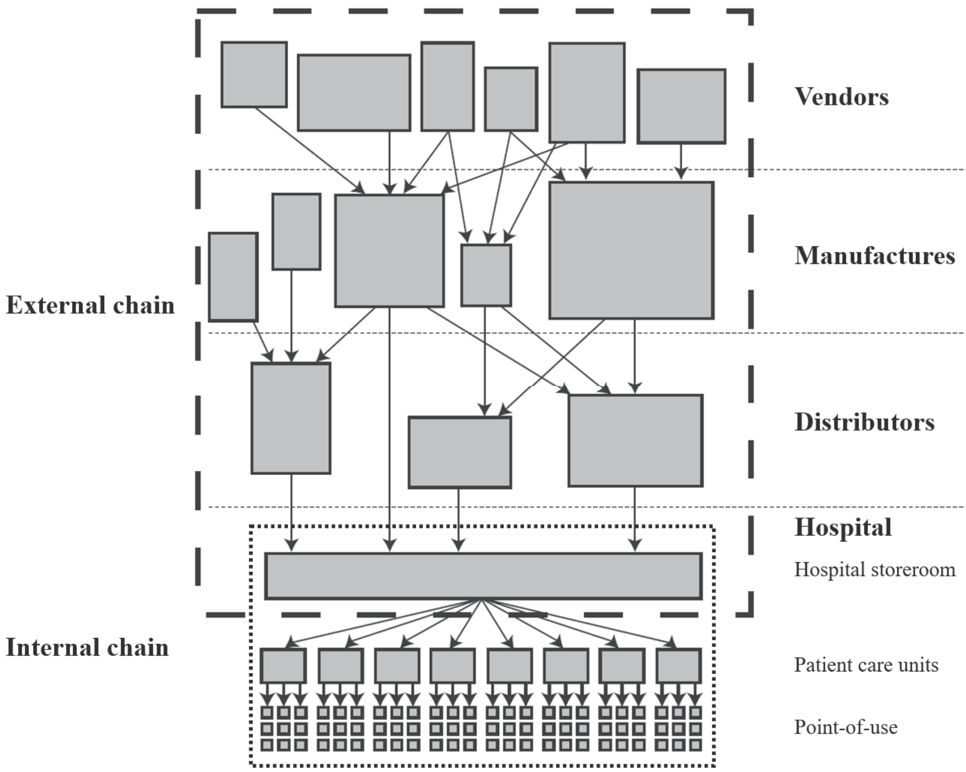



**Figure 2***:* External and internal hospital supply chain (Rivard-Royer et al., 2002)

In contrast to other industries, physicians can, with personal preference for a particular medical product or brand, decide on a different supplier (Ravankar et al., 2018). Therefore, the hospital supply chain is often characterized as follows: (I) regardless of profit, the dominant goal of healthcare organizations is to improve and save lives, (II) there are numerous actors involved in the healthcare supply chain, (III) there are many different channels to supply the hospital, (IV) many of the products are expensive, highly complex, and often require special handling, and (V) physicians are taking part in the selection of supplies to a great extent (Abdulsalam et al., 2015).

However, all necessary materials to provide healthcare services cannot be sent just-in-time from the suppliers or warehouses to treatment at the point-of-use. Many storage spaces and storerooms are spread within a hospital and must be replenished, keeping in stock medical supplies, linens, etc., for patients and hospital staff. Hospitals circulate a wide range of instruments and equipment to keep costs and inventory space low. In addition, the distribution of sterile instruments, food, linen and waste results in a complex transportation network (Rivard-Royer et al., 2002). The internal flow of materials must be well-managed to provide supplies to the hospital's core activity: patient care.

Therefore, hospital intralogistics, which focus on managing and developing the internal flows of materials in a hospital, are an extensive and essential part of healthcare. Intralogistics networks consist of materials with varying characteristics that must be produced in-house or by a supplier and moved from different departments to the point-of-use and back for reprocessing or waste disposal. Some of the most crucial and complex material flows (sterile instruments, food, linens, medical supplies, and waste) are described in the following paragraphs (A more detailed review on hospital intralogistics and material flows can be found in Paper 1, 2 and 4).

A variety of sterile instruments, from sutures, wound dressings, scalpels, and scissors to complex endoscopic equipment and battery-powered drills, are used daily in hospitals to perform patient care procedures. Sterile instruments are generally classified as either single-use or reusable (Volland et al., 2017). Since most can be reused, the logistics loop of sterile instruments can be classified as reverse and closed-loop logistics. All reusable instruments must be adequately cleaned, disinfected, and checked for functionality after each use. Since patient safety depends on medical instruments functioning properly with minimal contagion risk, hospitals must ensure that these instruments are always of high quality, sterile, and available when needed (Chobin et al., 2012). The main operational processes are sterile processing (i.e., washing, cleaning, inspecting, packaging, and sterilizing), storage, use, and transportation.

Food must be provided for patients, visitors, and staff throughout the day. The kitchens and distribution network must be both flexible to meet variable demands depending on patients' medical condition and efficient to reduce food waste. The role of intralogistics is to coordinate all actors (chefs, nurses, material handling equipment, other staff) involved in the forward logistics of preparing, processing, and distributing food and the reverse logistics of collecting and cleaning trays and dishes. Through all these intralogistics processes, requirements for food health and quality must be covered to ensure patient safety (Fatimah et al., 2011).

In today's hospitals, patients expect linens to be changed daily, and reliable laundry service is of utmost importance. The latter is responsible for providing to all users a clean and constant supply of linens, which includes all textiles used in the hospital, such as mattresses, pillow covers, blankets, bed sheets, towels, screens, curtains, doctors' coats, theatre cloths and tablecloths. The main operational processes of sorting, washing, extracting, drying, ironing, folding, mending, and delivering must be done under sanitary conditions to protect patients and staff from infection and contamination (Yajuan et al., 2015). The use of tracking technology has helped improve linen intralogistics by automatically classifying and counting bedclothes and by tracking their washing, disinfection, transportation processes, and usage conditions.

In the traditional distribution model, manufacturers provide medical supplies to distributors, which stock them and send them to hospitals when needed. This model creates large amounts of inventory in the system (Rossetti et al., 2012). A newer model has replaced the distributor with a centralized warehouse owned by the hospital or regional healthcare authority. Medical supplies are shipped directly to the central warehouse, and deliveries are broken down into smaller units. Hospital staff in departments can place orders, and the warehouse will pick, pack, and send medical supplies to the hospital up to several times a day. In this model, the central warehouse takes full responsibility for inventory management and material handling.

The flow of waste, which is 10%–25% medical and 75%–90% non-medical, must be thoroughly managed and carefully handled since it poses potential health and environmental risks both inside and outside the hospital (Baveja et al., 2000; Chaerul et al., 2008). Nevertheless, waste management practices vary among hospitals, where operational processes include segregation, collection, transportation, storage, treatment, and disposal (Tsakona et al., 2007). Material handling activities in these processes depend on the waste characteristics (solid, liquid, genotoxic, biological, chemical, radioactive, physically hazardous, or potentially infectious) and the available and necessary treatments (recycling, incineration, or burying). It is crucial for hospitals to establish and improve practices and methods to maintain regulatory environmental and security standards in an environment that is using increasingly more advanced materials for treatment and analysis (Blenkharn, 2005).

## 2.2. Material handling

Material handling involves the transportation and storage of materials inside a facility with the main objective of performing safely, efficiently, at low cost, on time, accurately, and without damage (MHI, 2021). It gives dynamism to static elements, such as materials, products, equipment, and layout (Lambert & Stock, 1993; Chopra et al., 2013), and it is connected to many different areas within a facility. The activities performed in one area or department of a facility will have an impact on another department. For instance, positioning a conveyor line in a facility can improve the material flow or expose it as an obstacle to plant traffic. Decisions, processes, and activities in material handling show great dependencies and should not be seen as isolated, independent procedures. Material handling should be seen within a system context (Kulwiec, 1985). The systems concept is particularly interesting because it identifies and analyzes interrelations within a system. Blanchard, Fabrycky, & Fabrycky (1990) define a system as a set of interrelated components working together with the common objective of fulfilling some designated need.

The design process of a material handling system focuses especially on the selection and configuration of equipment for material transportation (Chan et al., 2001). Fundamental principles for analyzing and determining solutions for material handling problems have been developed over time based on the experience of many material handling experts. The planning principle in material handling aims to analyze the material as well as movement to find suitable equipment. It considers every move, storage need, and any delay to minimize costs, and tries to answer the questions of "why, who, what, where, when, and how?" about each move, which allows identifying the most suitable solution. The material handling equation of "Materials + Moves = Methods" is a plan for a systematic approach for equipment solution (Figure 3) (Tompkins et al., 2010).

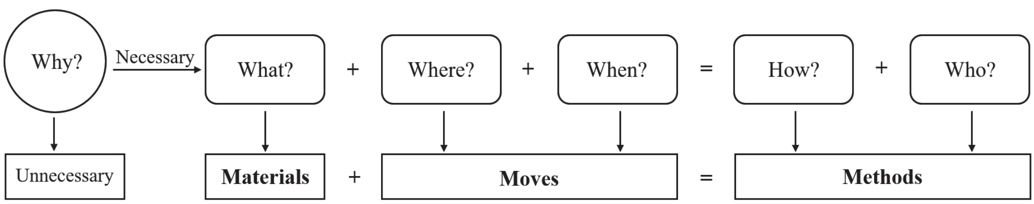



**Figure 3**: Material handling equation (Tompkins et al., 2010)

This design process is dependent on information from the main operations management areas of forecasting, resource allocation, production planning, flow and process management, inventory management and control, and customer delivery. The information can be grouped into material characteristics, flow rate, routing and scheduling, plant layout, and unit load principle.

However, in practice, material handling is frequently treated superficially by organizations, and a significant portion of expenses can be traced back to material handling activities (Groover, 2016). To give an example from manufacturing, 20% to 25% of costs are estimated to be associated with material handling (MHIA, 2011). A large-scale survey within warehousing and distribution revealed that the performance metrics (in parentheses, by share of respondents) of order accuracy (61%), throughput (58%), cost per order (30%), order fill rate (29%), on-time delivery (22%) and cycle time (17 %) have been improved by automated material handling equipment and systems (MHIA, 2011). Material handling foremost improves the performance of productivity, quality, and consequently, costs. Manufacturers and distributors of pharmaceuticals, medical devices, and supplies have, compared to hospitals, long used automated material handling equipment and systems in their intralogistics operations (Trebilcock, 2012).

Various manual, semi-automated, and automated material handling equipment and systems are currently used in hospital intralogistics. Many small and short deliveries of medical equipment, medicine, etc., are performed manually by nurses, physicians, porters, etc. Manual transportation is widely applied throughout the hospital, especially inside the departments close to the patient. For heavier loads, semi-automated material handling equipment such as trolleys and small trucks can support the hospital staff in transporting materials (Rimpiläinen & Koivo, 2008; Ozturk et al., 2014). Compared to other intralogistics environments, only some automated material handling equipment and systems are implemented and used in hospital intralogistics: automated vacuum collection systems, overhead transportation systems, pneumatic tube systems, AGVs, and AMRs (A more detailed review on material handling systems can be found in Paper 2, 3, 4, and 6).

Automated vacuum collection systems transport waste or linens from the inlets of terminals in the departments to containers in the basement of a hospital. The materials are transported through a pipeline system at high speed using differences in air pressure created by large industrial fans. The fast transportation method allows moving high volumes of materials. The terminals with inlets and pipeline systems are often integrated into the hospital layout and reduce floor space. Furthermore, the system is entirely sealed, and it provides safe and hygienic transportation and collection of materials (Yankova & Grigorova, 2020).

In an overhead transportation system, carriers travel on overhead tracks and transport materials weighing up to 15 kg. Compared to on-floor material handling equipment, which requires and occupies a significant amount of floor space in a facility, this system is greatly independent of floor space and traffic (Eggert et al., 1999). Transporting materials along the sealing allows for safe and reliable transportation of delicate items inside hospitals. The tracks can be horizontally and vertically mounted and enable the carrier to move between floors and so connect departments.

The pneumatic tube system is composed of sending and receiving stations connected by a network of tubes. The materials are inserted into carriers, which, thanks to an airflow generated by one or more blowers, travel inside the tubes. Compared to automated vacuum collection systems, it is used to transport materials with high safety requirements for the material. The handling of biological material can be carried out in total safety. For instance, samples and blood bags are kept at a constant temperature whilst moving at a controlled speed, thereby safeguarding the integrity of blood components from hemolysis (Fernandes et al., 2006).

An AGV is a driverless transportation system that is primarily used for the horizontal movement of materials. AGVs in hospitals can call and use elevators to move to different floors. Their main material handling tasks are loading, transportation, and unloading. This allows for the transportation of various materials, often in wagons from many different hospital points. AGVs are part of a system composed of vehicles, a control system, pickup and delivery stations, and a transportation network. While the vehicles transport the materials, the centralized control system regulates the transportation and is essential for achieving efficient routing, scheduling, and dispatching of the vehicles. The pickup and delivery stations operate as physical interfaces between storage and transportation. Finally, the transportation network forms the vehicles' routes between the pickup and delivery stations (Le-Anh et al., 2006; Vis, 2006).

AMRs provide new possibilities for material handling services in hospital intralogistics. The next section introduces AMRs and briefly presents their application within hospitals.

## 2.3. Autonomous mobile robots

The first generic AMR patent was issued in 1987 (Mattaboni, 1987). Since then, it has been discussed mainly in the fields of robotics and information technology, but has recently emerged in logistics applications and its importance is expected to increase significantly in the near future. AMRs can now be found performing a wide range of tasks in industrial, healthcare, hotel, security, and domestic settings.

AMRs can be used as assistive systems as they can interact with people like co-workers. In automotive car assembly, AMRs equipped with manipulators can assist workers and together mount heavy parts of a car body at different stages along the assembly line (Angerer et al., 2012), thus increasing both productivity and quality while simultaneously reducing fatigue among workers.

In warehouses, AMRs collaborate with operators in order picking. AMRs carry a few small containers inside the picking areas and stop in front of the location where the operator must pick the next item. They then move to the next location independently. When all items in a given order have been collected, the AMR autonomously travels to the packing and consolidation area, where it is emptied and assigned a new set of orders (Meller et al., 2018; Azadeh et al., 2019). This technique enables a zone-picking strategy that optimizes the operator and AMR picking and traveling efficiency.

In hospitals, AMRs can, due to their size and navigational flexibility, move and provide material handling services both inside and outside departments. In contrast, AGVs cannot enter departments and deliver only to their front entrance (Figure 4). These capabilities allow deliveries to the point-of-use – the patient – and so cover a wide service area. For many years, mobile robots were a virtually unimaginable and practically unacceptable solution in healthcare support. People could not associate hospitals with a production environment. The increased social acceptance of AMRs allows for their integration into departments and wards (Kriegel et al., 2021).

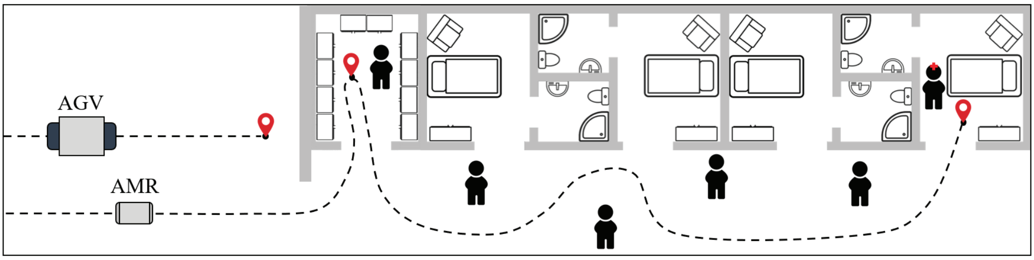



**Figure 4:** AGV and AMR transportation in hospitals

AMRs are an evolution of AGVs, and the guiding system that forms the core part of AGVs has evolved along various stages of mechanical, optical, inductive, inertial, and laser guidance into today's vision-based system (Figure 5).

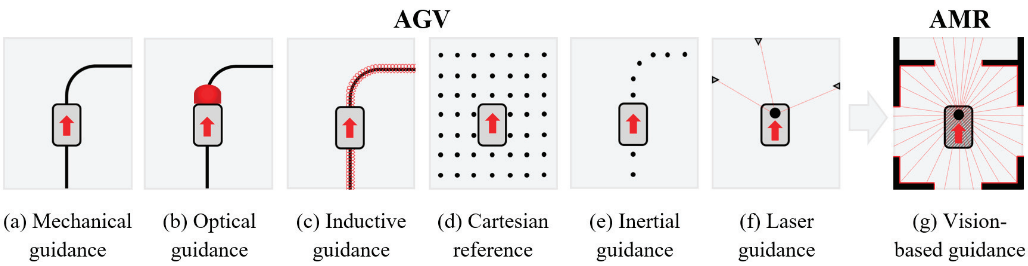



**Figure 5**: Guiding systems for AGVs and AMRs (top view of the system)

This vision-based system uses ubiquitous sensors, powerful onboard computers, AI, and simultaneous location and mapping technology, enabling the device to understand its operating environment and to navigate in facilities without the need to define and implement reference points in advance (Hernández et al., 2018). This has opened a new dimension in navigational flexibility. Conventional AGVs can only follow fixed paths and move to predefined points on the guide path. By contrast, AMRs can move to any accessible and collision-free point within a given area and adapt quickly to changes in the operating environment (A more detailed description of the technological parts and review of literature on AMRs can be found in the Paper 5).

The need for more flexibility has driven the development of AMRs, not only in navigational ability but also in the services they can provide. AMRs can provide many services beyond mere transportation and material handling operations, such as patrolling and sanitizing. In comparison, AGVs are often only used in intralogistics for repetitive transportation patterns. The AMR's capabilities and attributes facilitate a rethinking of material handling activities in intralogistics.

# Research Design 3

This chapter explains the research design of this research study. First, the applied research methods and the motivation for important methodology-related decisions that had to be made during this research process are described. Second, research quality in the four prevalent criteria is discussed.

## 3.1. Research methods

In this research study, a mixed-method research approach was selected because it produces a richer and more comprehensive understanding of a research area (Figure 6). It "combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration" (Johnson et al., 2007, p. 123). Therefore, four research methods are combined to answer the RQs and so fulfill the research objectives:

- Case research was selected to conduct in-depth and multiple-case studies and so explore the key characteristics, requirements, and challenges;
- Simulation modeling facilitated analyzing different hospital intralogistics scenarios and the SOQN model;
- The SLR supported aligning existent research and uncovering areas of AMR planning and control; and
- Based on the SLR, the SOQN has been identified as the most promising method to support the decision-making process for AMRs in intralogistics.

Case research was conducted to map the hospital intralogistics and material handling activities of multiple hospitals. Not all material flows or material transportation can be investigated in this research study. Therefore, this research study examined one of the most difficult and complex material flows and material transportation in hospitals, assuming that developed knowledge can be transferred to other material flows as much as possible. High complexity in a system is associated with numerous components and interconnections, interactions, or interdependencies that are difficult to predict, manage, and change (Isik, 2010). In sterile instrument logistics, there is a high number of components in the system (instruments, processes, etc.), a high number of interconnections and relationships among these components (physicians, patients, technicians, etc.), and high dynamism and uncertainty in the system (surgery demands, washing machine breakdowns, etc.). Therefore, this research study focuses to a large extent on mapping the material transportation of sterile instruments.

Analyzing the collected data from three case hospitals allowed identifying the sterile instrument transportation patterns and deriving crucial material transportation characteristics. To achieve high performance in material transportation, key performance indicators (KPIs) for material transportation could be identified. These KPIs can be interpreted as crucial requirements for material transportation in hospitals. Furthermore, by analyzing the case studies' results based on contingency theory, a strategic fit framework for material transportation and the material handling systems in hospital intralogistics could be developed. Since every hospital is unique in managing the material flows and material transportation, contingency theory can support to see the relationship between organizational characteristics and contingencies such as the size, environment, and strategy for reaching high performance (Donaldson 2001). The strategic fit framework indicates the ideal states of material handling systems in hospital intralogistics to achieve high performance in material transportation.

Simulation modeling was applied to explore and analyze material handling systems' challenges and to test the semi-open queuing network (SOQN) in hospital intralogistics. Replicating the hospital intralogistics and filling the simulation with a material handling system's historical transportation data, different material flow scenarios could be simulated to observe system behavior. Several challenges of current material handling systems have been identified. Moreover, simulation allowed comparison of different modeling approaches and analysis of their applicability in material transportation.

A systematic literature review (SLR) was conducted to map the current knowledge of AMR planning and control and propose a definition for AMRs in intralogistics. The SLR supported identifying the technological advances of AMRs that affect planning and control decisions and proposed a framework to plan and control AMRs. The current approaches and methods were grouped and reviewed based on the identified decision areas. This allowed us to evaluate the approaches and methods for AMRs in hospital intralogistics and propose a research agenda.

Lastly, SOQN modeling, one of the most promising methods for planning and controlling AMRs in hospital intralogistics, was developed. The method provides decision support for hospital planners when planning AMRs in hospital intralogistics.

Figure 6 provides an overview of the research design, showing the overall workflow and the relationships between the literature review, research questions, research methods, main outcomes, and papers. The following subsections will explain the main research methods in detail.

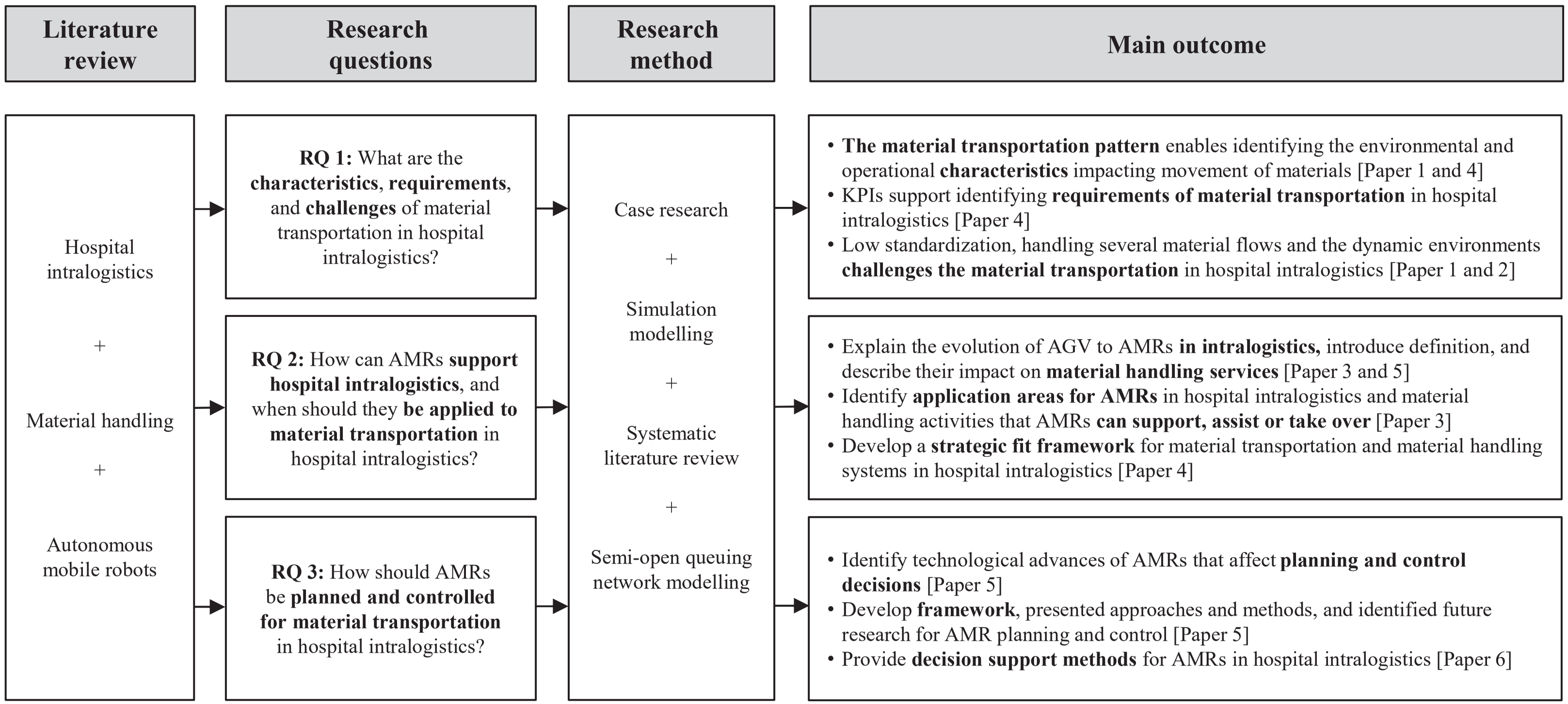



**Figure 6:** The research design of this research study, showing relationships between literature review, research questions, research methods, main outcomes, and papers

### 3.1.1. Case research

Case research was applied as the primary research method to investigate hospital intralogistics and material handling activities and identify characteristics, requirements, and challenges. This research approach is suitable for investigating a real-life phenomenon when the associated variables and complexity are not sufficiently understood (Creswell, 2012). Many researchers have highly recommended the case study research method as an excellent tool for improving the conceptual and descriptive understanding of phenomena (McCutcheon & Meredith, 1993; Barratt et al., 2011; Yin, 2017). The growing frequency and magnitude of developments in technology and managerial methods in operations management require researchers to apply field-based methods (Lewis, 1998). A case study is among the most powerful research methods in operations management (Fynes et al., 2015). While a single case study allowed for an in-depth analysis of hospital intralogistics and material handling processes, the multiple-case study approach allows for a more direct comparison of the similarities and differences between practices in different contexts (Dinwoodie & Xu, 2008).

Case selection is a vital element in the current type of research. When using the traditional approach, a sample of cases is built by selecting cases according to different criteria (Eisenhardt & Graebner, 2007). However, for multiple cases that resemble various experiments, it is crucial to focus on replicating logic rather than sampling logic (Yin, 2017). The study's strategy is based on achieving theoretical replication using information-rich cases that produce diverse results and maximum variation for predictable reasons (Voss et al., 2002; Bazeley, 2013). The selected hospitals have implemented different types of material handling systems with varying degrees of automation. The investigated hospitals are mainly located in Norway and Denmark and share similarities in how they are structured as organizations and how they provide healthcare.

The case studies data were collected through multiple sources, such as semi-structured interviews, visits and observations, documents, and material handling system data. Semi-structured interviews allowed interviewing key personnel who could provide helpful information regarding their hospitals' intralogistics and material handling activities and processes, logistics loops, and material handling systems. The interviews were conducted with hospital planners, leaders, operators, coordinators, and other personnel involved in the day-to-day transportation of material transportation to obtain information about decision-making at the operational, tactical, and strategic levels. Personnel from different departments were interviewed to represent several central stakeholders of hospital intralogistics. In preparation for the interviews, an interview guide was developed based on the literature review and adapted to match the subjects' backgrounds and education levels (Appendix A). Semi-structured interviews proved an effective way to collect data. We used NVivo 11 for coding the interviews and analyzed them using the recommendations made by Mayring (2004) for content analysis. Several visits were made to conduct observations in different departments in the hospitals. Observations were crucial because many occurrences concerning the transportation of materials, such as delays, often go unrecorded. Complex processes inside and outside the departments could be observed in their natural setting, allowing the researchers to study actual behavior. Relevant information was also obtained through documents, illustrations, and reports provided by the participants during the visits and interviews.

### 3.1.2. Simulation modeling

To investigate the challenges of a material handling system in hospital intralogistics, the research method of simulation modeling was selected because it allows quantifying and observing the system's behavior under many different circumstances. Agent-based simulation (ABS) modelling was selected because it allows precise reproduction of hospital intralogistics due to the huge amount of data available from a case hospitals.

The ABS method is new in operations management and often overlooked, as researchers have tended to rely on more traditional methods (Maidstone, 2012). ABS has garnered more interest among practitioners because it can model stochastic processes. At its core, ABS is built by autonomous resource units that follow a series of predefined rules to achieve their objectives whilst interacting with each other and their environment (Maidstone, 2012; Wurzer, 2013). These attributes are especially interesting since the hospital environment should be integrated to a higher degree in the models. Interactions between material handling systems and personnel or elevators can be included in the simulation model. A previous study has shown that ABS is especially useful in simulating complex logistics networks and understanding real-world systems in which representing or modelling many individual units is important (Siebers et al., 2010; Zhao et al., 2017). ABS is especially suitable for this study in modelling and simulating the hospital intralogistics with the different individual units and evaluating the transportation system.

A year’s worth of historical data of a material handling system performing material transportation in a case hospital were used to feed the simulation model. The data included details of jobs, battery information, errors, and elevator information. The model, different scenarios, and simulation results were presented and discussed in iterative loops with the case hospital's logistics planners and maintenance personnel. The feedback was utilized to improve the simulation model and analyze the challenges of a material handling system in hospital intralogistics.

The software Anylogic version 8.7.3 was used for simulating the ABS and SOQN models.

### 3.1.3. Systematic literature review

The literature review is a significant contribution to research progress. It intends to provide a historical perspective of the respective research area and an in-depth account of independent research initiatives (Mentzer & Kahn, 1995). The SLR is a review of clearly formulated questions that uses a systematic and evidence-based approach to identifying, selecting, and analyzing secondary data. This approach differs from other review methods because of its transparency, inclusivity, and explanatory and heuristic nature (Tranfield et al., 2003). Therefore, the SLR allows for a more objective overview of the search results and eliminates bias and error issues (Buchanan & Bryman, 2009). The main objective of the SLR is to facilitate theory development, align existing research, and uncover areas where additional research is needed (Webster & Watson, 2002).

The literature on planning and control of AMRs in intralogistics is fragmented and lacks a unified and accepted definition among practitioners and researchers. The SLR is an adequate approach to organize and unify knowledge within this field.

In this research, the SLR supported identifying and classifying research related to the planning and control of AMRs and proposed an agenda for future research in this field. As a first step, it was necessary to select appropriate search terms reflecting the focus area and address the research questions. Relevant keywords for AGVs could be identified based on the extensive literature review by Le-Anh et al. (2006) and Vis (2006). Since AMR in intralogistics is a much less established domain, a larger number of search terms were selected. The following keywords – and their variants – were used in the SLR: "Automated Guided Vehicle", "Autonomous Intelligent Vehicle", "Autonomous Mobile Robot", "Mobile Robotic Fulfilment", "Collaborative Mobile Robot", "Mobile Service Robot", and "Puzzle Based Storage System". The literature searches were conducted mainly through ScienceDirect and Web of Science. The search engine Google Scholar was only used to double-check that recently published articles were not missed. After obtaining the initial set of articles from the different databases, duplicates were removed.

An essential part of any SLR is establishing inclusion and exclusion criteria, thereby ensuring objective reasoning behind the choice of literature (Meline, 2006). In the SLR, only articles published in the last 15 years were included. Older material on AGVs has been adequately covered in two literature reviews by Le-Anh et al. (2006) and Vis (2006), which describe the main methods and approaches before 2006. Next, we excluded conference proceedings, professional journals, book chapters, and doctoral dissertations since we assume that significant research has eventually appeared in refereed academic journals. Furthermore, only articles with full English texts and published in high-impact journals (i.e., journals with a Scimago Journal Rank higher than 0.5) were included.

Next, we manually screened all 302 remaining article titles and abstracts and excluded articles that vaguely related to AMRs or AGVs. In the final step, all the remaining articles were full-text screened to confirm their relevance to the planning and control of AMRs. Examining the reference lists, some highly relevant articles that were cited multiple times but not previously identified were also added. A total of 108 articles were included in the final review.

These articles were inventoried in a database where they were sorted and categorized by prime objective, method, and application area. The SLR was supported by the software EndNote X7 for reference management and NVivo 11 for coding the literature.

#### 3.1.4. Semi-open queuing network

Based on the SLR, the SOQN has been identified as the most promising method to support the decision-making process of AMRs in intralogistics. SOQN can capture external wait times and accurately estimate system throughput times.

AMRs can be modeled as a server (open queuing network) or customer (closed queuing network) or to connect to a customer for specific tasks (SOQN). Different models have different application possibilities. In comparison, open queuing networks can be used at the operational decision level to estimate wait and throughput times. Closed queuing networks assume the system is the bottleneck, and as such, they are fit for assessing throughput capacity of a given configuration at the design decision level. SOQN modeling combines the advantages of open queuing networks (external queue to accommodate jobs whose entrance is delayed) and closed queuing networks (internal networks with a population constraint). Using a synchronization station, incoming customers waiting in an external queue can be paired with available resources in the resource queue (Figure 7). This modeling approach captures external wait times and accurately estimates throughput times (Roy, 2016).

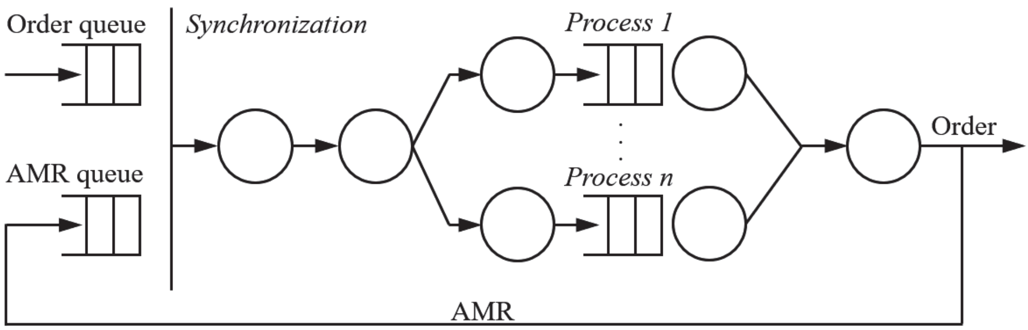



**Figure 7:** SOQN model with AMRs

## 3.2. Research quality

To judge the research quality, Karlsson (2016) recommends four requirements: construct validity, internal validity, external validity, and reliability. Although these criteria originate from quantitative research (Halldorsson & Aastrup, 2003), they have also been recognized to evaluate qualitative research, such as case studies (Voss et al., 2002; Yin, 2017). Since this research study applied quantitative and qualitative methods, these four tests were considered suitable for evaluating research quality. The following sections explain how these four criteria of research quality were considered during the research process.

### 3.2.1. Construct validity

Construct validity is "the extent to which correct operational measures have been established for the concept being studied" (Voss et al., 2002, p. 211). Yin (2017) proposes two critical aspects to account for construct validity adequately: (i) provide clear definitions of what is to be investigated, and (ii) demonstrate that the operational measures do indeed reflect what is intended to be investigated.

In this research study, the introduction provides a clear description of the scope. Definitions and explanations have been presented in all appended papers. Furthermore, we contribute a refined definition of the concept of AMRs in intralogistics. The use of multiple sources of evidence, such as interviews, data records, and observations were the main strategies used to ensure the second facet of construct validity. All sources of evidence pointed towards the same conclusions.

The results of this research have been discussed in workshops with hospital planners. This contributed significantly to the verification of collected data and the subsequent findings throughout the whole research study. For the simulation model, verification and validation tactics were used to ensure the model actually reflected what was intended.

### 3.2.2. Internal validity

Internal validity implies providing the correct causal relationships and not overlooking other factors that could explain these relationships (Karlsson, 2016). In other words, if it is concluded that X has taken place because of Y but overlooks that X happened because of Z, there is low internal validity. Internal validity is more applicable as evaluation criteria, especially for explanatory and causal studies and not necessarily in descriptive studies (Croom, 2009; Yin, 2017).

To ensure internal validity, the use of theoretical replication has been one of the main strategies in this research study. For example, in the multiple-case study, which compared three cases with different degrees of automation, the expected results were formulated based on literature before the data collection. Afterwards, the empirical findings were compared with this prediction. Additionally, in this study, the use of theoretical replication – search for contrasting cases – was used to select cases, meaning that three different cases were intentionally selected, and different results were expected.

For the simulation study, the system's behavior and identification of causality were the main curiosities that drove the whole research. In this case, causality was established by adjusting each independent variable individually and then evaluating the causal effects on the dependent variables. Thus, simulation is suitable for investigating causal relationships (Croom, 2009; Bertrand & Fransoo, 2016).

Lastly, Croom (2009) advises the use of method triangulation (e.g., case studies and simulation) and data triangulation (e.g., interviews and data records) to strengthen the support of proposed cause-and-effect.

### 3.2.3. External validity

External validity focuses on whether the results are generalizable from the research study's data and context to broader populations and settings (Cook et al., 1979).

To ensure external validity of case studies, Bell et al. (2018) recommended providing "thick descriptions" of the context in which the study was conducted. Such detailed descriptions allow others to make judgments on whether the research findings are transferable to other situations. Therefore, this research study aimed to provide precise reports of all the case hospitals studied.

Furthermore, to ensure the greatest generalizability of this research study, the investigated case hospitals vary strongly in their characteristics, such as by size, hospital type, number of departments, construction year, building layout, etc. These characteristics were incorporated into the development of the strategic fit framework. However, our case hospitals mainly consisted of Scandinavian ones. We cannot say for certain that our findings can be generalized outside of Scandinavia, although we expect the case to be so.

### 3.2.4. Reliability

Reliability refers to the extent to which a study can be replicated and arrive at the same results (Voss et al., 2002). The aim is to minimize bias so that the same findings and conclusions can be achieved by another researcher repeating the study.

To ensure reliability, different tactics have been applied. First, providing the research design and describing the methods used in this research study and each appended paper facilitate researchers' ability to replicate all the studies.

Secondly, to increase the reliability of the case studies, a semi-structured interview guide was developed, and the collected data were gathered in a case study database. Next, for simulation modelling, different statistical tests were conducted to evaluate its reliability. For the SLR, replicability is ensured by following a series of transparent steps. Lastly, the SOQN is compared with an agent-based simulation model to ensure the reliability of the results.

Additionally, we aimed to have several researchers involved in the research process and for them to investigate the data, as this may reduce bias from a single researcher.

# 4 Towards autonomous material transportation in hospital intralogistics

This chapter presents and discusses the results and findings of the research study.

Following the research design, at first, the characteristics, requirements, and challenges of material transportation in hospital intralogistics are investigated, providing insights on which decision-making methods can be built on. The results and findings are based on Papers 1, 2, and 4 and address **RQ1**. Next, autonomous mobile robots in hospital intralogistics are introduced, highlighting their application area. The results and findings are based on Papers 3, 4, and 5 and address **RQ2.** Furthermore, to apply and achieve high performance, knowledge is developed for the planning and control of autonomous mobile robots for material transportation in hospital intralogistics. The results and findings are based on Papers 5 and 6 and address **RQ3**.

Next, there is a discussion about the road towards autonomous material transportation, keeping the intralogistics at optimal levels, and allowing hospital staff to focus on patient care. Finally, the research study's contributions to theory and implications for practitioners are presented.

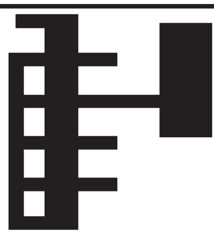
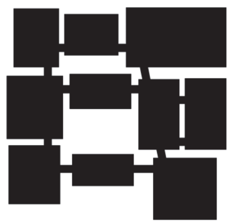
## 4.1. Characteristics, requirements, and challenges of material transportation in hospital intralogistics

Exploring, describing, and analyzing current practices allow for a comprehensive understanding of material transportation in hospital intralogistics. Studying material transportation patterns to characterize them, defining KPIs to identify the requirements, and investigating current challenges of material transportation and material handling systems provide insights into which decision support methods can build on.

<u>Characteristics:</u>

Mapping material transportation in hospital intralogistics is a crucial starting point for investigating hospital intralogistics. The multiple-case study format allowed for building a comprehensive understanding of hospital intralogistics and material transportation. As highlighted in the theoretical background in section 2.2, the essential parts of "materials," "moves," and "methods" can be used to map material transportation. However, mapping all material transportation in hospitals would exceed the research timeframe. Therefore, this research study investigated one of the most difficult and complex ones to transport in hospitals: sterile instruments. The sterile instrument intralogistics and material transportation are investigated in three case hospitals with different types of material handling systems: a material handling system using manual transportation and dedicated elevators (Hospital A), a shared AGV system (Hospital B) and a dedicated AMR system (Hospital C) both using elevators. They represent the different degrees of automation in the transportation of sterile instruments. A detailed description of hospital intralogistics and material transportation can be found in Paper 4. A short summary of the crucial characteristics of the three case hospitals is presented in Table 1.

**Table 1:** Summary of case hospitals

| | **Characteristics** | **Hospital A** | **Hospital B** | **Hospital C** |
|---|---|---|---|---|
| **Size and type** | *Size* | 700 beds | 750 beds | 300 beds |
| | *Type and number of departments* | University hospital | University hospital | Regional hospital |
| | *Construction year (Last major renovation or addition)* | 1961 (2008) | 1902 (2005) | 1988 (expected to be finished in 2024) |
| **Environmental** | *Building layout* |  |  |  |
| | *Buildings levels* | Up to 6 levels | Up to 7 levels | Up to 4 levels |
| | *Ratio of vertical to horizontal transportation* | 70% to 30% | 20% to 80% | 30% to 70% |
| **Operational** | *Sterile processing - Location* | Centralized, in-house | Centralized, in-house | Centralized, in-house |
| | *Sterile processing - Planning horizon* | Week | Day | Week |
| | *Sterile processing - throughput time* | 6 hours maximum | 24 hours maximum | 6 hours maximum |
| | *Inventory - Location* | Centralized | Decentralized | Centralized |
| | *Inventory - Replenishment method* | Kanban | Periodic review, until order-up-to | Kanban |
| | *Delivery to Point-of-use - Principle* | Just-in-time, pull | Push | Just-in-time, pull |

Identifying and analyzing logistics patterns enables deriving characteristics (Haag & Sandberg, 2020). Thus, through an iterative process, by combining empirical evidence from case hospitals, material transportation patterns were identified and analyzed to formulate characteristics. The following sections are based on the results and findings of Paper 4.

Whether small or large, regional or university, hospitals have demonstrated favorable flexibility, productivity, quality, service, and cost performance outcomes after applying an automated material handling system for hospital intralogistics. Even a small regional hospital can implement, use, and profit from an automated material handling system. For instance, while in a small case hospital it could substitute or free up at least one employee, in a large case hospital, up to six full-time employees could be freed up. It is not the hospital size that is crucial, but rather the environmental and operational characteristics are the most influential on material transportation.

The environmental characteristics can be broken down by building layout, the number of floors, and the ratio of vertical to horizontal transportation, and reflect the movement of materials in all three spatial dimensions. While the layout and number of floors help picture the hospital building, the ratio of vertical to horizontal transportation indicates the main movements of materials between the departments in the hospital. Hospitals with high manual material handling for material transportation have attempted to concentrate the departments with increased demand for material transportation. Reducing the distances between the pickup and delivery points by locating departments above one another and using elevators has been the primary measure to improve transport times. When manual transportation for a material flow is applied, hospital planners aim for a higher ratio of vertical to horizontal transportation.

However, according to the case hospitals' logistics planners, this ratio is challenged by two major identified trends. First, increased usage of IT allows for the sharing of hospital equipment across departments and increases medical service utilization. These departments are located throughout hospitals, so relocating them close to each other is nearly impossible in an operating hospital. Second, hospitals are expanding to handle the increase and complexity of patient care. New buildings and new departments must be incorporated into existent intralogistics. The restructuring and expansion of major hospitals while smaller ones are closed has been reported in many Western countries (Giancotti et al., 2017). The layout of hospitals is changing, and the ratio of vertical to horizontal transportation is decreasing and trending towards a more horizontal approach. Changing the ratio of vertical to horizontal transportation especially affects the productivity and cost performance of the material handling system. As horizontal transportation increases, the economic suitability of automated material handling systems, such as AGVs and AMRs, also increases because manual transportation reduces the value-added time of hospital personnel, which is associated with higher costs.

Operational characteristics incorporate production and storage principles and reflect the time dimension in material transportation. Two patterns are identified: an efficient one with centralized production, decentralized storage, and scheduled deliveries with a high time buffer, and a responsive one with centralized production, centralized storage, and just-in-time deliveries.

The first pattern relies on decentralized storage areas with high inventory levels in the departments at the point-of-use responding quickly in critical situations (Figure 8). This allows for longer replenishment lead times, thus reducing the pressure on delivery accuracy. The material handling system can perform deliveries with a high time buffer and low responsiveness. This pattern is convenient for transporting several material flows, thus reducing overall transportation costs. The suitable solution for this pattern has been the implementation of AGVs.

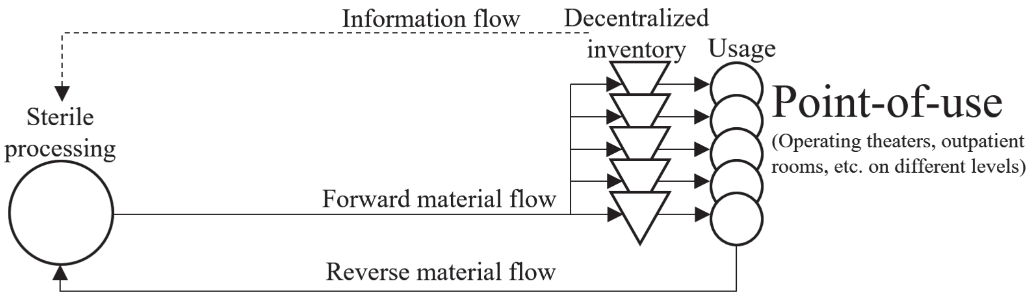



**Figure 8:** Efficient pattern with centralized production, decentralized storage, and scheduled deliveries with a high time buffer

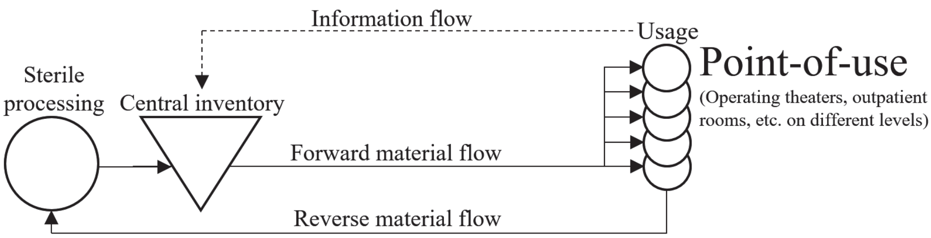



**Figure 9:** Responsive pattern with centralized production, centralized storage, and just-in-time deliveries

In contrast, the second pattern aims to achieve high performance with regard to flexibility and the provision of high-quality service in deliveries (Figure 9). This pattern focuses on centralizing storage and providing just-in-time deliveries. Applying the Kanban system allows inventory levels and costs to be kept low. This improves the quality of hospital supply chain services, moving away from a push with a high buffer towards a pull with just-in-time deliveries (Papalexi et al., 2016). This pattern requires a material handling system that can quickly adapt to changes and be responsive to deliver materials just-in-time to the many point-of-use locations throughout the hospital.

The characteristics can be summarized as:

**Environmental characteristics**

- Material transportation pattern with concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation; and
- Material transportation pattern with widespread pickup and delivery points and a low ratio of vertical to horizontal transportation.

**Operational characteristics:**

- Material transportation pattern with centralized production, decentralized storage, and scheduled deliveries with a high time buffer; and
- Material transportation pattern with centralized sterile processing, centralized storage, and just-in-time deliveries.

<u>Requirements:</u>

Requirements can be defined as "something that you must do" or "something you need" to achieve a goal (Dictionary, 2021). The goal of material transportation is to achieve high performance. The performance analysis evaluates how well a goal is met and provides input for decision-makers (Mentzer & Konrad, 1991). While defining KPIs is a crucial step in identifying the requirements, measurement provides information about inefficiencies. To determine the requirements for material transportation, this research study investigated the KPIs for material handling systems providing material transportation in several hospitals and used the findings to derive the requirements (Paper 4). The findings are based on material handling systems for material transportation of sterile instruments. The KPIs and their description are crucial contributions for the identification of material transportation requirements.

To assess the adequacy and select the appropriate KPIs, first, the main performance areas were based on the literature on material transportation in hospital intralogistics. Second, applied KPIs were identified in the case hospitals (Figure 10). Finally, relevant KPIs were selected in whole-day workshops at several hospitals with hospital planners. Furthermore, how to evaluate and rate the KPI of the hospitals' material handling systems was discussed. Table 2 describes the selected KPIs for material transportation in hospital intralogistics.

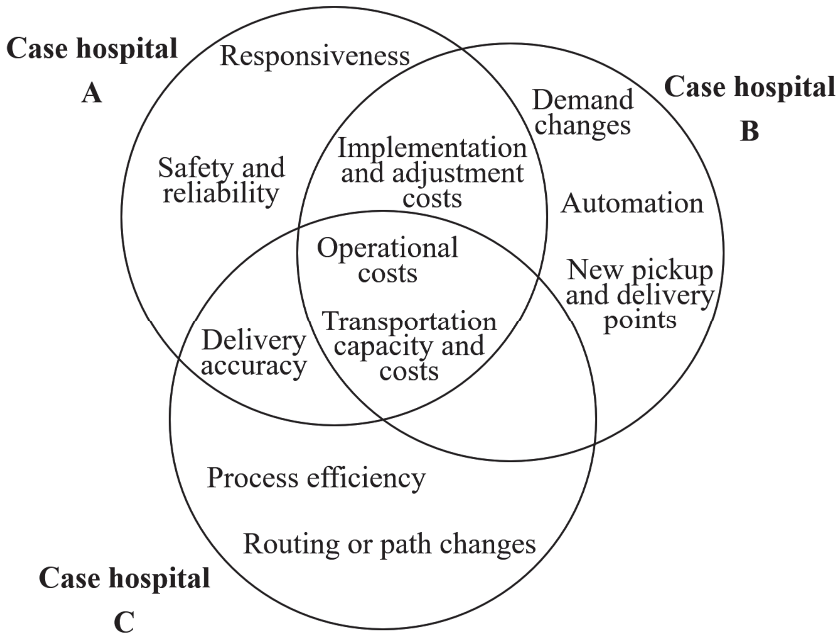



**Figure 10:** Identified KPIs for sterile instrument transportation in the three case hospitals

**Table 2:** KPIs for material transportation in hospital intralogistics

| Performance dimensions | KPI | Description |
|---|---|---|
| Flexibility | Demand changes | The degree of adaptation to changes in demand |
| | Routing or path changes | The degree of adaptation to new paths |
| | Add new pickup and delivery points | The degree of time and effort required to include and integrate new buildings, departments, and areas |
| Productivity | Transportation capacity | The number of transported items per delivery |
| | Automation | The ratio of machines to personnel time involved in deliveries |
| | Process efficiency | The ratio of value-added time to non-value-added time |
| Quality and service | Delivery accuracy | The proportion of correct and on-time deliveries |
| | Responsiveness | The time period for total transportation, including ordering, pickup, and delivery |
| | Safety and reliability | The number of system failures and errors |
| Costs | Implementation and adjustment costs | The costs of setting up and modifying the material handling system |
| | Transportation costs | The costs of single transport run |
| | Operational costs | The costs of operating and maintaining the material handling system |

The requirements of material transportation on material handling systems can be grouped into flexibility, productivity, quality, service, and costs. Material transportation in hospitals requires a high degree of flexibility. Material handling systems should adapt quickly to changes in demand and layout. Furthermore, they should facilitate including and integrating new buildings, departments, and areas in a short period of time. The requirements of productivity are reducing hospital staff's involvement to its minimum and providing efficient and effective transportation. To satisfy quality and service requirements, material handling systems should provide high delivery accuracy and be responsive to enable just-in-time deliveries. Material transportation must be performed safely –without harming people in hospitals – and reliably – by enabling robust intralogistics. Finally, costs should be kept low.

High implementation costs of material handling systems hinder the automation of material transportation. Moreover, the daily costs of transportation and maintenance must be low, since transportation is often a non-value-adding activity in patient care.

<u>Challenges:</u>

The current challenges of material transportation occur at different stages in hospital intralogistics. The in-depth case study (Paper 1) provides insights into material and information flows, while the simulation modelling study (Paper 2) focuses on challenges connected to the material handling system.

There are different methods to transport materials to the many point-of-use areas in the departments in the hospital supply chain. However, transportation ordering and delivery processes vary strongly. The material and information flows are often not standardized in all departments, and so many different methods are in practice. Furthermore, material management and material handling systems often do not communicate. Material handling systems are often stand-alone solutions that inhibit the tracking of supplies. Not using a common or at least an integrated information and communication system will lead to incoherent information sharing along the supply chain. Less information sharing leads to more uncertainties in the supply chain and, finally, in transportation.

Information exchange might break the "silo" culture in hospitals. Several in-house productions and points-of-use in the departments do not coordinate with each other. All the different production and delivery schedules from hospital intralogistics should be considered and integrated into the transportation scheduling problem of material handling systems. Not integrating them will lead to high material flow peaks and high variability in transportation and delivery times throughout the day, making the entire system less efficient.

Simulation modeling based on historical material handling data of an AGV system facilitated visualizing transportation patterns. Different scenarios were simulated to identify and analyze material transportation challenges in intralogistics and for the AGV system. The AGV's advantage of transporting many different materials is also one of its most significant problems. Handling many different material flows allows for only minimal adjustments. Improving the transportation performance of one material flow will significantly decrease another one's performance. Iterative processes of adapting the transportation schedule of an AGV system to satisfy all material flows are time-consuming and often result in low improvement in performance.

The simulation further exposed the challenge of AGVs' transportation reliability. AGVs are sensitive to the dynamic environments found in hospitals. In many cases, the AGV utilizes elevators and hallways also used by patients, visitors, and hospital staff. These interactions affect the transportation performance of the AGV system, as it cannot remove obstacles in the pathway. The AGV system is currently dependent on human monitoring. Errors or failures from elevators, human interactions, or obstacles resulting in AGV breakdowns must be corrected manually by an operator. These interactions and breakdowns have a substantial impact on the performance of the AGV system. Queues with AGVs can lengthen quickly in hospitals and affect the logistics system. If a queue lengthens, several AGVs are quickly affected. The hospital layout and corridors do not allow for several routing alternatives. Obstacles hindering the AGVs' movements or the maintenance team taking a long time to correct errors significantly impact the AGVs' transportation performance. Of the average of 60–100 errors counted per day by the case hospital's AGV system, only a few led to very long queues forming. Efforts undertaken to reduce errors and thus avoid queues can significantly reduce transportation times. The operator's attendance and surveillance currently restrict the AGVs' operating hours, emphasizing the need to expand the knowledge of operations of AGVs in hospital environments.

The presented results and findings of Papers 1, 2, and 4 address **RQ1**: **What are the characteristics, requirements, and challenges of material transportation in hospital intralogistics?** The first research question aims to map the characteristics, requirements, and challenges of material transportation in hospital intralogistics and to provide insights into which decision support methods can build on.

**The main findings can be summarized as:**

- The environmental characteristics of material transportation reflect the movement of materials in all three spatial dimensions. The ratio of vertical to horizontal transportation significantly impacts the material transportation since the material handling systems are especially suitable in some specific ratios. The two operational patterns of efficiency and responsiveness have a strong impact on the time dimension. The production and storage principles affect the delivery accuracy, buffer, and responsiveness of the material handling system.

- Analyzing the material transportation performance in terms of flexibility, productivity, quality, service, and costs enabled establishing a comprehensive overview of the requirements. The variety of KPIs allows capturing the requirements from different aspects and working towards them to achieve high performance.
- Material transportation and current applied material handling systems in hospitals face various challenges. Not standardizing the processes for material transportation and centralizing information flows will hinder successfully automating material flows in hospitals. Material handling systems have difficulty handling several material flows. Hospital planners must invest many hours to satisfy all the needs of material flows and reach high performance. Furthermore, dynamic environments stress some material handling systems.
- There is a need for more autonomous material handling systems in hospitals that can adapt to material transportation characteristics, meet the variety of requirements, and continuously optimize themselves to face current challenges.

## 4.2. Autonomous mobile robots in hospital intralogistics

The evolution of AGVs into AMRs has become possible due to technological advances. The development of the AMR's hardware and control software facilitates advanced capabilities for autonomous operation for navigation, object recognition, and object manipulation in unstructured and dynamic environments (Table 3). The identified technological advances are based on Paper 5, where a more detailed description of the technological parts can be found.

These developments have led to the decentralization of decision-making processes. Compared to an AGV system in which a central unit takes control decisions such as routing and dispatching for all AGVs, AMRs can communicate, negotiate independently, and make the decision themselves (Figure 11, Paper 5). This reduces the need for centralized and external control (Furmans & Gue, 2018). The AMR decentralized decision-making goal is to react dynamically to demand or changes and allow each vehicle to continuously optimize itself.

**Table 3:** Hardware and software developments of AMRs

| Hardware | Software |
|---|---|
| *Sensors:* AMRs are equipped with a wide array of small, low-cost, and power-efficient sensor technologies providing input data for autonomous navigation.<br><br>*Robot locomotion mechanism:* Different combinations, configurations, and arrangements of AMR wheels or legs exist to perform on varying terrain and satisfy the requirements of stability, maneuverability, and kinematics.<br><br>*Battery:* Limited battery capacity and long charging times were weak points of AGVs and reduced performance, utilization, and computational power. Traditional lead-acid high-capacity batteries require increasing vehicle size. The new high-capacity batteries (e.g., lithium-ion) enable longer operational times and provide more power for the calculations needed for autonomous navigation and operations.<br><br>*Manipulating equipment:* By combining AMRs with different manipulating equipment into a single unit, new services and material handling operations can be performed. Robotic manipulators enable AMRs not only to lift unit loads but also to pick single items. AMRs can collaborate with people and other AMRs to carry out transportation tasks jointly.<br><br>*Processing devices:* AMR's ability to navigate and operate in a dynamic environment results from its capacity to make real-time decisions. Previously, intelligent decision-making capabilities in mobile robots were limited because of the significant computational power required. With the introduction of ultra-low-power AI processors, real-time decision-making for AMRs became possible. | *Simultaneous localization and mapping:* The supportive technology for real-time navigation is responsible for creating detailed area maps of the environment and calculating an AMR's position on a map.<br><br>*Motion planning:* This component is an essential part of vision-based guidance systems and manipulation of equipment. It provides speed and turning commands to the vehicle actuators, such as wheels or manipulators, to reach the set of guidance points along the path.<br><br>*AI:* AI techniques such as vision systems and machine learning enable the identification and classification of obstacles. Fuzzy logic, neural networks, and neuro-fuzzy and genetic algorithms are examples of well-known fusion techniques that help move the robot from the starting point to the target while avoiding collisions with any obstacles along its path. Without these techniques, AMRs would react to all obstacles in the same way. The AI branches of vision, machine learning, and planning have been found to be very promising. |

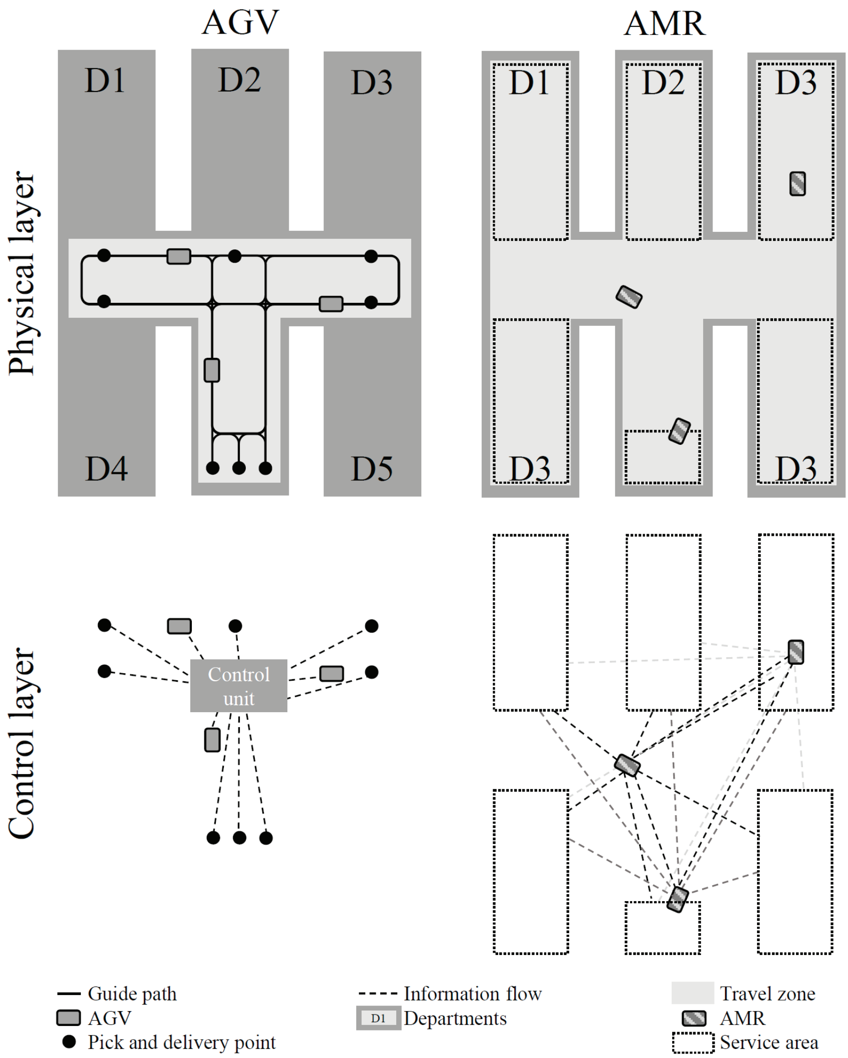



**Figure 11:** Centralized AGV control and decentralized AMR control

These capabilities are needed in hospital intralogistics. Simple small-scale systems can rely on centralized control structures to achieve optimal single-objective performance (Figure 12a). With a greater variety of operations and a more unstructured, large-scale environment such as hospitals, decentralized control can achieve high performance since multiple criteria are included in optimization (Figure 12b).

The computation time is significantly lower in decentralized than in centralized control, since the decision-making is distributed among multiple AMRs, taking only local factors into consideration (Figure 12c). This also allows a further reduction of recovery time after failure (Figure 12d) compared to centralized control, which requires a long time to evaluate the state of every single AMR after failure and to coordinate the entire fleet to recovery (Paper 5).

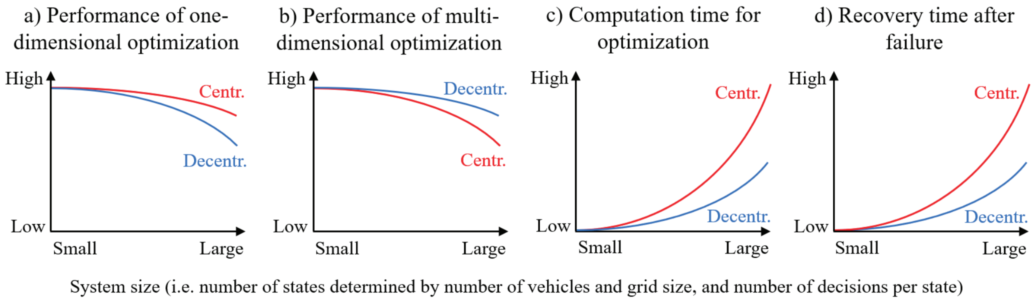



**Figure 12:** Centralized versus decentralized control in small and large systems

The following definition is proposed to summarize the capabilities and attributes of AMRs:

"Autonomous mobile robots are industrial robots that use a decentralized decision-making process for collision-free navigation to provide a platform for material handling, collaborative activities, and full services within a bounded area." (Paper 5)

The decentralization of decision-making enables significantly increasing an AMR's flexibility in navigation and performance of material handling activities in hospital intralogistics. A multiple-case study and examples from different hospitals allowed mapping how AMRs are extending the range of provision of material handling activities in hospital intralogistics. The important developments are based on Paper 3 and described in Table 4.

**Table 4:** AMRs providing material handling activities in hospital intralogistics

| Case and example | Description |
|---|---|
| 1.Sterile instrument intralogistics | • Sterile instruments are sent just-in-time to the operating theatres.<br>• Reliable transportation since AMRs can bypass obstacles, handle dynamic environments, and reach the destination pickup-and-delivery station to deliver sterile instruments.<br>• Hospital personnel can request, send, and track transportation via a tablet. |
| 2. Personalized cancer medicine transportation | • Personalized cancer medicine with a short lifetime between the two departments is transported with high-precision delivery, reliability, safety, and security.<br>• Healthcare personnel's responsibility and the amount of time involved in the transportation of medicine are reduced.<br>• Patient care and value-added time, thus enabling the return of initial investment within one year. |

| | |
|---|---|
| 3. AMRs providing telemedicine | • AMRs with teleoperating and medical equipment can be controlled by a person from far away and perform tasks in dynamic environments.<br>• Tele-operation enables a new method of using this valuable resource and eases the high risk of infectious disease transfer.<br>• Physicians and specialists can communicate with patients and perform some of their duties at a safe distance from infected patients. |
| 4. Assistive, collaborative AMRs in the hospital laboratory | • AMRs with manipulators can work alongside medical staff and help complete lab workers' repetitive tasks.<br>• They can take over a wide range of repetitive and time-consuming activities, such as preparation of medicine, loading and unloading centrifuges, pipetting and handling liquids, and picking up and sorting test tubes. |
| 5. AMRs disinfecting rooms | • AMRs with a UV-C system can autonomously disinfect hospital rooms.<br>• They can cover more surfaces compared to a fixed UV-C system and reduce the exposure of hospital personnel to bacteria.<br>• After the disinfection process, the AMRs can inform on the availability of the cleaned room and thus increase utilization of the rooms. |

AI can further support interaction between people and machines, enabling assistive or collaborative tasks. Vision-based sensors, manipulators for grabbing and handling probes, and the use of machine learning allow AMRs to learn to perform a wide variety of repetitive activities. AMRs can function as robotic co-workers in laboratories, autonomously improving both specific processes and overall performance. This allows for the reduction of workload for highly trained laboratory workers.

AMRs can be increasingly applied in the intralogistics activities within departments. For many years, mobile robots were a virtually unimaginable and practically unacceptable solution in healthcare support. People could not associate hospitals with a production environment. The increased social acceptance of AMRs allows for their integration into departments and wards.

The increased possibilities of using AMRs in hospital intralogistics raises the question: "when should AMRs be applied in hospital intralogistics?" Hospital planners need guidance in deciding when to apply which material handling systems, especially AMRs, to achieve optimal performance. A multiple case-study with three hospitals supported the development of a strategic fit framework for hospital planners, indicating high performance of material handling systems and consideration of the hospital's intralogistics (Paper 3).

The framework could be established thanks to the mapping of sterile instrument intralogistics, the identification of characteristics impacting the material handling system, and the performance measures of sterile instrument transportation. The environmental and operational characteristics set the framework dimensions. Thereby, the environmental characteristics are represented by two sets: concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation (E1) and widespread pickup and delivery points, and a low ratio of vertical to horizontal transportation (E2). The operational characteristics are represented by the two strategies described in the previous section: centralized sterile processing, decentralized storage, and scheduled deliveries with a high time buffer (O1), and centralized sterile processing, centralized storage, and just-in-time deliveries (O2).

Although the analysis of sterile instrument transportation positions the material handling systems, the performance measures (low, medium, and high) reveal the fit of the material handling systems for sterile instrument transportation (Figure 13, Paper 3).

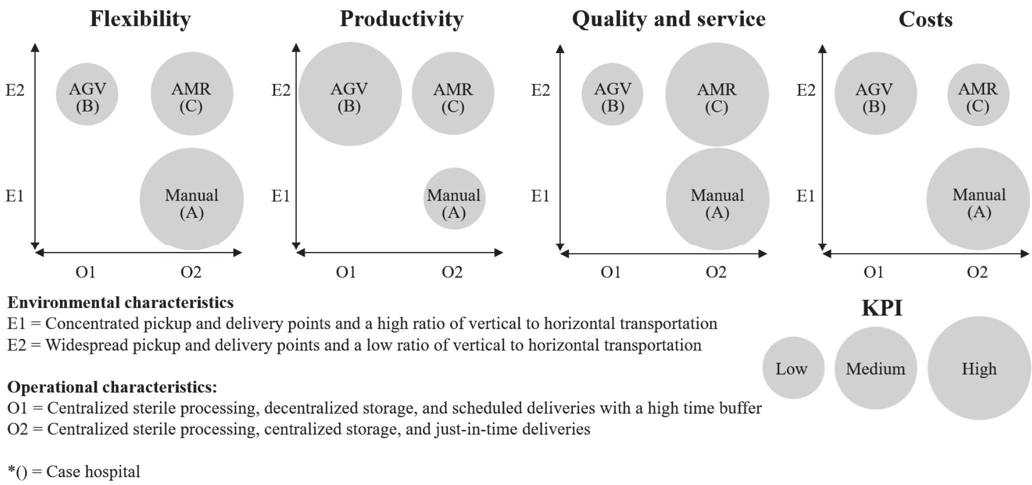



**Figure 13:** Strategic fit framework of the material handling systems for sterile instrument transportation

The strategic fit framework shows both the advantages and disadvantages of the material handling systems in sterile instrument transportation, thus exposing several interesting trade-offs. High productivity can be achieved with high automation. However, these achievements come with high flexibility and a drop in quality. Furthermore, the logistical setup must be adapted to handle long delivery times.

The introduced framework can be especially supportive in the decision-making process on a strategic level. In the planning phase of a new hospital, balancing the previously mentioned trade-offs allows for making better decisions regarding the layout, logistics system setup, and the material handling system to achieve high performance. Furthermore, it can support the decision-making process of automating sterile instrument transportation in existing hospitals by indicating which material handling systems are most suitable for the hospitals' characteristics and logistical setup.

Lastly, the strength of AMRs is their ability to navigate dynamic environments and enable high flexibility and quality in transportation. Their intelligent navigation system supports maintaining a high level of accuracy when delivering sterile instruments by bypassing obstacles and finding the fastest route. AMRs can be a useful automation alternative to the AGV system. They offer a low-cost solution and just-in-time deliveries.

The presented findings are based on the results of Papers 3, 4, and 5 and address **RQ2**: **How can AMRs support hospital intralogistics, and when should they be applied for material transportation in hospital intralogistics?** The second research question aims to identify the technological advances of AMR support in hospital intralogistics and investigate the applicability of AMRs for material transportation in hospital intralogistics. It allows identifying ideal states to achieve high performance by analyzing the relationships between material transportation characteristics and material handling systems.

**The main findings can be summarized as:**

- Both the hardware and software developments of AMRs have supported the decentralization of the decision-making process. The decentralized control outplays the centralized control in times of multiple-criteria optimization, computation time, and recovery time after failure. AMR decentralized decision-making allows reacting dynamically to changes and for each vehicle to continuously optimize itself. These capabilities are needed to face the challenges of material transportation in hospital intralogistics.
- Furthermore, AI opens up a new dimension of flexibility in navigation and providing material handling services in hospital intralogistics. AMRs can, besides transport materials, collaborate with hospital staff and take over repetitive intralogistics tasks. Based on the strategic fit framework, AMRs demonstrate suitability as a material handling solution in sterile instrument intralogistics by providing highly flexible and cost-efficient transportation.
- To apply AMRs in intralogistics, hospital planners need guidance to plan and control them to achieve high performance.

## 4.3. Planning and control of autonomous mobile robots for material transportation in hospital intralogistics

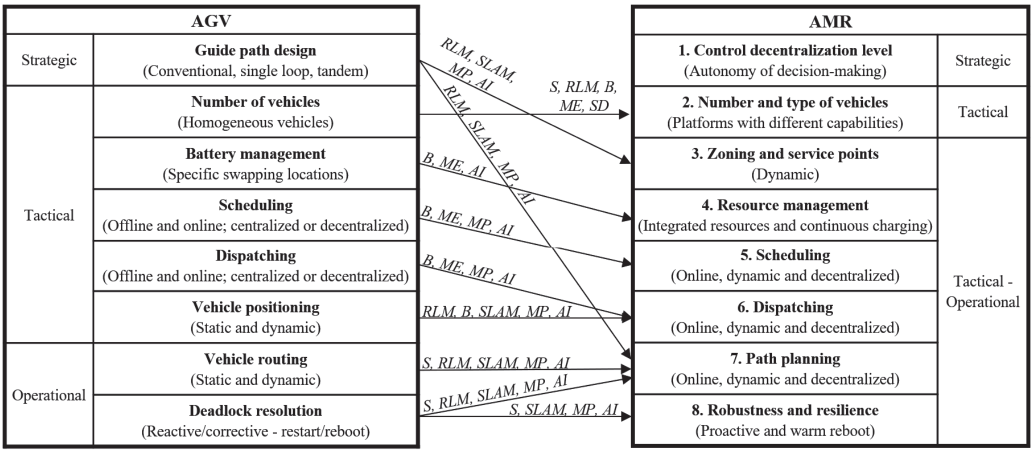
The planning and control of vehicles for material transportation has been dominated by the literature on AGVs. Vis (2006) and Le-Anh et al. (2006) distinguished key decision areas, such as guide path design and determining the number and locations of pickup and delivery points, while Bechtsis et al. (2017) provide a literature review focusing on the sustainability aspects of AGV planning and control. The recent hardware and software developments of AMRs affect these planning and control environments (Table 5). The developments and possibilities of AMRs, compared to AGV systems, require a new decision-making framework for planning and control. The following sections are based on the results and findings of Paper 5.

**Table 5:** Hardware and software developments affecting decision areas

| **Technology** | | **Description of developments affecting decision areas** |
|---|---|---|
| **Hardware** | *Sensors* | Compared to AGVs, AMRs are not "blind" but have full recognition of the environment. This affects decisions about guide path choice, collision and deadlock prediction and avoidance, and failure management. Sensing the environment allows an AMR to assist, collaborate, and interact with people and machines, thus making more decisions. |
| | *Robot locomotion mechanism* | The robot's locomotion mechanism and equipment enable the AMRs to follow paths and handle materials that AGVs cannot. The increased flexibility in the movement and positioning of AMRs requires appropriate path planning methods, and the service points should be determined correctly. Furthermore, AMRs can coordinate with multiple robots to reduce traffic. This navigation flexibility must be incorporated in path planning approaches. |
| | *Battery* | Higher energy capacity and improvements in charging methods, ranging from conventional plug-in connector power supplies to wireless power transfer, have a significant impact on the battery management of AMRs. In addition, the increased battery power encourages more intensive scheduling decisions. |
| | *Manipulating equipment* | The extended range of operations that AMRs offer must be planned over both the short and long term. This includes making new decisions on how to provide these services, developing methods on how AMRs can collaborate, and integrating their scheduling with production schedules to ensure collaboration at the right time and place. |
| | *Processing devices* | Enabling calculations of complex decisions allows for new ways of dynamic routing and scheduling, navigating and classifying, and reacting to obstacles appropriately. |
| **Software** | *Simultaneous localization and mapping* | Combining the sensing information to accurately determine the AMR's location at any time has proven to be a difficult challenge. AMR vehicles are no longer tied to a fixed guide path but instead can plan their path themselves and so freely move in predefined travel zones. The design of a guide path is therefore no longer necessary, but new decisions, such as defining zones in which AMRs can operate autonomously, must be taken. |
| | *Motion planning* | In dynamic environments, the motion planner allows the AMR to adapt to traffic or congestion by reducing speed or even by stopping the vehicle. If planned paths are no longer feasible due to an emerging obstacle, a new collision-free path will be generated. Decisions that must be made about the guide path, routing, and obstacle avoidance are all made by the AMR itself. |

| | |
|---|---|
| *AI* | As AI continues to advance, the ability to interact and collaborate with AMRs will increase. The human picker can use speech or gesturing instead of tactile communication to confirm that picking tasks have been completed or to ask for help in finding items. Like all intralogistic vehicles, AMRs must adhere to many standards (e.g., safety standards) before they can be brought to market. They must also be robust and reliable. Currently, AGV systems cannot work without human surveillance and support. Their sensitivity to a dynamic environment forces a strong focus on error and failure management by people. AI can support the recovery of AMRs after failure and find strategies to overcome such errors, making them more robust. |

The greater degree of autonomy, applicability, and flexibility provided by AMRs result in a large number of different decisions on the strategic, tactical, and operational levels that must be taken, and this number continues to grow. Thus, based on hardware and software developments, the traditional AGV decision areas are changing to the following for AMRs (Figure 14, Paper 5): 1. the control decentralization level; 2. number and type of vehicles; 3. zoning and service points; 4. resource management; 5. scheduling; 6. dispatching; 7. path planning; and 8. robustness and resilience. A detailed analysis of each decision area and description of methods to solve them can be found in Paper 5.




*Hardware - S: Sensors, RLM: Robot Locomotion Mechanism, B: Batteries, ME: Manipulating Equipment, SD: Semiconductor Devices.*
*Software - SLAM: Simultaneous Location And Mapping, MP: Motion Planning, AI: Artificial Intelligence.*

**Figure 14:** Planning and control decision areas for AMRs

The decision areas for planning and control of AMRs are valid and applicable for hospital intralogistics. Therefore, they are briefly described in this section:

<u>1. Control decentralization level</u>

The level of control decentralization is a fundamental strategic decision. In hospital intralogistics, it is necessary to determine at a strategic level which parts of the system should be controlled in a centralized or decentralized manner. Deciding on the control level affects all subsequent decisions in scheduling, zoning, path planning, etc.

2. Number and type of vehicles

AMRs provide a wide range of material handling services in hospital intralogistics, and thus, they differ in equipment, size, or function within a single fleet. The number of vehicles and type of equipment must be determined at the tactical level.

3. Zoning and service points

Determining the zones in hospital intralogistics has a significant impact on AMR performance. Dividing the service areas into several zones with single or multiple vehicles can improve costs and productivity performance. Furthermore, limiting the operating area for each vehicle improves the system's overall responsiveness since only short trips are performed and vehicles are available more quickly.

4. Resource management

The AMR platform allows for a wide range of resources for use and sharing. For instance, in hospital intralogistics, AMRs can share the task of disinfecting with cleaning equipment. The decision-making processes of location planning for equipment storing and scheduling equipment are essential for their optimal utilization and thus to high AMR productivity.

5. Scheduling

AMRs can provide many different material handling services, such as lifting, transporting, assisting, collaborating, interacting, etc., in hospital intralogistics. These tasks must be scheduled simultaneously with unit loads, equipment, and people. Decentralized scheduling methods in which AMRs negotiate or bid for tasks can be especially useful in hospital intralogistics. Decentralized scheduling distributes the computation and scheduling problems with many constraints, such as a high variety of services, and large-scale hospital areas can be included.

6. Dispatching

Time is critical in hospital intralogistics. Therefore, dispatching methods that allow AMRs to be close to the point of demand before an actual need is announced are of particular interest. The increased flexibility of accessing a wider area in hospitals (e.g., departments) and free positioning due to autonomous navigation create new opportunities for positioning and cruising while an AMR is idle. Each AMR will optimize its available time based on historical data and on data shared with neighboring AMRs. Continuous communication and negotiations will optimize the AMR’s ability to react quickly to demand.

7. Path planning
AMRs autonomously plan a deadlock-free path, with little congestion delay from the start to the goal position. Common path planning methods such as the A* Algorithms, which try to find the shortest path, will not necessarily result in the shortest travel time. Path planning methods in hospitals should include to a larger extent the factors of congestion and high traffic to not hinder AMR performance and increase travel time.

8. Robustness and resilience
A crucial attribute of AMRs is operating without human surveillance or interference and recovering after failure, thus guaranteeing a robust and resilient system. In hospital intralogistics, high reliability of AMRs performing tasks is required since patient safety and health can be affected.

Analyzing the literature on methods and approaches for planning and control of AMRs in hospital intralogistics enabled the identification of research gaps. Methods and approaches have been mainly developed outside of the hospital intralogistics environment. New approaches are needed to include the characteristics of hospital intralogistics. Therefore, here are some promising approaches:

- Agent-based simulations can support modeling different traffic scenarios with human interaction and analyze different path planning approaches to increase safety, quality, and transportation performance; and
- SOQN modeling can support determining the number of vehicles while minimizing customer waiting times and improving utilization and cost performance.

Based on the findings of the SLR, SOQN modeling has been further investigated to plan autonomous material transportation in hospital intralogistics (Paper 6). This modeling approach allows the integration of hospital intralogistics, the material handling processes, and the AMR's distinctive travel behavior.

The AMR material handling processes on each floor are modelled as a closed queue network (Figure 15). Integrating the closed queue network model of the hospital floor in the SOQN model allows representing the intralogistics processes of a hospital with multiple floors (Figure 16). The intralogistics processes in the SOQN model are initialized by synchronizing the orders of the open queue with the AMRs in the closed queue. There are multiple types of orders: pickup within one floor, delivery within one floor, both pickup and delivery within one floor, and pickup from one floor and delivery on another.

The discrete event simulation model allowed testing of the SOQN model and captured the external waiting and throughput times. Furthermore, the SOQN model was compared with an agent-based simulation model. These provide nearly the same results for analyzing the AMR fleet and hospital layout configurations. A significant difference can be observed between the time used to model and simulate different transportation scenarios. The SOQN model and discrete event simulation can provide quick results, which are especially useful at an early stage of a project. This allows investigating many different fleet and layout configurations in a short time and so to decide which is the most appropriate for autonomous material transportation.

The SOQN modeling and simulation approach supports hospital planners in determining the number of vehicles and in understanding hospital layout configurations, such as increased number of lifts and department size.

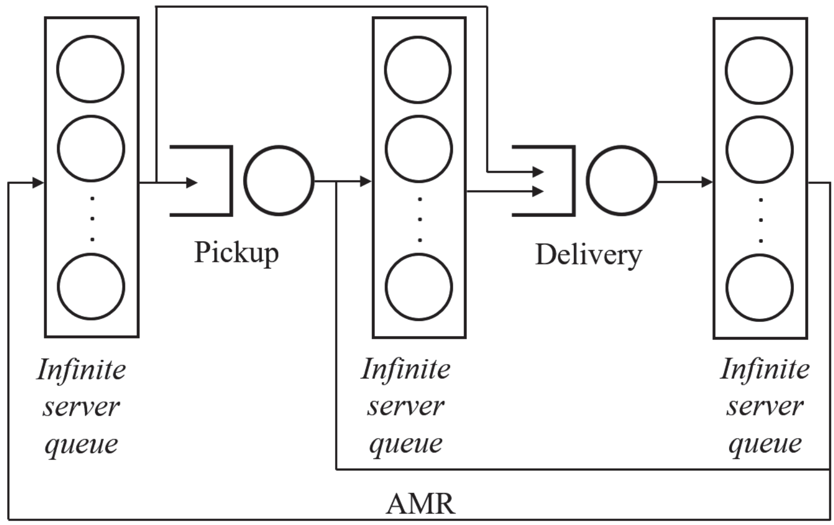



**Figure 15:** Closed queue network model of the hospital floor

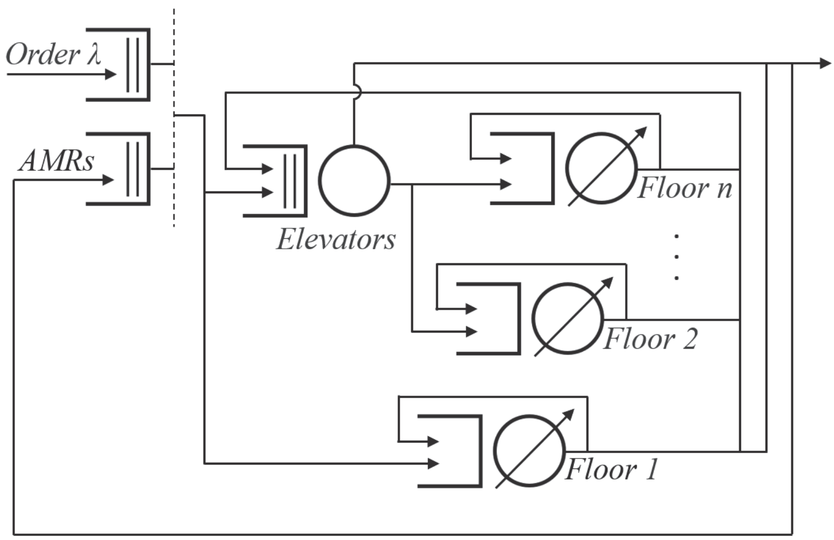



**Figure 16:** SOQN model of a hospital with multiple floors

The presented findings are based on the results of Papers 5 and 6 and address **RQ3: How should AMRs be planned and controlled for material transportation in hospital intralogistics?** The third research question aims to introduce an AMR planning and control framework to guide hospital planners in the decision-making process to achieve optimal performance. Furthermore, it provides methods for the decision-making process to apply AMRs in hospital intralogistics.

**The main findings can be summarized as:**

- The technological advances of AMRs affect the current planning and control decisions of vehicles for intralogistics and require a new decision-making framework. The greater degree of autonomy, applicability, and flexibility provided by AMRs results in many different decisions on the strategic, tactical, and operational levels that must be made, and this number continues to grow.
- Based on the hardware and software developments, a planning and control framework for AMRs has been introduced with the decision areas of: 1. the control decentralization level; 2. number and type of vehicles; 3. zoning and service points; 4. resource management; 5. scheduling; 6. dispatching; 7. path planning; and 8. robustness and resilience.
- The SLR revealed that methods and approaches have been mainly developed outside of the hospital intralogistics environment. New approaches are needed to include the characteristics of hospital intralogistics. Thereby, SOQN supported filling the identified gap. The model can support hospital planners in determining the number of vehicles and understanding the tradeoffs of the hospital layout configuration.

## 4.4. Discussion of the road towards autonomous material transportation

So how can hospitals move towards autonomous material transportation and address the overall healthcare challenges posed? Following a four-year research study on these topics, a few reflections and recommendations can be offered.

Hospital planners emphasize that hospitals cannot continuously expand departments to free up capacity for patient care. Compared to other intralogistics environments, such as manufacturing or warehousing, in which a high increase in demand can easily justify new production lines or automated material handling systems, hospitals must seek different alternatives instead of building new departments and hiring hospital staff. New methods are needed to increase flexibility, productivity, quality, service, and reduce costs, and so face overall healthcare challenges. The latest studies show that, especially in hospital intralogistics, there is vast potential for increasing performance (Moons et al., 2019).

There are many methods and practices in hospital intralogistics to transport materials in hospitals (Volland et al., 2017). Not standardizing the material handling processes and centralizing information flow will hinder the automation processes of the material flows in the hospitals. Hospitals can significantly benefit from information systems' technological progress and the emergence of new information technology tools (Ageron et al., 2018). The different actors along the supply chain communicate with separate communication systems, e.g., manually by phone, email, and scan, or automatically through the enterprise resource planning system, as seen in the case hospitals. Not using a common or at least an integrated information and communication system will lead to incoherent information sharing along the supply chain, as seen in the case study (Paper 1). Less information sharing leads to more uncertainties in the hospital supply chain (Chen et al., 2013). Material transportation in hospital intralogistics requires high flexibility to work and handle uncertainties. However, high flexibility is often accompanied by high costs and low productivity. Streamlining the material flow, standardizing the material transportation, and linking the information along the supply chain can help find patterns and reveal insights to improve hospital intralogistics.

However, hospitals' core competencies are providing healthcare and not continuously optimizing hospital intralogistics and material handling systems. Keeping the hospital intralogistics at a constant optimal level is time- and cost-intensive (Volland et al., 2017). Hospitals maintain their material handling systems but struggle to improve and optimize them continuously (Paper 2). The AGV system at one of the case hospitals has almost received improvements over several years, while at the same time, the hospital went through several changes. Fewer investigations and analyses of the AGV performances and, additionally, changes in the hospital intralogistics over time will reduce material transportation performance. Increasing the number of AGVs or changing the AGV schedule can have a short-term positive effect on AGV performance (Rimpiläinen et al., 2008). Still, without continuous optimization, it will return to the status quo after a period of time. There is a need for more intelligent material handling systems in hospitals that not only automate the material transportation but also continuously optimize it.

AMRs are changing how material handling services are provided in hospital intralogistics (Paper 3). Besides the standard material handling tasks of loading, transporting, and unloading, AMRs can collaborate in laboratories, disinfect rooms, and provide telemedicine. Furthermore, AMRs can enter departments and deliver materials closer to the point-of-use because of their intelligent navigation system and smaller size. Integrating AMRs more deeply into departments can help hospitals increase efficiency and meet demand (Kriegel et al., 2021). Currently, the last 50 meters, which refers to the innermost area of a hospital department, have not undergone much automation. The AMRs' ability to work in dynamic environments alongside patients, nurses, doctors, and visitors can lower the need for manual transportation in the last 50 meters and in the entire hospital. AMRs demonstrate suitability as a material handling solution in hospital intralogistics by providing highly flexible and cost-efficient transportation (Paper 4). Investigating sterile instrument transportation – one of the most complex material transportations in hospital intralogistics – allows for transferring the knowledge to other material flows and transportation. For instance, food can be transported in smaller batches to a group of patients or the individual patient by AMRs instead of being transported in big batches in front of the department by AGVs. Smaller deliveries can increase flexibility in providing food and individualize meals to fit the patient's diet or restrictions. This can improve the quality of stay for the patient. Furthermore, it reduces the time needed to distribute food and collects dirty dishes for hospital staff.

The technological advances of AMRs have significantly helped to achieve operational flexibility. Taking decisions autonomously thanks to AI promotes the decentralization of material handling activities. The aspiration of AMR's decentralized decision-making is to adapt to changes and allow each vehicle to optimize itself continuously (Paper 5). However, it is still difficult to estimate the long-term benefits that AMRs will bring and determine how they should be deployed to reap maximum benefits. AMRs are foremost studied in manufacturing and warehousing to provide decision support for planning and control of AMRs in intralogistics. This can be traced back to the strong promotion of Industry 4.0 for decentralizing material handling (Furmans et al., 2018). The SLR exposed that other intralogistics environments, including hospitals, are still far behind in this matter. The introduced SOQN model can support the planning of autonomous material transportation in hospital intralogistics (Paper 6). Simultaneously addressing different decision areas such as the number of vehicles, hospital service points, and hospital layout can additionally improve transportation performance.

AMRs can pave the road to move material transportation from manual over automated to autonomous. The decentralized control, with the support of AI, can help keep the intralogistics at an optimal level and allow hospital staff to focus on patient care.

## 4.5. Contributions to theory

This research study presents several theoretical contributions addressing relevant gaps in current theory. This section highlights these and further discusses their implications. Table 6 presents an overview of the key contributions in the six appended papers.

**Table 6:** An overview of the key theoretical contributions

| | Paper | | | | | |
|---|---|---|---|---|---|---|
| **Contribution to theory** | 1 | 2 | 3 | 4 | 5 | 6 |
| Identified characteristics for material transportation in hospital intralogistics | X | | X | | | |
| Defined KPIs for sterile instrument transportations | | | | X | | |
| Introduced agent-based simulation modelling for material handling system in hospital intralogistics | | X | | | | |
| Developed strategic fit framework of the material handling systems for sterile instrument transportation | | | | X | | |
| Proposed definition for AMRs in intralogistics | | | | | X | |
| Developed planning and control framework for AMRs in intralogistics | | | | | X | |
| Identified dominant approaches and methods in the literature on AMR planning and control | | | | | X | |
| Identified future research for AMRs in hospital intralogistics | | | | | X | |
| Developed SOQN model for autonomous material transportation in hospital intralogistics | | | | | | X |

The first contribution of this research study is the identification of characteristics for material transportation in hospital intralogistics. Due to different transportation methods, standards and best practices of how to transport materials in hospitals hardly exist (Volland et al., 2017). Analyzing the material transportation patterns allows closing the gap and provides insights about these transportations. The identified material transportation characteristics enable further development of decision support methods for hospital planners.

Second, defining KPIs for sterile instrument transportations allows for generalizing the information of several case hospitals and deriving the transportation requirements for material transportation. The variety of KPIs presented capture the requirements from different aspects. Furthermore, the KPI provides a detailed description of the transportation requirements and possibilities for evaluating the current material handling systems for material transportation. The material handling systems assessment allows hospital planners to improve material transportation with regard to flexibility, productivity, quality, service, and cost performance.

The agent-based simulation model uses and relies on historical data obtained from the AGV system, which contains a considerable amount of information representing “real” material flow. Compared to other industries, enterprise resource planning systems or tracking systems are less common and less integrated into hospitals. A strength of this simulation model is that it can investigate goods that usually have limited information available, such as catering or waste. Single material flow can be further investigated and analyzed. The model can be easily adapted for use in other hospitals and can consider several additional inputs.

Next, the strategic fit framework provides insights into material handling systems' ideal states in sterile instrument transportation to achieve high performance. The framework differs from earlier mapping frameworks in that it considers key hospital characteristics. The strategic fit framework based on the three case hospitals shows both the advantages and disadvantages of the material handling systems in sterile instrument transportation and helps expose several interesting trade-offs.

The SLR supported structuring and analyzing the literature and contributed to the literature in several ways. A definition of AMRs in intralogistics was introduced to unify and direct future literature. The extended review provides knowledge on how AMR technological advances affect planning and control decisions. Therefore, an AMR planning and control framework was presented to guide hospital planners in the decision-making process and support them in achieving optimal performance. Decision areas with applied objectives and approaches have been identified based on the literature. Lastly, an agenda for future research was introduced, presenting research priorities and directions.

The final key contribution is the development of the SOQN model for hospital intralogistics. The model can integrate crucial hospital layout characteristics and the AMR's distinctive travel behavior. The model supports hospital planners in the decision-making process and provides comparative results in a short period of time.

## 4.6. Implications for practitioners

Theoretical contributions aside, this research study's findings should also have practical relevance for practitioners interested in moving towards autonomous material transportation and applying AMRs in hospital intralogistics. The research study supports hospital planners in several frameworks, methods, and procedures.

Mapping material transportation in hospital intralogistics is crucial and a starting point for every investigation. This research study explains the step-by-step approach to map material transportation and further derive transportation patterns. Analyzing and comparing the transportation patterns among several materials can help hospital planners decide which materials can be transported with the same material handling system. Furthermore, characterizing the material transportation supports applying the different frameworks and models introduced in this research study.

The strategic fit framework indicates foremost the strengths and weaknesses of different material handling systems in material transportation. However, this framework can help hospital planners compare and evaluate the material handling systems in their hospital intralogistics and can indicate potential improvement areas. Our findings of material transportation requirements and challenges can additionally stimulate improvements. The proposed KPIs for material transportation can support measuring progress.

The potential and application areas of AMRs in intralogistics are enormous. Therefore, policymakers should provide regulations and guidelines for patient security and safety in areas in which the AMRs operate. Furthermore, numerous cameras in the AMRs can potentially share a patient's identity and data. Policymakers and AMR providers have to secure patients' identities and ensure that their data are secured.

This research study presents different cases and examples of AMRs applied in intralogistics. Furthermore, it explains the capabilities of AMRs providing material handling services. Hospital planners should be inspired to use AMRs in their hospital intralogistics and, in the best case, find new application areas.

After finding an application area in hospital intralogistics, this research study can support hospital planners in planning and control from the strategic to the operational levels. The presented framework guides the hospital planner through the necessary decisions and indicates methods to make these decisions. Furthermore, the introduced decision support methods can support achieving high transportation performance and provide advice on a hospital's layout.

# 5 Conclusion

This chapter summarizes the research study and provides concluding remarks. Furthermore, the research limitations are highlighted and recommendations for future research are presented.

## 5.1. Summary

The objective of this research study was to support hospital planners in applying AMRs in hospital intralogistics and thus move towards autonomous material transportation in hospital intralogistics. A mixed-method approach was applied, combining elements of qualitative and quantitative research to produce a richer and more comprehensive understanding of a research area:

- Case research provided in-depth knowledge about material transportation in hospitals and allowed for an exploration of key characteristics, requirements, and challenges;
- Simulation modeling enabled investigating different hospital intralogistics scenarios and testing the SOQN model;
- The SLR supported aligning existent research and uncovering areas of AMR planning and control; and
- SOQN modeling provided decision support to plan AMRs in hospital intralogistics.

Using these research methods in the investigations in the appended papers allowed answering the following three RQs:

> **RQ1: What are the characteristics, requirements, and challenges of material transportation in hospital intralogistics?**

The findings of Papers 1, 2, and 4 indicate that environmental and operational characteristics have a strong impact on material transportation. The KPIs for material transportation allowed establishing a comprehensive overview of the requirements and working towards them to achieve high performance. Material transportation and applied material handling systems face various problems, such as standardization of transportation, handling several material flows, and dynamic environments.

The findings addressing RQ1 support characterizing material transportation and provide insights on which decision support methods can be built on. Furthermore, they highlight the need for more autonomous material handling systems in hospitals that can adapt to material transportation characteristics, meet a variety of requirements, and continuously optimize themselves to face current challenges.

> **RQ2: How can AMRs support hospital intralogistics, and when should they be applied for material transportation in hospital intralogistics?**

The findings of Papers 3, 4, and 5 revealed that the hardware and software developments of AMRs have supported the decentralization of the decision-making process, which facilitates reacting dynamically to changes and continuous self-optimization. AI opens a new dimension of flexibility in navigation and providing material handling services in hospital intralogistics. The developed strategic fit framework indicates that AMRs can provide highly flexible and cost-efficient material transportation.

The findings addressing RQ2 help explain the capabilities and applicability of AMRs in hospital intralogistics. The decentralization of decision-making facilitated by technological advances plays a crucial role in integrating the AMRs closer to the point-of-use. However, hospital planners need guidance to plan and control AMRs in hospital intralogistics to achieve high performance.

> **RQ3: How should AMRs be planned and controlled for material transportation in hospital intralogistics?**

The findings of Papers 5 and 6 demonstrate that the technological advances of AMRs affect the current planning and control decisions of vehicles in intralogistics. A planning and control framework for AMRs has been introduced based on hardware and software developments. The SOQN modeling and simulation approach supported hospital planners in determining the number of vehicles and understanding hospital layout configuration, such as increased lifts and department size.

The findings addressing RQ3 support organizing and unifying the knowledge of AMR planning and control in intralogistics. Furthermore, it helped analyze the literature on methods and approaches for planning and control of AMRs in hospital intralogistics. The SOQN modeling and simulation approach helped fill some identified research gaps.

## 5.2. Concluding remarks

Hospital planners need new methods to increase flexibility, productivity, quality, service, reduce costs, and face overall hospital challenges. Great potential lies in improving intralogistics. However, hospitals need solutions that continuously support the improvement of hospital intralogistics, and AMRs might be one. The vision of AMRs in hospital intralogistics is to help and move from manual over automated to autonomous material transportation. Decentralized control supported by AI can especially support keeping the intralogistics at an optimal level and allowing hospital staff to focus on patient care.

Finally, this research study presented new application areas of AMRs in intralogistics to improve hospital logistics and patient care. AMRs can support the increased usage of telemedicine connecting physicians and specialists with patients around the globe. Furthermore, AMRs can assist and collaborate in hospital laboratories. They can take over a wide range of repetitive and time-consuming laboratory activities. Integrating deeper into the department allows AMRs to disinfect rooms and so increase their availability.

This new application area should be investigated to further increase hospital performance and improve patient care.

## 5.3. Research limitations

No research is conducted without limitations. This chapter highlights limitations of significant concern.

Due to time constraints, not all material flows and material transportation have been investigated. To map all of them and so get access to all departments, documents, etc., is not feasible in a four-year research period. Therefore, the research study focused especially on material flows such as food, linens, medical supplies, waste, and put even more focus on sterile instruments, since it is known as one of the most difficult and complex material flows. The assumption was that investigating the difficult and complex ones can provide knowledge that is transferrable to other material flows as much as possible. However, the developed knowledge was not tested on other material flows besides sterile instruments.

Furthermore, not all material handling systems found in hospitals were investigated in this study. The strategic fit framework indicates only the investigated material handling systems. Therefore, the applicability of the framework is limited. The decision support methods have been tested and compared with simulation. The findings of the decision support methods have been presented and discussed with hospitals. However, due to time constraints, this research study has not investigated further if the introduced methods provide the desired results after implementing and operating AMRs in hospitals.

One of the present study's limitations is its exclusive focus on Scandinavian hospitals. Each hospital's layout and its personnel's degree of acceptance of robots significantly impacted decisions regarding material handling systems. There were plans to visit hospitals in Asia and include them in the research study. The outbreak of Covid-19 restricted travel and limited the involvement of several case hospitals. This further affects the generalizability of the findings. The study is based on a few case hospitals. However, the research study provides a rigorous research design and many details about the involved case hospitals to increase generalizability.

The pandemic further limited the research study in several ways. The case hospital's time for supporting the investigation was reduced significantly. However, virtual meetings helped follow-up on important discussions and in providing information and documents. Furthermore, the research study interviewed mainly hospital planners and staff connected to logistics or production areas. Physicians, nurses, and patients could not be interviewed.

## 5.4. Future research

The developed knowledge of this research study should be tested on different material flows and material transportation in hospital intralogistics. The material flows and material transportation of food, linens, medical supplies, and waste have similar characteristics and provide a suitable start for applying the frameworks and methods. Testing frameworks and methods will support confirmation or improve their applicability. Furthermore, it should be investigated how AMRs can handle many different material transportations and various types of hospital layouts to achieve high performance.

The ratio of vertical to horizontal transportation significantly impacts material transportation since the material handling systems are especially suitable in some specific ratios. Future research should investigate which specific ratios the material handling systems are pivotal for material transportation performance.

Investigating AMRs applied in different hospitals worldwide can help analyze how different cultures accept AMRs that work closely with hospital staff and patients. The association and acceptance of robotics in hospitals are still critical. However, there is a great variety of AMRs in hospital intralogistics and other environments such as malls, airports, and hotels. The lessons learned from the different environments can support improving collaboration and acceptance of AMRs.

Furthermore, new approaches are needed to include the characteristics of hospital intralogistics in the decision areas at the control decentralization level, number and type of vehicles, zoning and service points, resource management, scheduling, dispatching, path planning, and robustness and resilience to achieve high performance. Paper 5 provides a detailed research agenda for each decision area.

Finally, more research on autonomous material transportation and AMRs is needed to support hospital intralogistics in the next pandemic. AMRs can support infection control by disinfecting areas and with material transportation in infection-isolated areas.

Therefore, future research should focus on path planning to disinfect areas and reduce virus spread when entering and leaving infection-isolated areas.

# References


Abdulsalam, Y., Gopalakrishnan, M., Maltz, A., & Schneller, E. (2015). Health care matters: Supply chains in and of the health sector. *Journal of Business Logistics* 36(4).

Ageron, B., Benzidia, S., & Bourlakis, M. (2018). Healthcare logistics and supply chain–issues and future challenges. Paper presented at the Supply Chain Forum: An International Journal.

Angerer, S., Strassmair, C., Staehr, M., Roettenbacher, M., & Robertson, N. M. (2012). Give me a hand—The potential of mobile assistive robots in automotive logistics and assembly applications. *IEEE International Conference on Technologies for Practical Robot Applications*, 111-116.

Augusto, V., & Xie, X. (2009). Redesigning pharmacy delivery processes of a health care complex. *Health care management science*, 12(2), 166-178.

Azadeh, K., De Koster, R., & Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. *Transportation Science*, 53(4), 917-945.

Banerjea-Brodeur, M., Cordeau, J.-F., Laporte, G., & Lasry, A. (1998). Scheduling linen deliveries in a large hospital. *Journal of the Operational Research Society*, 49(8), 777-780.

Barratt, M., Choi, T. Y., & Li, M. (2011). Qualitative case studies in operations management: Trends, research outcomes, and future research implications. *Journal of operations management*, 29(4), 329-342.

Baveja, G., Muralidhar, S., & Aggarwal, P. (2000). Hospital waste management–an overview. *Hospital today*, 5(9), 485-486.

Bazeley, P. (2013). Qualitative data analysis: Practical strategies. *Sage*.

Bell, E., Bryman, A., & Harley, B. (2018). Business research methods: Oxford university press, Oxford.

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(3), 273-293.

Bertrand, J. W. M., & Fransoo, J. C. (2016). Modelling and simulation. *Research Methods for Operations Management*, 306-346.

Blanchard, B. S., Fabrycky, W. J., & Fabrycky, W. J. (1990). Systems engineering and analysis (Vol. 4): Prentice hall Englewood Cliffs, NJ.

Blenkharn, J. (2005). Safe disposal and effective destruction of clinical wastes. *Journal of Hospital Infection*, 60(4), 295-297.

Bourlakis, M., Clear, F., & Patten, L. (2011). Understanding the UK hospital supply chain in an era of patient choice. *Journal of Marketing Management*, 27(3-4), 401-423.

Brunner-La Rocca, H.-P., Peden, C. J., Soong, J., Holman, P. A., Bogdanovskaya, M., & Barclay, L. (2020). Reasons for readmission after hospital discharge in patients with chronic diseases—Information from an international dataset. *PloS one*, 15(6), e0233457.

Buchanan, D., & Bryman, A. (2009). The Sage handbook of organizational research methods: Sage Publications Ltd.

Byrnes, J. (2004). Fixing the healthcare supply chain. Harvard Business School: Working Knowledge.

Böhme, T., Williams, S. J., Childerhouse, P., Deakins, E., & Towill, D. (2016). Causes, effects and mitigation of unreliable healthcare supplies. *Production Planning & Control*, 27(4), 249-262.

Chaerul, M., Tanaka, M., & Shekdar, A. V. (2008). A system dynamics approach for hospital waste management. *Waste management*, 28(2), 442-449.

Chan, F., Ip, R., & Lau, H. (2001). Integration of expert system with analytic hierarchy process for the design of material handling equipment selection system. *Journal of Materials Processing Technology*, 116(2-3), 137-145.

Chen, D. Q., Preston, D. S., & Xia, W. (2013). Enhancing hospital supply chain performance: A relational view and empirical test. *Journal of operations management*, 31(6), 391-408.

Chikul, M., Maw, H. Y., & Soong, Y. K. (2017). Technology in healthcare: A case study of healthcare supply chain management models in a general hospital in Singapore. *Journal of Hospital Administration*, 6(6), 63-70.

Chobin, N., & Swanson, K. (2012). Putting patient safety first: the sterile processing department and healthcare technology management. *Biomedical instrumentation & technology* (1), 27-31.

Chopra, S., Meindl, P., & Kalra, D. V. (2013). Supply chain management: strategy, planning, and operation (Vol. 232): Pearson Boston, MA.

Cook, T. D., Campbell, D. T., & Day, A. (1979). Quasi-experimentation: Design & analysis issues for field settings (Vol. 351): Houghton Mifflin Boston.

Creswell, J. W. (2012). Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative (Vol. Research. 4th ed.). Boston: Pearson.

Croom, S. (2009). Introduction to research methodology in operations management. *Researching operations management*, 43-83.

Dictionary, online. (2021). requirement Meaning in the Cambridge English Dictionary. [online]. Retrieved from https://dictionary.cambridge.org/dictionary/english/requirement

Dieleman, J. L., Squires, E., Bui, A. L., Campbell, M., Chapin, A., Hamavid, H., . . . Reynolds, A. (2017). Factors associated with increases in US health care spending, 1996-2013. *Jama*, 318(17), 1668-1678.

Dinwoodie, J., & Xu, J. (2008). Case studies in logistics: a review and tentative taxonomy. *International Journal of Logistics: Research and Applications*, 11(5), 393-408.

Donaldson, L. 2001. The Contingency Theory of Organizations. Thousands Oaks, CA: Sage Publications.

Eggert, A. A., Bowers, K. L., Smulka, G. J., Emmerich, K. A., Iwanski, A. L., & Quam, E. F. (1999). An overhead specimen handling system for variable workloads. *Journal of medical systems*, 23(1), 1-11.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of management journal*, 50(1), 25-32.

Fatimah, U. Z. A. U., Boo, H. C., Sambasivan, M., & Salleh, R. (2011). Foodservice hygiene factors—The consumer perspective. *International Journal of Hospitality Management*, 30(1), 38-45.

Fernandes, C. M., Worster, A., Eva, K., Hill, S., & McCallum, C. (2006). Pneumatic tube delivery system for blood samples reduces turnaround times without affecting sample quality. *Journal of emergency nursing*, 32(2), 139-143.

Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. *European Journal of Operational Research*.

Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., & Strandhagen, J. O. (2020). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research*, 1-19.

Furmans, K., & Gue, K. R. (2018). A Framework for Modeling Material Handling with Decentralized Control. 15th IMHRC Proceedings (Savannah, Georgia. USA – 2018), 17.

Fynes, B., Coughlan, P., Boer, H., Holweg, M., Kilduff, M., Pagell, M., . . . Voss, C. (2015). Making a meaningful contribution to theory. *International Journal of Operations & Production Management,* 35, 1231-52.

Giancotti, M., Guglielmo, A., & Mauro, M. (2017). Efficiency and optimal size of hospitals: Results of a systematic search. *PloS one*, 12(3).

Granlund, A., & Wiktorsson, M. (2014). Automation in internal logistics: strategic and operational challenges. *International Journal of Logistics Systems and Management*, 18(4), 538-558.

Grasselli, G., Pesenti, A., & Cecconi, M. (2020). Critical care utilization for the COVID-19 outbreak in Lombardy, Italy: early experience and forecast during an emergency response. *Jama*, 323(16), 1545-1546.

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

Haag, L., & Sandberg, E. (2020). Exploring key logistics characteristics supporting embeddedness in retailers' geographical expansion. *The International Review of Retail, Distribution and Consumer Research*, 30(1), 1-26.

Halldorsson, A., & Aastrup, J. (2003). Quality criteria for qualitative inquiries in logistics. *European Journal of Operational Research*, 144(2), 321-332.

Hernández, C., Bermejo-Alonso, J., & Sanz, R. (2018). A self-adaptation framework based on functional knowledge for augmented autonomy in robots. *Integrated Computer-Aided Engineering*, 25(2), 157-172.

Hichri, B., Fauroux, J., Adouane, L., Doroftei, I., & Mezouar, Y. (2019). Design of cooperative mobile robots for co-manipulation and transportation tasks. *Robotics and Computer-Integrated Manufacturing*, 57, 412-421.

Isik, F. (2010). An entropy-based approach for measuring complexity in supply chains. *International Journal of Production Research*, 48(12), 3681-3696.

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of mixed methods research*, 1(2), 112-133.

Karlsson, C. (2016). Research in operations management. *Research Methods for Operations Management*, 23-61.

Ketokivi, M., & Schroeder, R. (2004). Manufacturing practices, strategic fit and performance. *International Journal of Operations & Production Management*, 24 (1/2), 171-191.

Kriegel, J., Rissbacher, C., Reckwitz, L., & Tuttle-Weidinger, L. (2021). The requirements and applications of autonomous mobile robotics (AMR) in hospitals from the perspective of nursing officers. *International Journal of Healthcare Management*, 1-7.

Kudo, Y., Yoshimura, E., Shahzad, M. T., Shibuya, A., & Aizawa, Y. (2012). Japanese professional nurses spend unnecessarily long time doing nursing assistants' tasks. *The Tohoku journal of experimental medicine*, 228(1), 59-67.

Kulwiec, R. A. (1985). Basic materials handling concepts. *Materials Handling Handbook*, 1-18.

Lambert, D. M., & Stock, J. R. (1993). Strategic logistics management (Vol. 3): Irwin Homewood, IL.

Landry, S., & Philippe, R. (2004). How logistics can service healthcare. Paper presented at the Supply Chain Forum: An International Journal.

Lapierre, S. D., & Ruiz, A. B. (2007). Scheduling logistic activities to improve hospital supply systems. *Computers & Operations Research*, 34(3), 624-641.

Le-Anh, T., & De Koster, M. (2006). A review of design and control of automated guided vehicle systems. *European Journal of Operational Research*, 171(1), 1-23.

Lewis, M. W. (1998). Iterative triangulation: a theory development process using existing case studies. *Journal of operations management*, 16(4), 455-469.

Maidstone, R. (2012). Discrete event simulation, system dynamics and agent based simulation: Discussion and comparison. *System*, 1(6), 1-6.

Mattaboni, P. J. (1987). Autonomous mobile robot. In: Google Patents.

Mayring, P. (2004). Qualitative Content Analysis. In *A Companion to Qualitative Research* (pp. 159–176). London: Sage Publications.

McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of operations management*, 11(3), 239-256.

Meline, T. (2006). Selecting studies for systemic review: Inclusion and exclusion criteria. *Contemporary issues in communication science and disorders*, 33(Spring), 21-27.

Meller, R. D., Nazzal, D., & Thomas, L. M. (2018). Collaborative Bots in Distribution Centers. 15th IMHRC Proceedings (Savannah, Georgia. USA – 2018), 17.

Mentzer, J. T., & Kahn, K. B. (1995). A framework of logistics research. *Journal of business logistics*, 16(1), 231.

Mentzer, J. T., & Konrad, B. P. (1991). An efficiency/effectiveness approach to logistics performance analysis. *Journal of business logistics*, 12(1), 33.

MHI. (2021). Material handling Definition. Retrieved from https://www.mhi.org/fundamentals/material-handling

MHIA. (2011). Sentiments Towards Automation in Warehousing, Distribution and Manufacturing: MHIA, Charlotte, NC.

Michelon, P., Cruz, M. D., & Gascon, V. (1994). Using the tabu search method for the distribution of supplies in a hospital. *Annals of Operations Research*, 50(1), 427-435.

Moons, K., Waeyenbergh, G., & Pintelon, L. (2019). Measuring the logistics performance of internal hospital supply chains–a literature study. *Omega*, 82, 205-217.

Nachtmann, H., & Pohl, E. A. (2009). The state of healthcare logistics. Cost and quality improvement opportunities. *Center for Innovation in Healthcare Logistics*, University of Arkansas

Ozcan, Y. A. (2005). Quantitative methods in health care management: techniques and applications (Vol. 4): John Wiley & Sons.

Ozturk, O., Begen, M. A., & Zaric, G. S. (2014). A branch and bound based heuristic for makespan minimization of washing operations in hospital sterilization services. *European Journal of Operational Research*, 239(1), 214-226.

Papalexi, M., Bamford, D., & Dehe, B. (2016). A case study of kanban implementation within the pharmaceutical supply chain. *International Journal of Logistics Research and Applications*, 19(4), 239-255.

Peng, J., Wu, X., Wang, R., Li, C., Zhang, Q., & Wei, D. (2020). Medical waste management practice during the 2019-2020 novel coronavirus pandemic: Experience in a general hospital. *American journal of infection control*, 48(8), 918-921.

Poulin, E. (2003). Benchmarking the hospital logistics process: A potential cure for the ailing health care sector. *CMA Management*, 77(1), 20-23.

Ravankar, A., Ravankar, A. A., Kobayashi, Y., Hoshino, Y., & Peng, C.-C. (2018). Path smoothing techniques in robot navigation: State-of-the-art, current and future challenges. *Sensors*, 18(9), 3170.

Rimpiläinen, T. I., & Koivo, H. (2008). Modeling and simulation of hospital material flows. Paper presented at the Tenth International Conference on Computer Modeling and Simulation, 579-583.

Rivard-Royer, H., Landry, S., & Beaulieu, M. (2002). Hybrid stockless: a case study. *International Journal of Operations & Production Management*, 22(4), 412–25.

Rossetti, M. D., Buyurgan, N., & Pohl, E. (2012). Medical supply logistics. In *Handbook of healthcare system scheduling* (pp. 245-280): Springer.

Roy, D. (2016). Semi-open queuing networks: a review of stochastic models, solution methods and new research areas. *International Journal of Production Research*, 54(6), 1735-1752.

Schneller, E. S., Smeltzer, L., & Burns, L. (2006). Strategic management of the health care supply chain. Jossey-Bass, San Francisco, CA

Siebers, P.-O., Macal, C. M., Garnett, J., Buxton, D., & Pidd, M. (2010). Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation*, 4(3), 204-210.

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). Facilities planning: John Wiley & Sons.

Tortorella, G. L., Fogliatto, F. S., Mac Cawley Vergara, A., Vassolo, R., & Sawhney, R. (2020). Healthcare 4.0: trends, challenges and research directions. *Production Planning & Control*, 31(15), 1245-1260.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British journal of management*, 14(3), 207-222.

Trebilcock, B. (2012). Health care reform: Automated materials handling and data collection systems are transforming the health care supply chain. *Modern materials handling*. 67(4), 38-42.

Tsakona, M., Anagnostopoulou, E., & Gidarakos, E. (2007). Hospital waste management and toxicity evaluation: a case study. *Waste management*, 27(7), 912-920.

van de Klundert, J., Muls, P., & Schadd, M. (2008). Optimizing sterilization logistics in hospitals. *Health care management science*, 11(1), 23-33.

VDMA. (2021). Intralogistics Definition. Retrieved from https://foerd.vdma.org/en/viewer/-/v2article/render/16118581

Vis, I. F. (2006). Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research*, 170(3), 677-709.

Volland, J., Fügener, A., Schoenfelder, J., & Brunner, J. O. (2017). Material logistics in hospitals: a literature review. *Omega*, 69, 82-101.

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management*, 22(2), 195-291

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly*, xiii-xxiii.

Wieser, P. (2011). From health logistics to health supply chain management. Paper presented at the Supply Chain Forum: An International Journal.

Wittenberg, R., Sharpin, L., McCormick, B., & Hurst, J. (2017). The ageing society and emergency hospital admissions. *Health policy*, 121(8), 923-928.

Wubben, I., van Manen, J. G., Van den Akker, B., Vaartjes, S., & van Harten, W. H. (2010). Equipment-related incidents in the operating room: an analysis of occurrence, underlying causes and consequences for the clinical process. *Quality and Safety in Health Care*, 19(6), e64-e64.

Wurzer, G. (2013). In-process agent simulation for early stages of hospital planning. *Mathematical and Computer Modelling of Dynamical Systems*, 19(4), 331-343.

Yajuan, Z., Jun, W., Hongwei, R., Yan, H., & Yong, Z. (2015). The washing system based on RFID research. Paper presented at the 2015 International Conference on Computer and Computational Sciences (ICCCS).

Yankova, T., & Grigorova, I. (2020). Automated waste collection systems-possibilities, trends and application. International Multidisciplinary Scientific *GeoConference: SGEM*, 20(4.1), 219-226.

Yin, R. K. (2017). Case study research and applications: Design and methods: Sage publications.

Zhao, J., Wang, Y., Xi, X., & Wu, G. (2017). Simulation of steel production logistics system based on multi-agents. *Int. J. Simul. Model*, 16(1), 167-175.

# Appendix A: Semi-structured interview guide

**A. Background**

- Please introduce yourself (position and responsibilities, career background and years of employment)

**B. General and environmental information about the hospital**

- When was the hospital built, and what main changes have been made until now?
- What kind of hospital is it, and what does it specialize in?
- How many beds does the hospital have?
- How are the departments distributed in the hospital?

**C. Sterile processing**

- Where is the sterile processing department located?
- How are the resources for washing, inspection, packaging, and sterilization planned?
- What are the minimum, maximum, and average process times for washing, inspection, packaging, and sterilization?
- How are the carts and material handling equipment washed and checked?

**D. Inventory**

- Is the storage centralized or decentralized?
- Where is the storage area located?
- Describe the inventory control and refill processes.
- Describe the process from receiving an order until sending the cart.

**E. Material handling and transportation**

- What type of material handling system and equipment is used in the hospital?
- When was the material handling system implemented?
- How many pickup and delivery points are there in the hospital? How are they distributed?
- Explain the pickup and delivery processes.
- Who is responsible for the loading and unloading activities? How are the employees informed when the carts arrive at the department?
- How is the communication carried out between the material handling system and employees, doors, elevators, etc.?
- How is the human interaction with the material handling equipment? How is the collaboration and acceptance between employees and the automated material handling system?
- Are elevator bottlenecks in the hospital?

- What problems or disturbances have occurred regarding the material handling system and transportation of sterile instruments?
- Describe the maintenance of the material handling equipment.
- What is the infection control process of the material handling equipment? How do you clean the material handling equipment?

**F. Point-of-use**

- Describe the ordering process of sterile instruments.
- How many people are involved from the pickup and delivery points at the department level to the point-of-use?
- Who is responsible for picking up the carts at the department level, preparing the return of soiled instruments, and sending carts back?
- How are the sterile instruments received and checked for completeness or right of order?

# Part II: Collection of Papers

1. Fragapane, G. I., Bertnum, A. B., Hvolby, H. H., & Strandhagen, J. O. (2018).
   Material distribution and transportation in a Norwegian hospital: a case study.
   *IFAC-papersonline*, 51(11), 352-357.

2. Fragapane, G. I., Zhang, C., Sgarbossa, F., & Strandhagen, J. O. (2019).
   An agent-based simulation approach to model hospital logistics.
   *Int J Simul Model*, 18(4), 654-665.

3. Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2020).
   Autonomous Mobile Robots in Hospital Logistics.
   In *IFIP International Conference on Advances in Production Management Systems* (pp. 672-679). Springer, Cham.

4. Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2021).
   Autonomous mobile robots in sterile instrument logistics: An evaluation of the material handling system for a strategic fit framework.
   *Production planning & control.*

5. Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021).
   Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda.
   *European Journal of Operational Research.*

6. Fragapane, G., Roy, D., Sgarbossa, F., & Strandhagen (under review).
   Planning autonomous material transportation in hospitals.
   In *IFIP International Conference on Advances in Production Management Systems.* Springer, Cham.

# Paper 1

Fragapane, G. I., Bertnum, A. B., Hvolby, H. H., & Strandhagen, J. O. (2018). Material distribution and transportation in a Norwegian hospital: a case study. *IFAC-papersonline*, 51(11), 352-357.

*This is an accepted manuscript of an article published in IFAC-papersonline. The final authenticated version is available online at:*
https://doi.org/10.1016/j.ifacol.2018.08.316

# Material Distribution and Transportation in a Norwegian Hospital: A Case Study

**Giuseppe Ismael Fragapane[1], Aili Biriita Bertnum[1], Hans-Henrik Hvolby[1,2], Jan Ola Strandhagen[1]**

*[1]Department of Mechanical and Industrial Engineering, NTNU, Norwegian University of Science and Technology, Trondheim, Norway ({e-mail: giuseppe.fragapane,aili.b.bertnum,hans.h.hvolby,ola.strandhagen})@ntnu.no)*
*[2]Department of Materials and Production, Centre for Logistics, Aalborg University, Denmark (hhh@celog.dk)*

**Abstract:** Automated Guided Vehicles have shown significant importance in material transportation and distribution in today's hospitals. The increasing trends of shorter hospital stays and increase of treatments and surgeries in clinics, present new challenges for the supply of goods. The rise in patients in hospitals, and consequently the increase of treatments and surgeries, cause a growth of material usage and goods movement. This study used the Control Model methodology to analyze the material and information flow within the case hospital. Information sharing and integration is still a major issue in the case hospital. The study aims to stimulate further research in material handling and distribution in hospitals.

*Keywords:* Automated Guided Vehicles Systems; Control Model; Hospital Logistics.

## 1. INTRODUCTION

Automated Guided Vehicles (AGV) have shown significant importance in material transportation and distribution in today's hospitals. An AGV system can be described as "a material handling system that uses independently operated, self-propelled vehicles guided along defined pathways" (Groover, 2016). It is applicable where different materials are moved from various loading points to various unloading points.

There have been several decisions and changes in healthcare that made the AGV system a success and a standard in material transportation in Norwegian hospitals. The current policy in healthcare for several countries is to expand larger hospitals and restructure them, and simultaneously closing smaller hospitals (Giancotti et al., 2017). The design and layout of Norwegian hospitals tend to be widespread and flat. As a result, long distances and more horizontal than vertical movements have to be overcome to distribute all goods within the hospitals. Therefore, the AGV is the appropriate solution for material handling.

Several methods apply to distribute goods within hospitals. Small objectives, e.g., blood samples, are mainly sent with pneumatic tube systems in hospitals due to timely matters. For transportation of bigger or heavier goods, AGVs have demonstrated good results in distributing goods to many different pick-and-place positions and traveling long distances within hospitals. However, since the AGVs use the same facilities and elevators as patients, visitors and healthcare staff, the high usage of AGV at these hours will affect the whole hospital logistics.

The increasing trends of shorter hospital stays and an increase of treatments and surgeries in clinics (OECD, 2014), present new challenges for the supply of goods. The rise in patients in hospitals, and consequently the increase of treatments and surgeries, cause a growth of material usage and goods movement. In a typical hospital, 25–30% of the budget is used for medical supplies and the handling of the supplies (Ozcan, 2005). A Norwegian hospital has adapted to this challenge by adding more resources to the supply and delivery of goods. Adding more resources to supply the demand for goods shows short-term positive results. However, for long-term positive results, the internal logistics has to be adapted.

Logistics-related activities have one of the highest costs, after personnel costs (Volland et al., 2017). Decisions, processes, and activities of material handling show great dependencies and should not be seen as isolated, independent procedures. Materials handling should be seen within a system context (Kulwiec, 2008). The distribution and material handling of hospital goods are closely interrelated. To reduce material-related logistics costs, academics, as well as practitioners, have recognized the potential of applying quantitative methods in hospitals. In other industries, such as manufacturing or service industries, these methods have already proven their potential.

In this study, the Control Model methodology has been used to analyze the material and information flows within a hospital. The Control Model is a method to organize and control the logistics and activities of a supply chain (Strandhagen and Skarlo, 1995), and is often used as a framework when analyzing the current situation of a supply chain. This research will end with recommendations for further improvements for the case hospital and future research within this topic.

## 2. THEORETICAL BACKGROUND

In the traditional distribution model, the suppliers ship their products to distributors. At the distributor, the products are packed and shipped to the warehouse of the hospitals according to the order. The hospital warehouse stores the products until they are needed in the hospital, and then sends the products to the departments on order. Sometimes, products are delivered directly from distributors to the hospital's departments based on order. The deliveries are relatively few, which leads to low transportation and ordering costs. However, this traditional model causes large amounts of inventory in the system, causing high costs of both holding inventory and due to the high amount of material handling (Rossetti et al., 2012).

A newer model, used by Mercy hospitals, replaces the distributor with a centralized warehouse system (Rossetti et al., 2012). In this model, the amount of products stores at the hospital's warehouse can be largely reduced. The suppliers ship directly to the central warehouse. At the central warehouse, the deliveries are broken down into smaller units, which are then prepared for being used in the hospitals. The materials are sent directly from the central warehouse to the hospitals. In this model, the central warehouse takes full responsibility for material handling and inventory management.

Several hospitals using AGVs for material handling are discussed in the literature. Currently, the application of AGVs for material handling in hospitals are described (Castleberry, 1991, Ullrich, 2015), but there has been a larger focus on discrete-event simulation for AGVs in previous years. The use of discrete-event simulation has been the most appropriate method for design and validation of an AGV system in hospitals (Čerić, 1990, Ross and Cheung, 1978, Swain and John III, 1978). The simulation models and programs were used to conduct series of simulation experiments with the aim of minimizing the required vehicle fleet size and to maximize resource utilization. The transportation schedules, system queueing and transportation performances could be derived from the simulations.

A recent case study performed by Peda, Grego, and Plinta (2017) shows that the use of AGVs in hospitals relieves hospital staff, allowing them to focus on care of patients. The transportation and delivery of laundry and food are some tasks that reduce the time of healthcare workers. Implementing AGVs in the studied hospital have demonstrated great results through reduction of operating costs and increase of healthcare quality. The field of hospital-internal distribution and scheduling is less discussed in literature. A literature review in this field identified four publications concerning optimization models with the objective of minimizing work routes, workloads and costs (Volland et al., 2017). The optimization models have been evolved with both simulations and heuristic approaches, and are applied to the goods of pharmaceutics, laundry, medical supply, bed-related goods, and meals (Augusto and Xie, 2009, Banerjea-Brodeur et al., 1998, Lapierre and Ruiz, 2007, Michelon et al., 1994). The issues of routing and scheduling, and material management systems are mainly discussed in these publications. It is noted that due to different material handling equipment and delivery methods, standards and common practices of how to transport goods in hospitals hardly exist. There are several issues to take into account when designing an AGV system. Flow path layout, traffic management, number and location of pick-up and delivery points, vehicle requirements, vehicle dispatching, routing and scheduling, and positioning of idle vehicles are some of the issues (Vis, 2006). Also, battery management and AGV failures affect the performance of the transportation system by requiring that the specific AGV is taken out of operation for charging and maintenance (Vis, 2006). Implementation of an AGV system in healthcare systems also requires safety and clinical quality, productivity, user-friendliness, effective technology utilization, and information and patient management (Pedan et al., 2017).

## 3. RESEARCH METHOD

This research uses the Control Model as a basis for analyzing the material and information flows of the hospital supply chain. It provides a method for data collection, a visualization of the material and information flow between the actors (Strandhagen and Skarlo, 1995), analyzation of the actors, investigation of possible improvement areas, and design and implementation of the revised Control Model (Alfnes and Strandhagen, 2000). Relevant data collection involves characteristics of material flow, inbound and outbound logistics, service to market, and reliability and flexibility of the production system (Strandhagen and Skarlo, 1995). In this research, the production system entails the overall AGV system in the hospital. However, this research will not consider the design and implementation of the revised Control Model in the hospital, as more in-depth analyzations are required of the AGV system at the department level.

Several individual and group interviews have been conducted with employees from both the operating and planning departments of the hospital. The positions of the interviewed hospital employees are Technical System Administrator, Supply Planner, Operating Manager and Operating Technician. Interviews are considered to be the most important source of evidence in case studies (Yin, 2013), making it possible to reconstruct the unexperienced situation (Rubin and Rubin, 2011). The interviews were supported by a semi-structured interview guide that can provide reliable and comparable data, in addition to providing guidelines for keeping the interview within the scope (Cohen and Crabtree, 2006).

The validity of the case study is given by applying the triangulation procedure. Triangulation is used to search for convergence among many information sources (Creswell and Miller, 2000). In this research, in addition to the interviews, documents explaining the extent of the AGV system in the hospital, and observations related both to the operation of AGVs and the employees responsible for operating the AGVs have been taken into account.

*Case description*

The case study was carried out with a large Norwegian hospital that has a capacity of 1000 beds. The hospital treats yearly 60'000 inpatients (patients who live in the hospital as long as being given treatment) and 370'000 outpatients (patients who visit the hospital for treatment without staying overnight).

The hospital implemented and launched the AGV system in 2009. Today, the AGV system consists of 21 laser-guided AGVs, transporting approximately 50-70 tons of goods every week between 114 pick-up and delivery stations in different buildings, at different levels and departments. The AGV system is operated with a centralized structure.

Related to simulations, a transportation schedule for the AGV system has been defined. This schedule has been adapted to the demand of goods over the years. Orders are dispatched to the nearest AGV. This dispatching rule was chosen to reduce AGV idle transportation time.

The hospital has integrated a radio frequency communication system, connecting the different buildings, doors and elevators with the AGV system. The AGV can lift and move the wagons within the 4500-meter guide-path that connects all departments. The AGVs can operate continuously for approximately three hours and is then sent to be charged for one hour.

## 4. CONTROL MODEL

There are six main groups of goods supporting the daily operations of the hospital. The six groups consist of consumer goods, laundry, food, sterile goods, pharmaceutics, and waste. Many suppliers are connected to the hospital supply chain, shipping goods directly to the hospital or to its warehouse. At the warehouse, the products are stored and sent to the departments when needed. The hospital's warehouse packs the wagons according to the orders from the departments and places an RFID-tag on the wagon that includes information about its final destination. Trucks transport the packed wagons several times during a day to the

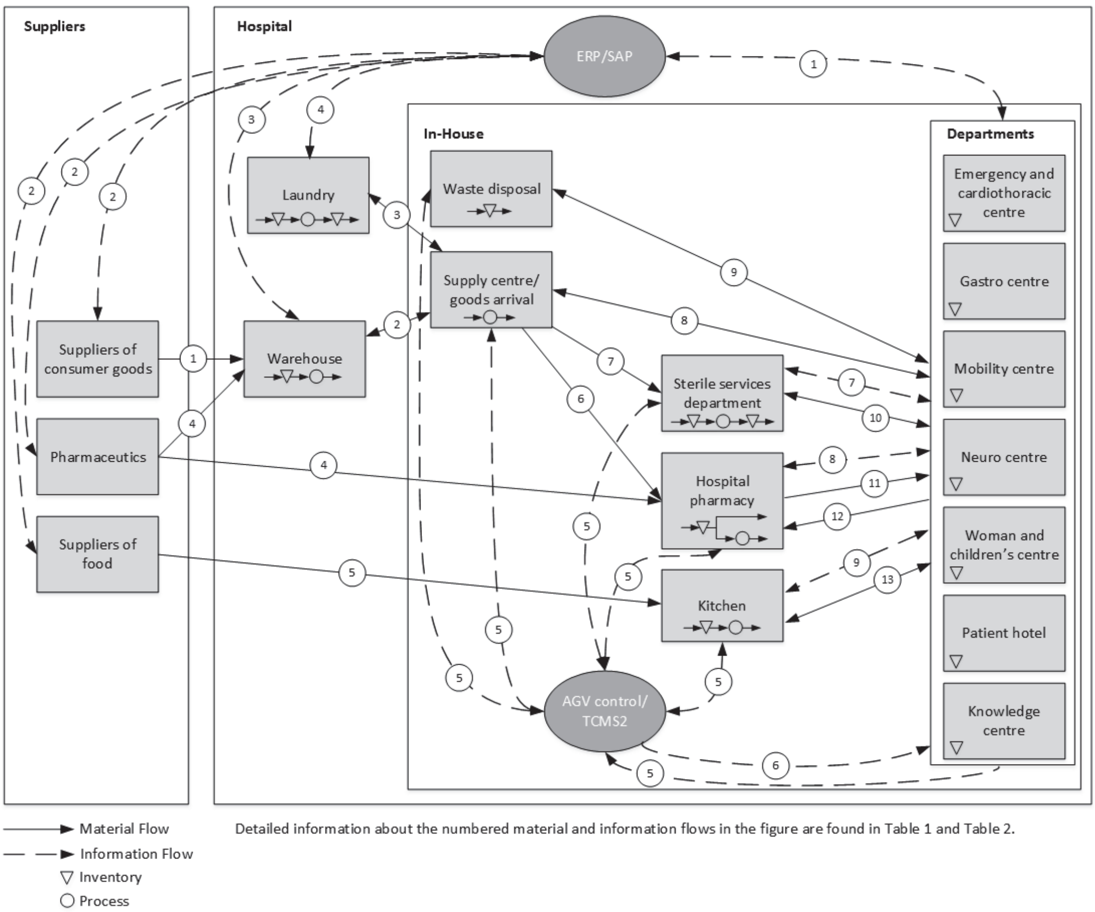



Fig. 1. Control model of the case hospital

goods arrival at the hospital, based on a schedule. When the truck returns, it takes the empty wagons back to the warehouse. On a daily basis, clean fabrics at the laundry are packed into wagons and shipped by trucks to the goods arrival at the hospital. At goods arrival, the wagons are moved to the AGV pick-up station. The RFID-tag will be read by a RFID-reader on the AGV, which sends information to the AGV system. The RFID-tag contains information about the order and delivery destination. On the return, the truck takes the dirty fabrics and wagons back to the laundry.

In general, the goods on the wagons are transported to specified delivery places at the departments. When the wagon arrives at its destination, the AGV system sends a message to the department and its person in charge. The person in charge collects the goods, and then the wagon is placed at a pick-up station or is filled with a new order of goods before being placed at a pick-up station. To initiate return transportation of a wagon by an AGV, the wagon has to be placed at a pick-up station with a RFID-tag informing the wagons final destination. The wagon is then picked up by the AGV and transported to the final destination.

There are two methods to transport the wagons containing goods within the hospital. Either an AGV picks up a wagon and delivers it to the final destination by reading the RFID-tag or an employee pulls the wagon with an electric tractor. The AGVs are operating Monday to Friday from 6.30 to 19.30. Outside of these hours, transportation of all groups of goods is performed manually by an employee.

**Table 1. Material flow**

| # | What | How | How often |
|---|---|---|---|
| 1 | Consumer goods | Truck | Several times a day |
| 2 | Consumer goods on wagons | Truck | Several times a day |
| 3 | Laundry/Fabrics on wagons | Truck | Once a day |
| 4 | Pharmaceutical products and medicine | Truck | Once a day |
| 5 | Food | Truck | Once a day |
| 6 | Pharmaceutical products and medicine | Manual | Several times a day |
| 7 | Goods sterilised and equipment for sterilisation | Manual | Several times a day |
| 8 | Consumer goods and laundry | AGV or manual | Several times a day |
| 9 | Empty wagons to departments, full wagons to waste disposal | AGV or manual | Several times a day |
| 10 | Sterile goods to department, dirty goods to sterile services department | AGV or manual | Several times a day |
| 11 | Pharmaceutical products and medicine | Manual | Several times a day |
| 12 | Empty wagons | AGV or manual | Several times a day |
| 13 | Warm food to departments, empty wagons to kitchen | AGV or manual | Several times a day |

Some of the goods groups have special transportation demands. Food delivered from the kitchen to the departments has to arrive warm and on time. The sterile goods have to follow a production schedule for washing and sterilization, and there are high requirements related safety and security during transportation. Waste, especially hazardous waste, has to be transported in special wagons because of the risk of contagion. Lastly, medicine is always transported manually to the departments, due to safety and security reasons. Furthermore, some medicine is produced in-house and has to be delivered within a certain, short time frame due to perishability.

The inventory levels at each department are checked daily manually by an employee by scanning the materials. Inventory levels at the warehouse are synchronized with the Enterprise resource planning (ERP) system. Low inventory levels of a certain type of goods indicate that it should be reordered. The supply department is responsible for ordering the materials from the supplier or the hospital's warehouse.

There are two types of fabrics replenished in the hospital. The first type is labeled employee. Sensors in the cupboards where the clothes and fabrics related to this fabric type are stored monitors the inventory levels. When the reorder point is reached, an order is automatically sent to the laundry. The second fabric type is related to patients or departments. Orders for this fabric type are placed directly to the laundry by the individual departments in need of fabrics.

Each department has to place orders for sterile goods the day before they are needed, to make sure the sterile goods are being delivered on time. The sterile services department follow a schedule for supplying the different departments with the ordered amount of sterile goods.

**Table 2. Information flow**

| # | What | How | How often |
|---|---|---|---|
| 1 | Order | Manual scan | Several times a day |
| 2 | Order | Automatic or email | Weekly |
| 3 | Order | Automatic | Several times a day |
| 4 | Order | Automatic | Once a day |
| 5 | Wagon at Pick/ Delivery station | Automatic | Real-time |
| 6 | Message | Automatic | Real-time |
| 7 | Order | Email | Once a day |
| 10 | Order | Phone or email | Several times a day |
| 11 | Order | Email | Once a day or weekly |

## 5. DISCUSSION

The case hospital is part of a traditional supply chain and does not have a centralized structure. There are different methods to supply the hospital departments with goods. Also, neither the material nor the information flows are standardized for ordering and delivery of goods. Not standardizing the processes and centralizing the structure will interfere with the automation process of the material flows in the hospital.

Hospital flows benefit from the technological progress of information systems and the emergence of new information technology tools, with many benefits. Some examples are RFID and ERP system. (Ageron et al., 2018). The different actors along the supply chain communicate with separate communication systems, e.g., manually by phone, email, and scan or automatically through the ERP-system. Not using a common or at least an integrated information and communication system will lead to incoherent information sharing along the supply chain. Less information sharing leads to more uncertainties in the supply chain. It will also lead to decentralized control. Performance of the whole system will be improved if each actor achieves improvements from information sharing (Yu et al., 2001). There are many inventories across the hospital supply chain. Sharing information about inventories will positively affect both position, replenishment and amount of goods in the inventories.

Information exchange might break the "silo" culture in hospitals. The case hospital has, like many other hospitals, several in-house productions and departments that often are not coordinated with each other. Food, pharmacy, and sterile goods have to be distributed with the given material handling resources. Products of both catering and pharmacy have to be consumed within a certain period. Therefore, the products are produced and delivered directly to the patients without keeping intermediate inventories. This is common practice in catering service industries, producing and delivering food to the customers directly, without intermediate inventories. However, the challenge is to find a joint schedule of production and distribution (Chen and Vairaktarakis, 2005). In such industries, the objective function for optimizing production and distribution operations have to take into account both customer service level and total distribution cost. However, at the same time, the distribution and delivery of sterile goods should not be neglected. The delivery precision of sterile goods has a major impact on the operations schedule of the operating theater. Sterilization services have been mainly discussed in literature about outsourcing the activity and the related logistical challenges (Volland et al., 2017). Outsourcing often results in longer distances, longer logistic loops, and lower instrument availability. According to van de Klundert et al. (2008), changing the logistics management principles, optimizing the composition of the nets of sterile materials and using appropriate information technology will improve material availability and reduce costs.

All the different production and delivery schedules have to be taken into account and integrated into the AGV scheduling problem, to fulfill transportation and delivery demands of the hospital. Most studies on scheduling problems of the AGV focus on the manufacturing environment and the scheduling objective of minimizing the make span (Kaoud et al., 2017). Multi-objective studies are scarcely discussed, but are significant for achieving an overall efficiency of the AGV system. There is a need to develop models for more complex AGV system (Vis, 2006), managing multiple material flows and the challenges faced in hospitals.

The challenges of the material flow in the case hospital are closely related to the hospital's environment and layout. The hospital has built and added several buildings over time. Consequently, the transportation layout has changed. The distances that the AGV has to overcome for delivery of wagons are long. In many cases, the AGV has to use elevators and hallways also used by patients, visitors and healthcare staff. These interactions affect the transportation performance of the AGV system. Obstacles in the pathway cannot be removed by an AGV. The AGV system is currently dependent on human monitoring. Errors or failures from elevators, human interactions or obstacles resulting in AGV breakdowns have to be corrected manually by an operator. These interactions and breakdowns have a strong impact on the performance of the AGV system. The AGVs operating hours are currently restricted by the operator's attendance and surveillance. Emphasizing the need to expand the knowledge of operations of AGVs in hospital environments.

## 6. CONCLUSSION

The study aimed to analyze the current situation of the hospital's supply chain focusing on material and information flow. Information sharing and integration is still a major issue both in the case hospitals as well as in AGV systems. Several hospitals using AGVs as a part of the material handling system should be compared to ensure that this is a common problem needing in-depth understanding.

Future research should focus on how the information of both the constraints of the hospital environment and the in-house production can be integrated into the AGV system. Furthermore, research on how internal distribution and transportation by AGVs can be moved to times where there is less activity in the hospital, to avoid the problem of sharing facilities with patients, visitors, and healthcare staff. Related to this, it should be investigated how machine learning methods can support the AGV system to operate AGVs 24 hours a day without human surveillance.

## ACKNOWLEDGEMENT

This research received funding from the strategic research area NTNU Health in 2017 at NTNU, Norwegian University of Science and Technology. The authors also gratefully acknowledge the case hospital that made it possible to carry out this study.

## REFERENCES

Ageron, B., Benzidia, S. & Bourlakis, M. Healthcare logistics and supply chain–issues and future challenges. Supply Chain Forum: An International Journal, 2018. Taylor & Francis, 1-3.

Alfnes, E. & Strandhagen, J. O. 2000. Enterprise design for mass customisation: The control model methodology. *International journal of logistics,* 3**,** 111-125.

Augusto, V. & Xie, X. 2009. Redesigning pharmacy delivery processes of a health care complex. *Health care management science,* 12**,** 166-178.

Banerjea-Brodeur, M., Cordeau, J.-F., Laporte, G. & Lasry, A. 1998. Scheduling linen deliveries in a large hospital. *Journal of the Operational Research Society,* 49, 777-780.

Castleberry, G. 1991. The AGV Handbook. *A Handbook for the Selection of Automated Guided Vehicle*.

Čerić, V. 1990. Simulation study of an automated guided-vehicle system in a Yugoslav hospital. *Journal of the Operational Research Society,* 41, 299-310.

Chen, Z.-L. & Vairaktarakis, G. L. 2005. Integrated scheduling of production and distribution operations. *Management Science,* 51, 614-628.

Cohen, D. & Crabtree, B. 2006. Semi-structured interviews. *Qualitative research guidelines project*.

Creswell, J. W. & Miller, D. L. 2000. Determining validity in qualitative inquiry. *Theory into practice,* 39, 124-130.

Giancotti, M., Guglielmo, A. & Mauro, M. 2017. Efficiency and optimal size of hospitals: Results of a systematic search. *PloS one,* 12, e0174533.

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

Kaoud, E., El-Sharief, M. A. & El-Sebaie, M. Scheduling problems of automated guided vehicles in job shop, flow shop, and container terminals. Industrial Engineering and Applications (ICIEA), 2017 4th International Conference on, 2017. IEEE, 60-65.

Kulwiec, R. A. 2008. Basic materials handling concepts. *Materials Handling Handbook, 2nd Edition*, 1-18.

Lapierre, S. D. & Ruiz, A. B. 2007. Scheduling logistic activities to improve hospital supply systems. *Computers & Operations Research,* 34, 624-641.

Michelon, P., Cruz, M. D. & Gascon, V. 1994. Using the tabu search method for the distribution of supplies in a hospital. *Annals of Operations Research,* 50, 427-435.

OECD 2014. OECD Reviews of Health Care Quality: Norway 2014: Raising Standards.

Ozcan, Y. A. 2005. *Quantitative methods in health care management: techniques and applications*, John Wiley & Sons.

Pedan, M., Gregor, M. & Plinta, D. 2017. Implementation of Automated Guided Vehicle System in Healthcare Facility. *Procedia engineering,* 192, 665-670.

Ross, B. T. & Cheung, F. H. Simulation study of a hospital automated materials handling system. Proceedings of the 11th annual symposium on Simulation, 1978. IEEE Press, 115-144.

Rossetti, M. D., Buyurgan, N. & Pohl, E. 2012. Medical supply logistics. *Handbook of healthcare system scheduling*. Springer.

Rubin, H. J. & Rubin, I. S. 2011. *Qualitative interviewing: The art of hearing data*, Sage.

Strandhagen, J. O. & Skarlo, T. 1995. A Manufacturing Business Process Reengineering Method: Design and Redesign of a Production Control Model. *Re-engineering the Enterprise*. Springer.

Swain, R. W. & John III, M. J. 1978. A simulation analysis of an automated hospital materials handling system. *AIIE Transactions,* 10, 10-18.

Ullrich, G. 2015. Automated guided vehicle systems. *Springer-Verlag Berlin Heidelberg. doi,* 10, 978-3.

van de Klundert, J., Muls, P. & Schadd, M. 2008. Optimizing sterilization logistics in hospitals. *Health care management science,* 11, 23-33.

Vis, I. F. 2006. Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research,* 170, 677-709.

Volland, J., Fügener, A., Schoenfelder, J. & Brunner, J. O. 2017. Material logistics in hospitals: a literature review. *Omega,* 69, 82-101.

Yin, R. K. 2013. *Case study research: Design and methods*, Sage publications.

Yu, Z., Yan, H. & Edwin Cheng, T. 2001. Benefits of information sharing with supply chain partnerships. *Industrial management & Data systems,* 101, 114-121.

# Paper 2

Fragapane, G. I., Zhang, C., Sgarbossa, F., & Strandhagen, J. O. (2019).
An agent-based simulation approach to model hospital logistics.
*Int J Simul Model*, 18(4), 654-665.

*This is an accepted manuscript of an article published in International Journal of Simulation Modelling. The final authenticated version is available online at:*
https://doi.org/10.2507/IJSIMM18(4)497

Int j simul model 18 (2019) 4, 654-665
ISSN 1726-4529 Original scientific paper

# AN AGENT-BASED SIMULATION APPROACH TO MODEL HOSPITAL LOGISTICS

Fragapane, G. I.*; Zhang, C.**; Sgarbossa, F.* & Strandhagen, J. O.*
* Department of Mechanical and Industrial Engineering, NTNU,
Norwegian University of Science and Technology, Trondheim, Norway
** KTH Royal Institute of Technology, Stockholm, Sweden
E-Mail: giuseppe.fragapane@ntnu.no, chenzh@kth.se, fabio.sgarbossa@ntnu.no,
ola.strandhagen@ntnu.no

**Abstract**
The increasing rate of hospital admissions has resulted in a commensurate increase in the number of treatments and surgeries performed, as well as resource and material usage, and requires planners to improve hospitals' internal logistics. Logistics modelling of internal goods and corresponding material handling systems and simulating future scenarios can provide planners with necessary decision support. Introducing an agent-based simulation model using historical data generated by an automated guided vehicle (AGV) in a case hospital facilitates analysing the goods delivery system's current status and potential countermeasures to improve internal logistics. In comparison with other industries, such as manufacturing, AGVs utilised in hospitals have to interact with persons, patients and elevators, transport several different types of goods and cover a sizeable multi-floor area. By including these factors, the simulation model represents an appropriate method to test different scenarios and improve delivery performance and AGV utilisation. The study highlights the constraints related to operating AGVs in dynamic environments, such as those encountered in hospitals.

**Key Words:** Logistics, Hospital logistics, Automated Guided Vehicle, Agent-Based Simulation, Performance Analysis

## 1. INTRODUCTION

Advances in technology and hospital management have helped reduce patients' lengths of stay [1] and introduced new methods for treating patients [2]. The resulting improvements have led to shorter hospitalisations and enabled care providers to treat patients in outpatient or daily clinics instead of hospitalising them for several days. Over the next 20 years, the treatment of somatic patients is expected to increase by about 35–40 % throughout all departments [3]. The increasing hospital admission rate and the commensurate increase in the number of treatments and surgeries performed have also caused increased resource and material usage. This trend can be observed in most Western countries, especially in hospitals located in major cities [4]. Furthermore, the increase in the number of patients has been accompanied by the restructuring and expansion of larger hospitals and closure of smaller hospitals [5]. To provide patient-care services, resources and medical goods must be continuously adapted and managed to meet demand. The increasing pressure caused by increased goods consumption and costs forces hospital practitioners to continually improve and optimise their goods' supply chain and internal hospital logistics.

In a typical hospital, 25–30 % of the budget is spent on the logistics of medical supplies [6]. According to Poulin et al. [7], half of logistics costs can be eliminated with efficient logistics management, and while increasing logistics efficiency might not directly influence patient care, it will afford medical staff more time for patient-related activities [8, 9]. Developing effective and efficient logistics activities can be challenging, considering that the hospital supply chain is usually characterised as highly complex [10]. The external supply chain has been given the most attention in the literature; however, in practice, the internal supply chain and internal logistics are the weakest links in the entire chain [8, 11]. Granlund and Wiktorsson [12] argue that the internal supply chain's performance significantly impacts the organisation's overall performance and emphasise the importance of continuous improvement of this segment to achieve competitiveness.

The high degree of flexibility and automation of automated guided vehicles (AGV), compared to other material handling systems, has made it a suitable alternative for goods transportation in hospitals [13]. An AGV can be defined as a driverless transportation system used for the horizontal movement of materials to facilitate flexible material handling [14]. As described in a study by Benzidia et al. [15], AGV systems can automate the flows of pharmaceuticals, catering, laundry and waste on a daily basis in hospitals. While AGVs undergo routine maintenance, the control system and the logistics setup are reviewed and improved less frequently. Recruiting employees with relevant expertise who can further improve hospitals' automated material handling systems and internal logistics is challenging [15]. Hospitals are currently changing significantly to handle the patients of today and the future. Departments are expanded, moved within the hospital or outsourced. These changes affect goods consumption and material flow patterns. Not properly investigating the hospital's logistics and corresponding AGV system on a regular basis can lead to increased vehicle idle times, high material flow peaks, and high variability in transportation and delivery times, which make the entire system less efficient. Most of the literature on how to plan and control AGV systems originate from the manufacturing, warehousing and container terminal industries [14, 16, 17]. The characteristics of these environments have a significant impact on the planning and control of AGV systems. For instance, optimisation studies of flexible manufacturing systems have different requirements and challenges, which lead to different assumptions in comparison to hospitals. Neglecting traffic problems or handling only a single material flow [18, 19] makes these models less applicable to hospitals.

In comparison to other industries, AGVs in hospitals must interact with persons, patients and elevators, which have a considerable impact on AGVs' traffic and transportation performance. Furthermore, in hospitals, AGVs transport goods throughout the entire facility and cover a large area, whereas, in an industrial facility, they only cover a limited, small area. Implementing AGVs in hospitals requires adhering to safety standards and ensuring clinical hygiene [20]. AGV use in hospital logistics, in comparison to other industries, remains relatively unexplored, and the complexity of hospital logistics is not adequately considered in current simulation models.

The objective of this study is to investigate the impacts of the hospital environment and AGVs' characteristics on hospital logistics performance. By achieving this objective, the study aims to support hospital planners in continuously improving the material flow in hospitals. The study begins by mapping the AGV system and material flow in a case hospital. Next, since hospitals are a good example of a dynamic environment, we introduce a simulation model for goods transportation by AGVs in hospitals. Finally, several scenarios are simulated to investigate the impact of transporting more goods, lengthening the AGV's operating time, and increasing the number of AGVs and their battery capacity, as well as error reduction. The study supports improving AGVs' picking, delivery and utilisation performance in the case hospital.

## 2. THEORETICAL BACKGROUND

Hospital logistics set the baseline of this study and can be defined as the set of the activities, such as purchasing, inventory management, and transport management, in hospitals to provide and supply goods and services for the overall medical services facilitating patient care [21]. Hospital logistics requires handling the complexity of the hospital system to provide supplies for physicians and a clientele with a particular variability and unpredictability profile and enable both planned and ad hoc treatments [22]. Some medical goods cannot be sent just-in-time from the suppliers for treatment at the point-of-care. Many storerooms are spread throughout a hospital complex, stocking the medical supplies, clothes, laundry and related items for nurses and physicians. The distribution of pharmaceuticals, office supplies, food, maintenance, cleaning, sterilisation, linen and waste further complicates the transportation network in a hospital [5].

Modelling and simulation are methodologies applied to study logistics systems in hospitals and provide necessary decision support. An extensive review by Volland et al. [8] finds that few publications on modelling the material flow in hospitals have been published. The main focus of this literature is on optimising flows of goods for pharmaceuticals, laundry and medical supplies, as well as bed-related goods, with the objective of minimising work routes, workloads and costs. Routing, scheduling and material management system issues are mainly discussed in these publications. Furthermore, only a few studies investigate the material handling or delivery methods in hospitals [8]. A study conducted by Rimpiläinen and Koivo [23] models and simulates a manual truck delivery system for hospitals. The authors investigate the scheduling of meal transportation, and the impact of a number of drivers of transportation capacity are analysed.

Discrete-event simulation is commonly used to design and validate AGV systems in hospitals [24, 25]. Simulation models are used to conduct a series of simulation experiments with the goal of minimising the required vehicle fleet size or maximising resource utilisation. From these simulations, information can be derived for transportation scheduling, system queueing and transportation performance. However, these simulation models do not account for several crucial factors, such as battery management. Numerous models and simulations can be found in other industries to design and define an AGV system. However, these models do not consider hospitals-specific characteristics and factors.

Evaluation studies conducted in hospitals [26, 27] using stochastic models mainly seek to optimize patient logistics rather than the flow of goods. Interventions for sources of uncertainty are discussed in these simulation-based studies; however, again, very few discussions address the interdependency of the dynamic system and, especially, the automated material handling infrastructure to evaluate technologies in service systems.

Mixed methods research with simulation as the core of the framework is used for healthcare management, but its use remains somewhat underdeveloped in hospitals' internal logistics management. Zhang et al. [28] observe that although simulation studies of certain types of material flow in hospital environments have been performed, evidence-based on validated simulation models, as well as guidelines for selecting the right parameters and inputs when building logistical simulation models, is largely lacking.

None of these studies, however, investigate factors affecting material handling systems in hospitals or include a dynamic environment in the models. To the best of our knowledge, the existing literature is lacking in this regard. To bridge this gap, this research combines quantitative and qualitative approaches to model and simulate the material flow performed by AGVs and investigate how managers can solve their hospital's internal logistics problems.

## 3. METHOD

This research used a mixed-methods approach that combines qualitative and quantitative methods to strengthen the results' credibility and generalisability. The research design consists of an in-depth case study and agent-based simulation model of the case hospital using historical AGV data. Observations and semi-structured interviews were conducted to identify the hospital's logistics problems and the main factors affecting the AGV system. Based on the findings of the case study and internal logistics information gathered, an agent-based simulation model was developed and introduced. This method is new in operations research and often overlooked as researchers have tended to rely on more traditional methods [29]. Agent-based simulation (ABS) has garnered more interest among practitioners because it can model stochastic processes. At its core, ABS is built by autonomous resource units that follow a series of predefined rules to achieve their objectives whilst interacting with each other and their environment [29, 30]. These attributes are especially interesting since the hospital environment should be integrated to a higher degree in the models. Interactions between AGVs and personnel or elevators can be included in the simulation model. A previous study has shown that ABS is especially useful in simulating complex logistics networks and understanding real-world systems in which representing or modelling many individual units is important [31, 32]. ABS is especially suitable for this study in modelling and simulating the hospital's logistics with the different individual units and evaluating the transportation system.

Case selection is a vital part of the research process. Our strategy is based on achieving theoretical replication and using an information-rich case to produce contrary results and maximum variation but for predictable reasons. This research is based on a single hospital. Hospitals can differ greatly from each other in layout and services provided. However, the selected case hospital represents a major university hospital and has all the departments common to hospitals, a capacity of 850 beds and, currently, more than 8,000 employees; it also relies heavily on an automated transportation system for internal logistics. Several hospitals using AGV systems with a similar setup for material handling have been studied in the literature [13].

AGV data collected from the internal material transportation system between January 2017 and the end of December 2018 were used to feed the simulation model. The data included details of AGV jobs, AGV battery information, errors and elevator information. The model and simulation results were presented and discussed in iterative loops with the case hospital's logistics managers and maintenance personnel. The feedback was utilised to improve the simulation model.

## 4. CASE DESCRIPTION

The logistics network consists of goods arrival and several in-house productions, including catering and sterile processing services, as well as departments, such as the wards, operating theatre and points-of-care. Several transportation methods can be applied when moving goods within a hospital. As stated by the hospital managers, most of the goods are transported by the AGVs. This implies the material flow of food, sterile goods, laundry, goods delivered from the central warehouse, pharmaceuticals and waste. The goods that have to be transported are packed onto wagons and placed at pick/delivery (P/D) stations, where radio-frequency identification tags transmit information regarding the order and delivery destination to the AGV control system. The AGV system is operated via a centralised structure, and jobs are dispatched to the nearest AGV to reduce the AGVs' idle time. The hospital has integrated a radio frequency communication system that allows AGVs to open doors and call elevators. Using connecting tunnels between different buildings and elevators, AGVs can access, to a considerable extent, the entire hospital. In each building, they can access up to six different floors. When a wagon arrives at its final destination, the AGV system sends an arrival message to the department. The wagon and goods are moved from the P/D station to the department manually. To initiate the return transportation of a wagon, the wagon has to be placed at a P/D station.

An influence diagram was used to map both the interactions of the various elements of the decision setting and the transportation tasks performed by the AGVs (Fig.1).

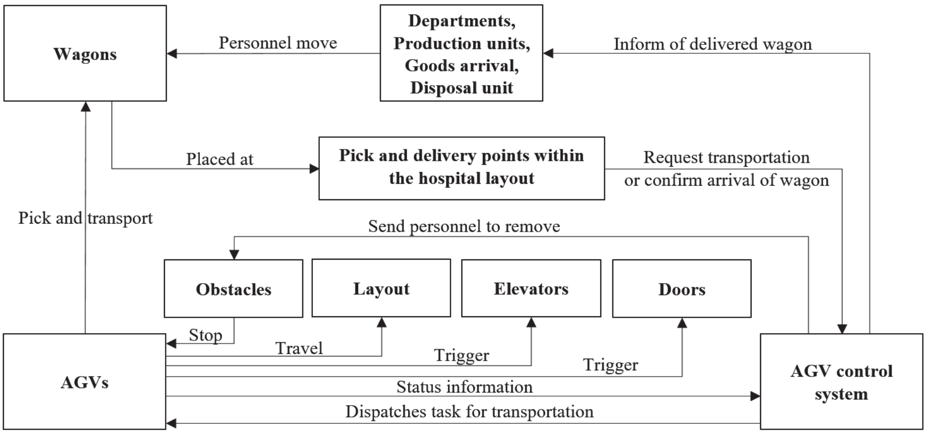



Figure 1: Influence diagram showing interactions within the transportation network

AGVs lift and move wagons along the 4500 m guide-path. Currently, the AGV system consists of 21 laser-guided AGVs transporting approximately 50–70 tons of goods per week among 114 P/D stations distributed across the hospital.

# 5. SIMULATION MODEL ARCHITECTURE

## 5.1 Model Assumptions

The assumptions made to facilitate model development are listed below:

- Departments with medical units generally require more supplies and transportation services than the hospital's supporting units.
- The transportation schedule is set for at least 12 hours of work per day with possible extensions or reductions.
- An infinite number of wagons are available to be packed.
- Only one AGV can access and use an elevator at a time.
- AGVs can operate bi-directionally in 40 % of the corridors.
- AGVs charge their batteries between transportation orders and, in most cases, access a randomly selected charging station.

## 5.2 Material flow simulation modelling in hospital environments

The selected hospital serves as the reference system and the empirical sources for exploring the impact of resource configurations in the management of material flow. The hospital's logistics managers identified eight departments needing material delivery services: the emergency and cardiothoracic centre, the administration centre, the laboratory centre, the neuro centre, the knowledge centre, the mobility centre and the gastro centre. The departments are located in different areas of the hospital. Each department has unique demand patterns. Populating the simulation environment enabled obtaining a process-oriented structure in which asynchronous agents exist, as shown in Fig. 2. The process simulation represents material flow handling in the reference system, with the following fundamental logic of high fidelity to the investigative system:

1. Goods arrive at a department (i.e., a local department or the supply centre) as the sender.
2. A processing slot is assigned, and a staff member prepare the goods to send.
3. The staff return available when the preparing job is finished, after which the nearest available AGV with an adequate energy supply is assigned to pick the goods.
4. The AGV picks up the goods and navigates through the hospital network towards the destination department, which is pre-defined by the sender.
5. The AGV delivers and unloads the goods at a slot at the destination department.
6. The goods are received by a staff member at the destination department.
7. The unloaded AGV returns available and to the pre-defined cruising mode.

The arrival rate tables are specified for the hospital centres. These specifications are performed inside the arrival module according to historical data regarding item types, hourly rates, item senders and receivers. The simulation model couples the agent-based sub-models and a discrete-event simulation model. The steering agents are containers and AGVs, operating according to the logistics processes, which include sending and receiving goods, as well as battery charging for the AGVs. These processes are recreated by the discrete-event simulation as the living environment of the agents. Meanwhile, metrics can be obtained and automatically updated with information provided by asynchronous agents. By doing so, it was able to obtain the following metrics for the validation of a baseline scenario, enabling a simulation-based evaluation and prediction of the logistics system:

- arrival and discharge patterns of goods;
- performance of picking, delivery and utilisation of AGV vehicles.

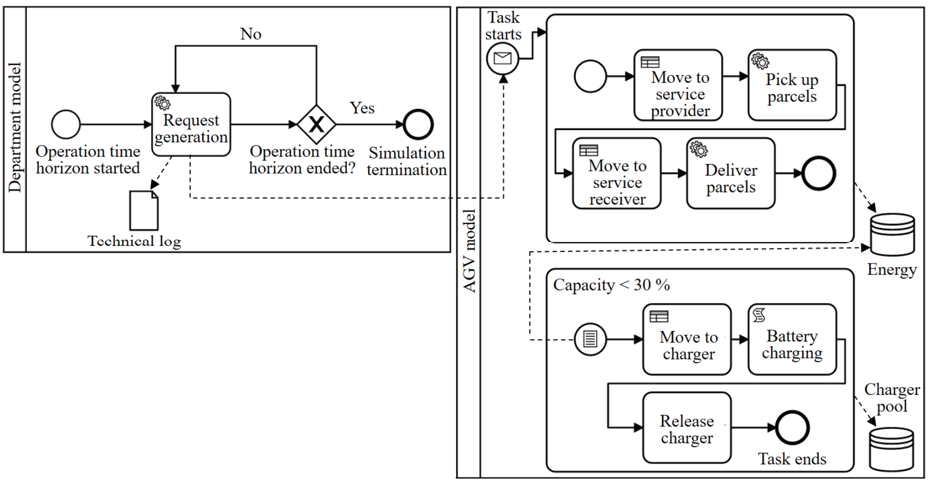



Figure 2: Architecture of the simulation model

An observation of the system shows that the battery discharge rate depends on the weight of the load carried by the AGV and the distance travelled. To ensure maximum availability, the vehicle manufacturer aims to maintain the battery system at a state of charge from 50 to 80 %. This means that when not in service, the AGVs are directed to charge as often as possible, even if they charge for only a few minutes. The 100A charge current will recharge around one-third of the battery modules' capacity in less than 20 minutes. Given these details, a critical consideration when operating AGV transport systems is recharging since the vehicles are powered by batteries and require on-hold and charging processes in autonomous states. Agent-based modelling is highly appropriate for modelling such robotic and proactive actors because of its ease of interacting with a circulative system. In agent-based modelling, AGVs are modelled as a collection of autonomous decision-making ownership entities. Each agent individually assesses the energy consumption situation and triggers behaviours according to pre-defined criteria. The model is validated on the micro-level since the construction is based on observational data, historical data and existing flowcharts.

### 5.3 Modelling material handling processes

The Weibull distribution is ideal for modelling the processes of AGVs picking up goods and delivering them to a receiver, as Table I summarises. To seek the best fit based on the collected data, the Kolmogorov–Smirnov test for distribution was used, which is widely used to simulate industrial processes. Weibull, exponential, gamma, logistic, normal and lognormal distributions were tested. The distribution with a minimised square error was selected. The quality test determined that all of the parameter estimations of the selected distributions were significant with corresponding *p*-values less than 0.05, while the Weibull distribution was suitable for modelling the material handling behaviours.

Table I: Service duration modelling (in minutes).

| Process | Sample size | Mean | Standard deviation | Distribution formulation | Parameter significance *t*-test |
|---|---|---|---|---|---|
| Picking | 151306 | 15.7 | 14.2 | Weibull ($\lambda$=167.9; k=1.2)* | $p<0.05$ |
| Delivery | 151306 | 12.3 | 8.8 | Weibull ($\lambda$=13.9; k=1.6)* | $p<0.05$ |

* = $\lambda$ is the scale parameter; k is the shape parameter

## 6. RESULTS

### 6.1 Simulation model verification and validation

Model verification and validation are performed to ensure reliable projections, which are an important characteristic of simulations in logistical applications. The validation of an ABS model for future scenarios is particularly challenging for simulation projects of future designs and scenarios given that the system's mechanical computation might neglect behavioural aspects. Therefore, as a non-statistical validation technique, participatory simulation is considered appropriate and has been used to endorse the simulated environment of a logistics system [33].

No discrepancies regarding entity movements were found because the simulation model recreated the processes and asynchronous agents. All the AGVs are docked in charging slots when not engaged in transporting orders. The AGVs and containers that are currently involved in relevant simulation building blocks are visualised on the interface. It can be observed that containers are transported from the sender to the receiver with necessary resource attachments. These resource attachments are personnel supports and are moved by transporters. The arrival of orders follows the daily pattern.

The model was implemented using the simulation software AnyLogic. Special attention was devoted to validating the model to ensure that the simulation outputs are adequately represented in the system under investigation. One-year steady-state results, based on 80 independent and identically distributed replications (with different random seeds) and a warm-up period of three months, were determined. Validation was based on a Student's *t*-test comparing the empirical and average simulated results of the monthly supply and disposals. The null hypothesis (H0) was tested under a probability of rejecting the model at the $\alpha = 0.01$ level. The corresponding critical values of the test were $t(48,0.99) \approx 2.40$, $t(49,0.99) \approx 2.40$, $t(50,0.99) \approx 2.40$, $t(51,0.99)$

≈ 2.40. Table II reports the statistical test results for each month and material group. The results indicate the model's ability to represent the real system.

Table II: Student's *t*-test results for sterile throughput.

| | Supply transportation | | | | Return transportation | | | |
|---|---|---|---|---|---|---|---|---|
| Day of week | Real value | Average simulated output | Diff | *t*-test | Real value | Average simulated output | Diff | *t*-test |
| Monday | 283 | 280 | -3 | 0.51 | 290 | 282 | -8 | 1.62 |
| Tuesday | 268 | 260 | -8 | 1.84 | 296 | 287 | -9 | 2.03 |
| Wednesday | 264 | 271 | 7 | -1.55 | 296 | 300 | 4 | -0.82 |
| Thursday | 254 | 246 | -8 | 1.79 | 293 | 282 | -11 | 2.02 |
| Friday | 270 | 279 | 9 | -2.00 | 297 | 290 | -7 | 1.36 |

The focus was on the average throughput for each hour of the workday for transported wagons, which was one of the most relevant measures to evaluate and coordinate the allocation of resources throughout the day with the demand profile. Breaking down this datum into daily dynamics, Fig. 3 shows how this throughput varied throughout the workweek. By making changes in department modules, the user can directly level the transportation and then predict the demand profile, which is a challenging part of the current logistics operation.

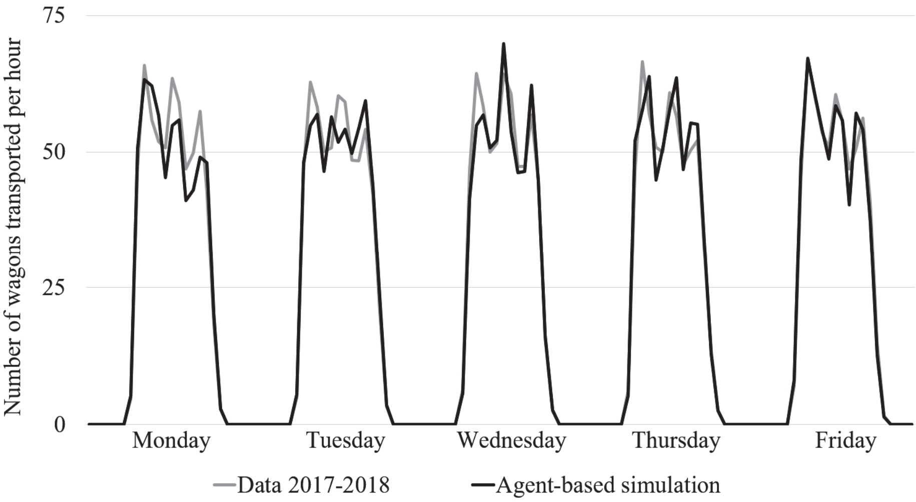



Figure 3: A comparison of historical AGV data and ABS results

### 6.2 Simulation-based system evaluation

The impact of increased goods transportation and the impact of implementing different countermeasures were simulated to study the current status and future challenges. The countermeasures included levelling transportation, increasing the reliability of delivery operations, and increasing the transportation capacity. Levelling transportation can minimise the transportation peaks and shorten the AGVs' response time. Therefore, investigating which material flows can be transported outside of the high-traffic hours and how the AGV transportation schedule might have to be adapted were considered relevant. By expanding the AGVs' operating time and adapting the transportation schedule, different single-material flow patterns could be varied and simulated to analyse their impact on delivery performance.

The reliability of current delivery operations has been criticised by the case hospital's logistics managers. The dynamic environment clearly stresses the AGV system, leading to material flow disturbances and longer waiting times. The AGVs use and share corridors and elevators with personnel, patients and visitors, which affect delivery performance. AGVs cannot avoid persons or obstacles by going around them. The maintenance operators have to remove obstacles from in front of the AGVs several times a day. The guide paths of the AGVs are unknown to visitors or those who are unfamiliar with the hospital. Parked wheelchairs or other items on the guide path can cause queues and delays. Therefore, different adaptions to the guide path in high traffic areas and obstacle avoidance scenarios were investigated and simulated.

Lastly, the effects of increased transportation capacity have been investigated. Varying vehicle properties, such as the type or number of vehicles, the battery, and transportation load, might influence the AGV system's performance. Alternatives regarding the number of vehicles and battery management were further examined in this study since they were identified as most relevant by the logistics managers.

Using the ABS, the performance of picking, delivery and utilisation were determined to evaluate the different approaches. The following tables show some of the results of the different investigations.

Table III: Impact of increased goods transportation.

| | **0 %** | **5 %** | **10 %** | **15 %** | **20 %** | **25 %** | **30%** |
|---|---|---|---|---|---|---|---|
| Picking | 15.7 min | 15.8 min | 15.9 min | 16.0 min | 16.2 min | 19.0 min | 23.4 min |
| Delivery | 12.3 min | 12.3 min | 13.2 min | 13.3 min | 13.4 min | 15.2 min | 18.4 min |
| Utilisation | 63.3 % | 66.3 % | 69.7 % | 72.9 % | 79.1 % | 85.2 % | 92.8 % |

Table IV: Impact of expanding the operating time.

| | **0 %** | **5 %** | **10 %** | **15 %** | **20 %** | **25 %** |
|---|---|---|---|---|---|---|
| Picking | 15.7 min | 15.1 min | 15.1 min | 15.2 min | 14.9 min | 14.9 min |
| Delivery | 12.3 min | 11.9 min | 12.0 min | 11.8 min | 11.7 min | 11.7 min |
| Utilisation | 63.3 % | 51.3 % | 46.8 % | 38.0 % | 30.3 % | 29.1 % |

Table V: Impact of increasing the number of vehicles.

| | **0 %** | **5 %** | **10 %** | **15 %** | **20 %** | **25 %** |
|---|---|---|---|---|---|---|
| Picking | 15.7 min | 14.1 min | 13.3 min | 12.9 min | 12.8 min | 12.8 min |
| Delivery | 12.3 min | 11.1 min | 10.2 min | 10.1 min | 9.8 min | 9.8 min |
| Utilisation | 63.3 % | 51.3 % | 47.5 % | 48.1 % | 46. 8% | 44.4 % |

Table VI: Impact of increased battery capacity.

| | **0 % (~3 h)** | **100 % (~6 h)** | **200 % (~9 h)** | **300 % (~12 h)** |
|---|---|---|---|---|
| Picking | 15.7 min | 12.9 min | 12.6 min | 12.5 min |
| Delivery | 12.3 min | 10.4 min | 10.5 min | 10.4 min |
| Utilisation | 63.3 % | 53.8 % | 49.5 % | 49.1 % |

Table VII: Impact of deadlock, obstacle avoidance and error reduction.

| | **0 %** | **5 %** | **10 %** | **15 %** | **20 %** | **25 %** |
|---|---|---|---|---|---|---|
| Picking | 15,7 min | 12.3 min | 11.5 min | 10.8 min | 9.7 min | 9.6 min |
| Delivery | 12.3 min | 10.4 min | 9.7 min | 8.5 min | 8.0 min | 8.0 min |
| Utilisation | 63.3 % | 56.3 % | 50.6 % | 45.6 % | 40.5 % | 40.4 % |

## 7. DISCUSSION AND CONCLUSION

Different scenarios were simulated to analyse various improvement approaches, including levelling the transportation volume, increasing the reliability of delivery operations and increasing transportation capacity, to address the increasing demand for transported goods in the hospital. In the previous chapter, the most important results were presented. Based on insights gained from the simulation, hospital planners can evaluate forecasted needs and countermeasures. Different potential solutions were tested to determine how these changes impact the logistics and material handling system. The results indicate a non-linear progression, which can be helpful in recognising the limits and boundaries of the implemented material handling system.

The increase in goods transportation affected the AGV system' performance slightly until the tipping point at 25 %, with a continuous, strong increase afterwards (see Table III). The case hospital's AGV system has been designed to meet not only current demand but also handle future transportation demand to some extent. However, the evaluation of the logistics system shows that after 20 %, a strong performance loss can be expected in the robustness of the system. Small demand changes, at this point, can have a stronger impact. To address this challenge, different alternatives were investigated. Expanding operating hours has a small effect on performance because the transportation demand pattern has high peaks during the hospital's core activity hours, and many transportation activities cannot be allocated outside of these hours. For instance, food cannot be served early in the morning or at night. Increasing the number of AGVs and their battery capacity are two alternatives with potential for improvement. It was observed that without increasing the number of elevators, the increased AGV capacity quickly reached its limits (see Tables III and V). In these cases, bottlenecks develop at or in the elevators and cause queues, resulting in minimal further performance improvement.

Queues with AGVs can lengthen quickly in hospitals and affect the logistics system. If a queue lengthens, several AGVs are quickly affected. The hospital layout and corridors do not allow for several routing alternatives. Obstacles hindering the AGVs' movements or the maintenance team taking a long time to correct errors has a significant impact on the AGVs' transportation performance. Of the average of 60–100 errors counted per day by the case hospital's AGV system, only a few lead to very long queues forming. Improvement efforts undertaken to reduce errors and, thus, avoid queues, can significantly reduce transportation times (see Table VII).

This study has highlighted constraints related to operating AGVs in dynamic environments. The simulation model uses and relies on historical data obtained from the AGV system, which contains a considerable amount of information representing the 'real' material flow. Compared to other industries, in hospitals, enterprise resource planning systems or tracking systems are less common and less integrated. The ABS approach enables depicting on the current and modified material flows. The validation of the simulation model achieved good results, further emphasising the relevance of our approach. One of the strengths of this simulation model is that it can investigate goods that usually have limited information available, such as catering or waste. Single material flow can be further investigated and analysed.

The model can be easily adapted for use in other hospitals and can take several additional inputs into consideration; hence, it can be used to evaluate the implementation of new or different material handling systems. Furthermore, according to the hospital managers and the results of the simulation, AGVs are sensitive to the dynamic environments found in hospitals. In recent years, technological advances have been rapid and influenced the indoor mobility of robots. Increased battery power, cameras for high-quality environment recognition, and increased on-board computational power have enabled greater autonomy in mobile robots' navigation. Obstacle avoidance and dynamic pathfinding make autonomous mobile robots more appropriate for dynamic environments, such as hospitals. However, this kind of material handling system is still not widely applied and investigated in hospitals.

Future research should investigate the benefits and boundaries of autonomous mobile robots in hospitals to promote the use of this innovative technology. Additionally, the applicability of this simulation model should be explored in other hospitals, and its effects on the material handling system's long-term performance should be investigated.

## ACKNOWLEDGEMENT

This research received funding from the strategic research area NTNU Health in 2019 at NTNU, Norwegian University of Science and Technology, the environment and sustainable development project (number VDLA04) and Jubileumsanslaget grant (grant number V-2019-0611/1) at KTH, Royal Institute of Technology. The authors also gratefully acknowledge the case hospital that made it possible to conduct this study.

## REFERENCES

[1] Williams, C.; Asi, Y.; Raffenaud, A.; Bagwell, M.; Zeini, I. (2016). The effect of information technology on hospital performance, *Health Care Management Science*, Vol. 19, No. 4, 338–346, doi:10.1007/s10729-015-9329-z

[2] Barbash, G. I. (2010). New technology and health care costs--the case of robot-assisted surgery, *The New England Journal of Medicine*, Vol. *363, No.* 8, 701, doi:10.1056/NEJMp1006602

[3] St. Olavs Hospital HF (2018). Utviklingsplan 2019-2035. from *http://stolav.no/Documents/Utviklingsplan/Vedtatt%20Utviklingsplan%20220218.pdf,* accessed on 30-06-2019

[4] OECD/EU. (2018). *Health at a Glance: Europe 2018: State of Health in the EU Cycle*, OECD Publishing, Paris

[5] Giancotti, M.; Guglielmo, A.; Mauro, M. (2017). Efficiency and optimal size of hospitals: Results of a systematic search, *PloS One*, Vo.. 12, No. 3, e0174533, doi: 10.1371/journal.pone.0174533

[6] Ozcan, Y. A. (2005). Quantitative Methods in Health Care Management: Techniques and Applications, Vol. 4, John Wiley & Sons, San Francisco

[7] Poulin, É. (2003). Benchmarking the hospital logistics process, *CMA Management*, Vol. 77, No. 1, 20

[8] Volland, J.; Fügener, A.; Schoenfelder, J.; Brunner, J. O. (2017). Material logistics in hospitals: A literature review, *Omega*, Vol. 69, 82–101, doi:10.1016/j.omega.2016.08.004

[9] Jarrett, G. (1998). Logistics in the health care industry, *International Journal of Physical Distribution Logistics Management*, Vol. 28, No. 9/10, 741–772, doi:10.1108/09600039810248154

[10] Rivard-Royer, H.; Landry, S.; M. Beaulieu, M. (2002). Hybrid stockless: A case study: Lessons for health-care supply chain integration, *International Journal of Operations & Production Management*, Vol. 22, No. 4, 412–424, doi:10.1108/01443570210420412

[11] Landry, S.; Philippe, R. (2004) How logistics can service healthcare, *Supply Chain Forum: An International Journal*, Vol. 5, No. 2, 24–30, doi: 10.1080/16258312.2004.11517130

[12] Granlund, A.; Wiktorsson, M. (2014). Automation in internal logistics: Strategic and operational challenges, *International Journal of Logistics Systems and Management,* Vol. 18, No. 4, 538–558

[13] Ullrich, G. (2015). *Automated Guided Vehicle Systems,* Springer, Berlin, doi: 2015,10:978-3

[14] Vis, I. F. (2006). Survey of research in the design and control of automated guided vehicle systems, *European Journal of Operational Research*, Vol. 170, No. 3, 677–709, doi:10.1016/j.ejor.2004.09.020

[15] Benzidia, S.; Ageron, B.; Bentahar, O.; Husson, J. (2018). Investigating automation and AGV in healthcare logistics: A case study based approach, *International Journal of Logistics Research and Applications*, Vol. 22, No. 3, 273–293, doi:10.1080/13675567.2018.1518414

[16] Le-Anh, T.; De Koster, M. (2006). A review of design and control of automated guided vehicle systems, *European Journal of Operational Research*, Vol. 171, No. 1, 1–23, doi:10.1016/j.ejor.2005.01.036

[17] 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*, Vol. 142, 3970–3984, doi:10.1016/j.jclepro.2016.10.057
[18] Udhayakumar, P.; Kumanan, S. (2010). Task scheduling of AGV in FMS using non-traditional optimization techniques, *International Journal of Simulation Modelling*, Vol 9, No. 1, 28-39, doi:10.2507/IJSIMM09(1)3.139
[19] Mousavi, M.; Yap, H. J.; Musa, S. N.; Dawal, S. Z. M. (2017). A fuzzy hybrid GA-PSO algorithm for multi-objective AGV scheduling in FMS, *International Journal of Simulation Modelling*, Vol. 16, 58-71, doi:10.2507/IJSIMM16(1)5.368
[20] Pedan, M.; Gregor, M.; Plinta, C. (2017). Implementation of automated guided vehicle system in healthcare facility, *Procedia Engineering*, Vol. 192, 665–670, doi:10.1016/j.proeng.2017.06.115
[21] Dembińska-Cyran, I. (2005). Internal and external supply chain of hospital, *LogForum* , Vol. 1, No. 1, 5, ISSN 1734-459X
[22] Wieser, P. (2011). From health logistics to health supply chain management, *Supply Chain Forum: An International Journal*, Vol. 12, No. 1, 4–13, doi:10.1080/16258312.2011.11517249
[23] Rimpiläinen, T .I.; Koivo H. (2008). Modeling and simulation of hospital material flows, *UKSIM 2008: Tenth International Conference on Computer Modelling and Simulation*, 579–583, doi:10.1109/UKSIM.2008.44
[24] Čerić, V. (1990). Simulation study of an automated guided-vehicle system in a Yugoslav hospital, *Journal of the Operational Research Society*, Vol. 41, No. 4, 299–310, doi:10.1057/jors.1990.51
[25] Swain, R. W.; John III, M. J. (1978). A simulation analysis of an automated hospital materials handling system, *AIIE Transactions*, Vol. 10, No. 1, 10–18, doi:10.1080/05695557808975178
[26] Chockalingam, A.; Jayakumar, K.; Lawley, M. A. (2010). A stochastic control approach to avoiding emergency department overcrowding, *Proceedings of the 2010 Simulation Winter Conference*, 2399–2411, doi:10.1109/WSC.2010.5678936
[27] Hagtvedt, R.; Ferguson, M.; Griffin, P.; Jones, G.T.; Keskinocak, P. (2009). Cooperative strategies to reduce ambulance diversion, *Proceedings of the 2009 Simulation Winter Conference*, 1861–1874, doi:10.1109/WSC.2009.5429194
[28] Zhang, C.; Grandits, T.; Härenstam, K. P.; Hauge, J. B.; Meijer, S. (2018). A systematic literature review of simulation models for non-technical skill training in healthcare logistics, *Advances in Simulation*, Vol. 3, No. 1, 15, doi:10.1186/s41077-018-0072-7
[29] Maidstone, R. (2012). Discrete event simulation, system dynamics and agent based simulation: Discussion and comparison, *System*, Vol. 1, No. 6, 1–6
[30] Wurzer, G. (2013). In-process agent simulation for early stages of hospital planning, *Mathematical and Computer Modelling of Dynamical Systems*, Vol. 19, No. 4, 331–343, doi:10.1080/13873954.2012.761638
[31] Siebers, P. O.; Macal, C. M.; Garnett, J.; Buxton, D.; Pidd, M. (2010). Discrete-event simulation is dead, long live agent-based simulation!, *Journal of Simulation,* Vol. 4, No. 3, 204–210, doi:10.1057/jos.2010.14
[32] Zhao, J. Y.; Wang, Y. J.; Xi, X.; Wu, G. D. (2017). Simulation of steel production logistics system based on multiagents, *International Journal of Simulation Modelling*, Vol. 16, No. 1, 167–175, doi:10.2507/IJSIMM16(1)CO4
[33] Anand, N.; Meijer, D.; Van Duin, J. H. R.; Tavasszy, L.; Meijer, S. (2016). Validation of an agent based model using a participatory simulation gaming approach: The case of city logistics, *Transportation Research Part C: Emerging Technologies*, Vol. 71, 489–499, doi:10.1016/j.trc.2016.08.002

# Paper 3

Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2020).
Autonomous Mobile Robots in Hospital Logistics.
In *IFIP International Conference on Advances in Production Management Systems*
(pp. 672-679). Springer, Cham.

*This is an accepted manuscript of an article published in*
*IFIP International Conference on Advances in Production Management Systems.*
*The final authenticated version is available online at:*
https://doi.org/10.1007/978-3-030-57993-7_76

# Autonomous Mobile Robots in Hospital Logistics

Giuseppe Fragapane[1(✉)], Hans-Henrik Hvolby[1,2], Fabio Sgarbossa[1], and Jan Ola Strandhagen[1]

[1] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway
giuseppe.fragapane@ntnu.no

[2] Centre for Logistics, Department of Materials and Manufacturing Engineering, Aalborg University, Aalborg, Denmark

**Abstract.** The recent advances in technology have increased flexibility in indoor mobility and human-robot collaboration, opening up new opportunities to perform material handling tasks, especially in narrow, dynamic environments, such as hospitals. Sensing devices, powerful on-board computers, artificial intelligence, and collaborative equipment allow autonomous mobile robots (AMRs) to drive and fulfill material handling activities autonomously. In hospitals, material handling activities are widely performed manually. This study investigates five innovative applications of AMRs, highlighting their benefits compared with other material handling systems applied in hospitals, and presenting research needs. The study concludes that AMRs can support and collaborate closely with hospital personnel to increase value-added time for patient care.

**Keywords:** Autonomous mobile robots · Material handling · Hospital · Logistics

## 1 Introduction

Automating material handling activities can significantly improve efficiency and productivity in the healthcare sector, since hospitals, compared to other industries, still, often perform these activities manually. A large survey conducted in the US, Canada, and Germany exposed that nursing's none–value-adding and non-nursing activities (e.g., delivery and retrieval of food trays, ancillary, or housekeeping services) consume around 40% of nurses' time [1]. Many of these activities could have been accomplished by other hospital personnel or advanced material handling systems [2–4]. However, finding the appropriate material handling system and level of automation for addressing hospitals' and patients' requirements is quite challenging [5]. The common material handling systems applied in hospitals allow low flexibility in mobility. Automated guided vehicles (AGV) cannot bypass obstacles and enter wards or departments due to safety and space concerns. Automated vacuum collection systems, pneumatic tube systems, and overhead transportation systems often have only fixed pick and/or delivery stations in departments. The low flexibility in mobility makes it difficult to automate material handling in the so-called last 50 m, referring to the distance in the department to the patient, as well as in other departments.

The need for more flexibility has pushed the development of autonomous mobile robots (AMRs). Thanks to ubiquitous sensors, powerful on-board computers, artificial intelligence (AI), and simultaneous location and mapping (SLAM) technology, AMRs can understand their operating environments and navigate in facilities without the need to define and implement reference points in advance. AMRs are often small and agile, and they show their strength in high-traffic environments and low-volume transportation. Due to AMRs' characteristics, they can access narrower areas, interact with healthcare personnel and patients, and provide more services, such as assistive activities. AMRs have shown great potential in automotive, warehousing and process industry, in which they have supported increased production flexibility and productivity [6]. The potential of AMRs' high accessibility and flexibility in providing services has not been exploited and investigated in hospital environments.

Therefore, the aim of this paper is (I) to describe innovative material handling services and applications of AMRs in hospitals, (II) to compare them with other material handling systems in hospitals, and (III) to highlight future research needs for AMRs in hospital logistics. Two case studies have been conducted and three examples from the literature are presented to achieve these objectives.

The rest of the paper is organized as follows. The next section provides background information on traditional material handling systems in hospitals. Section three introduces and explains the cases and examples in which AMR has been applied in hospitals. The fourth section compares AMRs with other material handling systems in hospitals. The study ends with recommendations for future research areas for hospital logistics and AMRs.

## 2 Theoretical Background

### 2.1 Material Handling Systems in Hospitals

Logistics and material handling are crucial parts of the healthcare industry. Depending on the characteristics of the goods and the delivery requirements, a material handling system can be assigned to these tasks. Small objects, e.g., samples being delivered to laboratories, are mainly sent via pneumatic tube systems in hospitals due to time constraints. While automated vacuum collection systems are only used for return transportation of waste or linen, overhead transportation systems are used for both incoming and return transportation of loads of up to 15 kg to different departments. For transportation of heavier and bigger goods, AGVs have demonstrated good results in distributing high-volume goods to many pick-and-place positions and traveling long distances within hospitals without disturbing the hospital traffic [7]. The current material handling systems in hospitals are still largely dependent on human interaction for preparing, loading/unloading, and sending the items.

In contrast, AMRs have been recently introduced to hospitals, and their applicability in hospital logistics has not been exploited. AMRs possess a wide array of small and power-efficient sensing technologies, such as integrated laser scanners, 3D cameras, accelerometers, gyroscopes, etc., which allow them to digitalize an environment. Processing the sensing data with simultaneous location and mapping technology enables an AMR to create a map of its environment and calculate its position [8]. Unlike AGV systems, in which the central unit makes all routing and thus navigation decisions for all AGVs, AMRs can plan collision-free paths, make real-time decisions to avoid collisions, and so navigate in dynamic and unpredictable environments. AI techniques such as vision systems and machine learning enable the identification and classification of obstacles. These learning techniques enable AMRs to solve complex control problems in unfamiliar, real-world environments.

The main characteristics of the aforementioned material handling systems are shown in Table 1. A recent literature review in material logistics pointed out that standards and best practices for how to transport goods in hospitals barely exist [9]. To the best of the authors' knowledge, the applicability and research needs of AMRs in hospital logistics have not been addressed.

**Table 1.** Characteristics of automated material handling systems in hospitals

| | Automated guided vehicle | Autonomous mobile robot | Automated vacuum collection system | Overhead transportation system | Pneumatic tube system |
|---|---|---|---|---|---|
| Capacity load | 1–500 kg | 1–100 kg | 1–50 kg | 1–15 kg | up to 2 kg |
| Transportation speed | 1–2 km/h | 3–4 km/h | 20–70 km/h | 2–3 km/h | 10–25 km/h |
| Services provided | Transportation | Transportation, collaboration, assistance, etc. | Only return transportation | Transportation | Transportation |
| Service points | Fixed pick and delivery points | Flexible pick and delivery points | Fixed pick and delivery points | Fixed pick and delivery points | Fixed pick and delivery points |
| Navigation | Fixed guided path | Autonomous in predefined zones | Fixed tube path | Fixed guided path | Fixed tube path |

# 3 Cases and Examples

## 3.1 Case 1: Sterile Instrument Transportation

Sterile instruments are transported in wagons from and to departments in a closed-loop logistics system by an AMR. The sterile processing department is responsible for picking and sending the sterile instruments required for medical treatment from the storage area to the departments. After usage at the department level (e.g., operating room), the goods are sent back to the central sterile processing department for cleaning, inspection, and sterilization. Hospital personnel can request, send, and track transportation via a tablet. Due to the logistics setup and the reliable transportation offered by the AMR, sterile goods can be sent Just-in-Time and demand-based on demand (Fig. 1).

There are 10 pick and delivery stations located among five different levels in the case hospital. The AMR can open doors, use elevators, enter departments, bypass obstacles, handle dynamic environments, and reach the destination pickup-and-delivery station to deliver the sterile instruments. The AMR delivers approximately 60 wagons daily and substitutes one full-time employee.

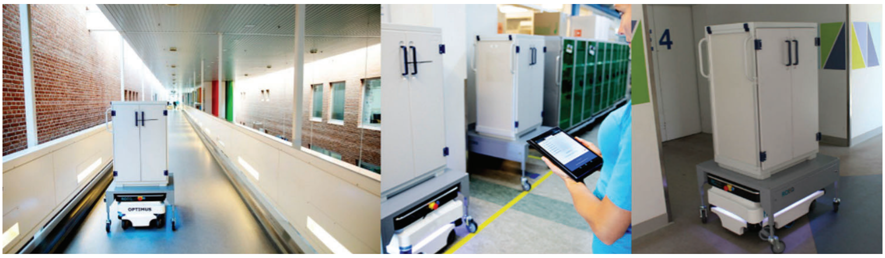


**Fig. 1.** AMR in sterile instrument logistics [10]

### 3.2 Case 2: Personalized Cancer Medicine Transportation

In chemotherapy treatments, patients receive personalized cancer medicine that has a short lifetime and can cost several thousand euros. The medicine is produced in the pharmaceutical department in the basement of the case hospital, while the actual treatment takes place several floors above it. Therefore, high-precision delivery, reliability, safety, and security are required for the transportation of medicine between the two departments.

The case hospital uses an AMR to transport the medicine in a locked drawer from the basement through the hospital to the final destination in the department [10]. After delivery, the AMR returns to the pharmaceutical department and waits to receive the next order (Fig. 2). The AMR reduces the healthcare personnel's responsibility and the amount of time involved in the transportation of medicine. This helps healthcare personnel increase patient care and value-added time and thus has enabled the return of the initial investment within one year.

**Fig. 2.** Sending and delivery of cancer medicine with secured transportation [10]

### 3.3 Example 1: AMR Providing Telemedicine

AMRs with teleoperating and medical equipment can be controlled by a human from a long distance and perform tasks in dynamic environments [11]. Tele-operation enables a new method of using this valuable resource and eases the high risk of infectious disease transfer. Physicians and specialists can communicate with patients and perform some of their duties at a safe distance from infected patients. A telemedicine robot with autonomous navigation technology has been introduced in hospitals in the US [12]. While the AMR moves from room to room, the physician can easily connect for patient consults and access clinical documentation, patient data, and medical imaging (Fig. 3). Digitizing and robotizing the material handling activities will provide data for and insights into new options for process improvement.

**Fig. 3.** AMR providing telemedicine [12]

### 3.4 Example 2: Assistive, Collaborative AMR in the Hospital Laboratory

AMRs with manipulators can assist workers by interacting with humans as robotic coworkers. In other industries, AMRs are used as assistive systems and can mount several heavy parts of a car body together at different stages along the car assembly line [13], thus increasing both productivity and quality while simultaneously reducing fatigue levels among workers. A dual-arm mobile robot has been introduced to a US hospital laboratory [14]. The AMR was designed to work alongside medical staff and help complete lab workers' repetitive tasks (Fig. 4).

**Fig. 4.** Assistive, collaborative AMR in a hospital laboratory [14]

It can sense and navigate its way around its human coworkers autonomously and simultaneously learn to find optimized routes from one location to another. The vision for using AMRs in laboratories is that they will take over a wide range of repetitive and time-consuming activities, such as preparation of medicines, loading and unloading centrifuges, pipetting and handling liquids, and picking up and sorting test tubes.

### 3.5 Example 3: AMR Disinfecting Rooms

Hospitals must clean and disinfect rooms after usage to reduce the spread of hazardous bacteria. Hospitals are strategizing to reduce the risk of such spread and simultaneously increase awareness [15]. The development of UV-C light systems significantly supports the destruction of bacteria. UV-C light systems need 10 min of exposure time to kill 99.99% of bacteria [16]. While the equipment can often be found on wheels and is moved manually from room to room, AMRs provide a platform for autonomously transporting the equipment into and within rooms (Fig. 5a). Therefore, an AMR can cover more surfaces compared to a fixed UV-C system and reduce the exposure of hospital personnel to bacteria (Fig. 5b). Further, it can collect relevant data during the disinfection process and communicate when the room is ready for usage.

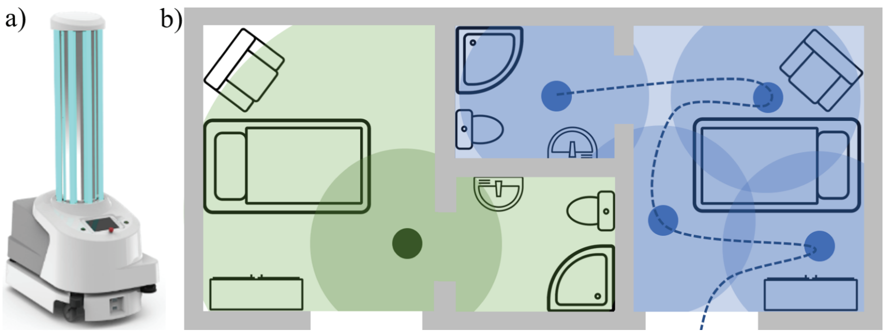



**Fig. 5.** **a**: AMR with disinfection equipment [16]. **b**: Left room disinfected with stationary equipment; right room disinfected by AMR (green/blue areas symbolizes disinfection range)

## 4 Discussion and Conclusion

Unlike other material handling systems applied in hospitals, AMRs utilize AI for decision making, which significantly increases their flexibility in performing material handling activities in hospitals. AI especially supports AMRs' decision making in path and motion planning. While typically, an A* algorithm is applied in path planning to find the shortest path, AI allows analysis of the dynamic environment and reacts appropriately to congestions. Machine learning techniques can suggest optimized paths based on previous deliveries. These processes increase the reliability of precision delivery, which is crucial in hospitals since small delivery deviations can have large impacts on patient treatment. For instance, missing instruments or medicine will postpone treatments or negatively impact the health of the patient. Robust and reliable material handling systems like AMRs are crucial for transferring material flows that can highly impact patient health from manual to automated.

AI can further support interaction between humans and machines, enabling assistive or collaborative tasks. Vision-based sensing, manipulators for grabbing and handling probes, and the use of machine learning allow AMRs to learn to perform a wide variety of repetitive activities. AMRs can function as robotic coworkers in laboratories, autonomously improving both specific processes and overall performance. This allows for the reduction of workload for highly trained laboratory workers.

AMRs can deliver to the point-of-use, the patient, and so cover a wide service area. For many years, mobile robots were a virtually unimaginable and practically unacceptable solution in healthcare support. People could not associate hospitals with a production environment. The increased social acceptance of AMRs allows integration into departments and wards. AMRs can deliver to the point of use, the patient, and so cover a wide service area. The integration of AMRs as transporting, collaborating, or assisting robots allows a rethinking of logistics and material handling activities in hospitals. Therefore, future research should focus on:

- What manual material handling activities should AMRs assist with or take over, and when?
- How should AMRs interact with hospital personnel and patients to achieve high social acceptance and safety?
- How should hospital goods be transported by AMRs to achieve high reliability, productivity, safety, and quality?
- How should AMRs be integrated with AGVs and other stationary automated material handling systems?
- How should AMRs be designed and planned at the strategic level in hospitals?
- How can the optimal number of AMRs be determined in hospital logistics?
- How should path planning and motion planning be adapted for hospital environments?

**Acknowledgment.** This research received funding from the strategic research area of NTNU Health in 2020 at NTNU. The authors would also like to express their gratitude to the Regional Development Fund in Denmark for supporting the project “Reference architecture and open standards”. Finally, the authors gratefully acknowledge the case hospitals that made it possible to carry out this study.

## References

1. Yen, P.Y., et al.: Nurses’ time allocation and multitasking of nursing activities: a time motion study. In: AMIA Annual Symposium Proceedings, vol. 2018, p. 1137. American Medical Informatics Association (2018)
2. Aiken, L.H., et al.: Nurses’ reports on hospital care in five countries. Health Aff. **20**(3), 43–53 (2001)

3. Kudo, Y., Yoshimura, E., Shahzad, M.T., Shibuya, A., Aizawa, Y.: Japanese professional nurses spend unnecessarily long time doing nursing assistants' tasks. Tohoku J. Exp. Med. **228**(1), 59–67 (2012)
4. Wong, D., Bonnici, T., Knight, J., Gerry, S., Turton, J., Watkinson, P.: A ward-based time study of paper and electronic documentation for recording vital sign observa-tions. J. Am. Med. Inform. Assoc. **24**(4), 717–721 (2017)
5. Granlund, A., Wiktorsson, M.: Automation in internal logistics: strategic and operational challenges. Int. J. Logist. Syst. Manage. **18**(4), 538–558 (2014)
6. Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., Strandhagen, J.O.: Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. Ann. Oper. Res., 1–19 (2020). https://doi.org/10.1007/s10479-020-03526-7
7. Fragapane, G.I., Bertnum, A.B., Hvolby, H.H., Strandhagen, J.O.: Material distribution and transportation in a norwegian hospital: a case study. IFAC-papersonline **51**(11), 352–357 (2018)
8. Bloss, R.: Simultaneous sensing of location and mapping for autonomous robots. Sens. Rev. **28**(2), 102–107 (2008)
9. Volland, J., Fügener, A., Schoenfelder, J., Brunner, J.O.: Material logistics in hospitals: a literature review. Omega **69**, 82–101 (2017)
10. MIR Homepage. https://www.mobile-industrial-robots.com/en/insights/case-studies/. Accessed 4 Apr 2020
11. Papadopoulos, I., Koulouglioti, C., Lazzarino, R., Ali, S.: A systematic review of enablers and barriers to the implementation of socially assistive humanoid robots in health and social care. BMJ Open **10**(1), 1–13 (2019)
12. Intouch Homepage. https://www.businesswire.com/news/home/20130506005495/en/InTouch-Health-iRobot-Announce-Customers-Install-RP-VITATM. Accessed 4 Apr 2020
13. Angerer, S., Strassmair, C., Staehr, M., Roettenbacher, M., Robertson, N.M.: Give me a hand—the potential of mobile assistive robots in automotive logistics and assembly applications. In: 2012 IEEE International Conference on Technologies for Practical Robot Applications (TePRA), pp. 111–116. IEEE (2012)
14. Yumi Homepage. https://new.abb.com/news/detail/37301/abb-demonstrates-concept-of-mobile-laboratory-robot-for-hospital-of-the-future. Accessed 4 Apr 2020
15. Goldmann, D.A., et al.: Strategies to prevent and control the emergence and spread of antimicrobial-resistant microorganisms in hospitals: a challenge to hospital leader-ship. JAMA **275**(3), 234–240 (1996)
16. UVD Robots Homepage. http://www.uvd-robots.com/. Accessed 4 Apr 2020

# Paper 4

Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2021).
Autonomous mobile robots in sterile instrument logistics: An evaluation of the material handling system for a strategic fit framework.
*Production planning & control.*

*This is an accepted manuscript of an article published in Production planning & control.*
*The final authenticated version is available online at:*
https://doi.org/10.1080/09537287.2021.1884914

PRODUCTION PLANNING & CONTROL
https://doi.org/10.1080/09537287.2021.1884914

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

# Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework

Giuseppe Fragapane[a], Hans-Henrik Hvolby[b], Fabio Sgarbossa[a] and Jan Ola Strandhagen[a]

[a]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway; [b]Department of Materials and Production, Centre for Logistics, Aalborg University, Denmark

**ABSTRACT**
The logistics activities of sterile instruments are both labour- and cost-intensive. Automating sterile instrument transportation offers an excellent opportunity to reduce staff members' responsibilities and time committed to that task. With recent technological advances in material handling, autonomous mobile robots offer an innovative solution for transporting sterile instruments, especially in dynamic environments such as hospitals. However, hospital planners need guidance in deciding when to apply which material handling systems to achieve optimal performance. This study uses a multiple case study to map sterile instrument logistics and evaluate the transportation performance of material handling systems in terms of flexibility, productivity, quality/service, and costs. Applying contingency theory and analysing the relationships between material handling systems and hospital characteristics, we contribute with a strategic fit framework showing the ideal states to achieve high performance.

**ARTICLE HISTORY**
Received 16 June 2020
Accepted 30 January 2021

**KEYWORDS**
autonomous mobile robots; sterile instrument logistics; material handling; strategic fit; multiple case study

## 1. Introduction

The well-being and recovery of patients seeking help depend heavily on hospitals' responsiveness in providing treatment in both emergency cases and elective procedures (Soremekun, Takayesu, and Bohan 2011; Siciliani, Moran, and Borowitz 2014; Nikolova, Harrison, and Sutton 2016). Ensuring a high level of responsiveness requires hospitals to manage – in addition to human and machine resources – the flow of materials, such as sterile instruments, to provide emergency and planned treatments or surgeries. Maintaining the high availability of sterile instruments requires efficient and reliable logistics (Volland et al. 2017). Many of these instruments are expensive and can only be used for a specific type of procedure. To keep costs low, hospitals circulate a wide range of instruments, often several times per day, between point-of-use stations – such as operating theatres and outpatient rooms – and their central sterile processing department (CSPD). All reusable instruments must be properly cleaned, disinfected and checked for functionality after each use. Since patient safety depends on medical instruments functioning properly with minimal contagion risk, hospitals must ensure that these instruments are always of high quality, sterile and available when needed (Chobin and Swanson 2012).

However, hospitals struggle to manage an efficient sterile instrument logistics system, which includes processing, storage, usage and transportation, to keep the balance between low costs and high availability of instruments. A recent study revealed that in hospitals, up to 46% of the delays in operation rooms (ORs) can be traced back to the unavailability of sterile instruments (Wubben et al. 2010). These delays not only cause longer working hours for doctors and staff – additional costs for the hospitals – but also negatively impact the quality of care, and so adverse effects can occur. The logistics of sterile instruments impact the hospital's overall performance in terms of flexibility, productivity, quality and costs (Di Mascolo and Gouin 2013).

Activities connected to the logistics of sterile instruments, such as cleaning, processing, inspecting, packaging, storing and transporting, are both labour- and cost-intensive and represent an opportunity to reduce costs for many hospitals (van de Klundert, Muls, and Schadd 2008; Di Mascolo and Gouin 2013). Previous studies have identified that transportation has a significant impact on the performance of sterile instrument logistics and is one of the major drivers of costs (Hammami et al. 2006; van de Klundert, Muls, and Schadd 2008; Tlahig et al. 2013). Transportation requests can vary considerably in frequency, distance and quantity, and the requested period from ordering to receiving sterile instruments can be very short because of, for instance, patients arriving unexpectedly and in need of emergency surgery (van de Klundert, Muls, and Schadd 2008). Furthermore, the number of carts used for the transportation of sterile instruments to the operating theatre varies. The same surgical procedure can require different or additional instruments depending on the patient's age, sex and physical condition

CONTACT Giuseppe Fragapane Giuseppe.fragapane@ntnu.no Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway

and the surgeon's preferences. Therefore, a great challenge lies in managing transportation resources of the material handling system to respond quickly in times of emergency and keeping regular transportation efficient at the same time.

Hospitals are continuously strategising about the automation of transporting hospital goods with the aim of reducing staff members' responsibilities and the amount of time required for transportation, hence increasing patient care and reducing costs (Pedan, Gregor, and Plinta 2017). Sterile instrument transportation has proven challenging to automate. Only one out of 39 hospitals in Norway uses an automated material handling system – in this case, automated guided vehicles (AGVs) – to transport sterile instruments (Ullrich 2015). The difficulty lies in finding the appropriate material handling system and level of automation for the physical and organisational needs of hospitals (Granlund and Wiktorsson 2014). The necessary level of flexibility in sterile instrument transportation has often been achieved by human labour, so manual transportation is the primary choice between a hospital's CSPD and its various point-of-use stations.

The growing logistics sector requires more highly tailored machines and could benefit from robotics (Hichri et al. 2019). Recent technological advances have had a positive impact on robots' indoor mobility. More powerful batteries, high-quality cameras for environmental recognition and increased onboard computational power enable greater autonomy of mobile robots' navigation. These changes have led to the introduction of autonomous mobile robots (AMRs) that can navigate freely within a predefined area and provide material handling services (Fragapane et al. 2021). Because of their obstacle avoidance, dynamic pathfinding and smaller vehicle dimensions, AMRs can be implemented in busy environments, such as areas with patients present and narrow hallways and doors, leading to a higher degree of integration in hospitals. Compared with an AGV, no physical reference points need to be preinstalled to guide an AMR through a hospital, and implementation time and costs can be greatly reduced. User-friendly controls enable employees to send, receive and track each transportation with ease. Technologies promoting the exchange of information have been identified as a key factor in streamlining material flow and improving collaboration in hospitals (Marques, Martins, and Araújo 2020). AMRs offer an opportunity to reduce the involvement and responsibilities of humans in material handling activities (Fragapane et al. 2020). Indeed, the implementation of AMRs may increase the responsiveness of a hospital's sterile instrument logistics while retaining the necessary level of flexibility to ensure that items are available and service levels maintained.

Most material handling systems originate and are operated in industrial settings, but to ensure long-term performance benefits, technologies must adapt to hospital characteristics – for instance, handling high levels of human interaction in a narrow and dynamic environment (Fragapane et al. 2019; Tortorella et al. 2020). Because of the variability in these traits, standards and best practices on how goods should be transported in hospitals are lacking (Volland et al. 2017). Hospital planners need guidance to achieve high performance when applying advanced technologies (Tortorella et al. 2020). The identification of the drivers of high performance and examination of the conditions under which specific practices, resources or setups are used are all vital for planning and controlling a logistics system (Ketokivi and Schroeder 2004; Böhme et al. 2016). The literature is still lacking in this regard (see Section 2). Material handling systems for sterile instrument logistics have not been investigated enough to provide hospital planners with enough support to achieve high performance in transportation while still considering crucial hospital characteristics. An approach to filling this gap is to analyse different material handling systems based on several key performance indicators (KPIs) and apply contingency theory to identify the impact of organisational characteristics with contingencies – in this case, hospital characteristics – to achieve high performance. The results and insights of this type of investigation can be used to develop a strategic fit framework for hospital planners, indicating the high performance of material handling systems and taking into consideration the hospital characteristics and contingencies.

Based on the information above, the present study's objectives are as follows:

1. Identify KPIs that are useful in evaluating the performance of sterile instrument transportation;
2. Apply contingency theory to describe and explain the impact of hospital characteristics and contingencies on the performance of the material handling systems; and
3. Based on the findings in objectives 1 and 2, align material handling systems, hospital characteristics and contingencies to achieve high performance, thus identifying the strategic fit.

To achieve these objectives, a multiple case study was conducted at three hospitals that each use different material handling systems to transport sterile instruments: manual transportation with dedicated elevators, a shared AGV system and a dedicated AMR system.

The remainder of the current paper is organised as follows: The next section reviews the related literature on sterile instrument logistics, the KPIs applied, contingency theory and strategic fit to frame the gap in existing research. Section 3 describes the multiple case study method and contingency theory employed, including case selection, data collection and analysis, while Section 4 describes the characteristics of the three case hospitals. Section 5 presents the KPI results for each case hospital, Section 6 explains the impact of hospital characteristics on material handling systems, and Section 7 explains the strategic fit between material handling systems and hospital characteristics. We conclude the study in Section 8 and offer recommendations for future research.

## 2. Literature review

### 2.1. Sterile instrument logistics

Instrument sterilisation in hospitals has evolved from a decentralised service performed by nurses in an operating room annexe to a centralised activity in which large-scale sterilisation is performed in a separate department by specialised technicians. Centralising the sterilisation process has made it possible to apply operations management techniques and optimise reverse, closed-loop logistics with the operational activities of sterile processing, storage, usage and transportation.

Regarding sterile processing, Di Mascolo and Gouin (2013) propose a generic simulation model for hospital planners to design the CSPD (e.g. determine the number of machines or loading machines policies) and evaluate the different sterile processing activities in the utilisation or throughput times. Ozturk, Begen, and Zaric (2014) propose that a typical bottleneck in sterile processing is the washing step. The arrival patterns of contaminated sterile instruments often result in significant accumulation throughout the CSPD (Lin et al. 2008). Ozturk, Begen, and Zaric (2014) introduce a branch-and bound-based heuristic to optimise the washing machine schedule, minimising the makespan of parallel job batches.

To reduce costs and increase the efficiency of CSPD, several studies have investigated decentralising and outsourcing the sterilisation process in hospitals. van de Klundert, Muls, and Schadd (2008) investigate the optimisation problems that must be resolved when redesigning the supply processes of the decentralised CSPD to improve the availability of materials and reduce costs; the introduced lot-sizing and transportation model aims to find the minimal inventory and transportation costs by using dynamic programming for different replenishment methods. Outsourcing implies keeping safety stocks on site at the hospital. The study by van de Klundert, Muls, and Schadd (2008) highlights the difficulty of setting the safety stock for keeping inventory and transportations low and availability high at the same time. Rather than the number of instruments, it is their immense variety that is challenging for the outsourcing process of the CSPD. Information technology is identified as a valuable opportunity for improvement. Therefore, the model has been extended to a dynamic, nondeterministic setting to highlight the value-added of real-time information availability. In two different scenarios and sterilisation service structures, a recent study by Tlahig et al. (2013) compares the in-house sterilisation and outsourced sterilisation services supplying a network of several hospitals. The introduced model aims to find the optimal setup, location and capacity with the objective function of minimising the total costs, which consist of transportation, sterilisation, resource transfer and acquisition.

Studies about sterile processing have included the constraint of transportation to a larger extent than storage and point-of-use. However, for storage activities, Landry and Beaulieu (2010) present and describe the most common inventory control methods applied in sterile logistics, and Ahmadi et al. (2019) provide an overview of the optimisation approaches to reduce inventory levels, space requirements and costs. Lean tools have mainly supported reducing waste and improving process efficiency at the point-of-use (Costa and Godinho Filho 2016; Villarreal et al. 2018; Fogliatto et al. 2020).

To plan transportation and design material handling systems in hospitals, discrete-event simulations have been the most appropriate approach, especially for AGVs (Čerić 1990; Chikul, Maw, and Soong 2017). Le-Anh and De Koster (2006) provide an overview of the strategic, tactical and operational decisions for planning and controlling AGVs. Fragapane et al. (2019) apply an agent-based simulation model to assess the AGV system in hospitals, investigating the different transportation scenarios to improve delivery time and resource utilisation. A case study by Benzidia et al. (2019) investigates the different goods flows in hospitals and highlights the complexity of the distribution networks performed by AGVs; the study points out that hospitals are more likely to decide to keep manual transportation in case the demand is less predictable and the variety of a single category of goods is high.

In summary, studies in sterile instrument logistics apply significantly higher quantitative methods than qualitative or mixed methods. Mathematical modelling and simulation have been the preferred approaches for planning and optimising the activities of sterile processing, storage, use and transportation of sterile logistics. Furthermore, decision support systems for planning transportation or the material handling system mainly focus on the tactical and operational levels, such as scheduling, routing, battery and traffic management.

### 2.2. Key performance indicators for sterile instrument transportation

Measuring performance can provide information about optimal status or deficiencies in sterile instrument transportation and can serve as the basis for planning, optimisation, improvement, control or evaluation purposes. According to Behn (2003), an evaluation is the most common reason for measuring performance because it tries to answer the following question: How do the operations and practices of this organisation compare with the ones that are known to be most effective and efficient? To compare the actual performance of an organisation against the performance criteria, a variety of outcome measures combined with some input measures should be defined (Behn 2003).

The literature review on sterile instrument logistics allows for identifying the different KPIs applied in previous studies and grouping them in terms of their flexibility, productivity, quality, service and costs. Benzidia et al. (2019) and Fragapane et al. (2019) investigate how well the material handling system in hospitals can adapt to transportation demand changes and how well it can handle different flows of goods. Automating the material flows can reduce the degree of personnel involved in deliveries (Volland et al. 2017). Thereby, measuring and comparing the value-added time supports a comparison of the productivity of an automated material handling system with a manual one. To assess the quality of deliveries, Čerić (1990) uses lead time as a KPI to optimise the transportation schedule of AGVs. Moons, Waeyenbergh, and Pintelon (2019) argue that measuring the response time to urgent requests and reliability of timely and correct deliveries can improve transportation quality. Investigating the reliability and robustness of AGV transportation in hospitals, Fragapane et al. (2019) analyse the number of errors and their effects on transportation performance.

Unsurprisingly, measuring cost performance has received the most attention in hospital logistics (Moons, Waeyenbergh, and Pintelon 2019). For the evaluation of automated material handling systems, the implementation and adjustment costs are especially important to consider because these costs can be quite high and make the automation of material flows unprofitable in hospitals (Chikul, Maw, and Soong 2017). The operational costs of transportation are not to be underestimated; these costs can be crucial when deciding on outsourcing a sterile processing department from the hospital (van de Klundert, Muls, and Schadd 2008).

Overall, in sterile instrument transportation, the defining performance indicators and performance measurements are for planning, optimisation and improvement purposes. Thereby, only a single material handling system has been assessed in these studies. The introduced KPIs allow only for reflection and discussion on a small aspect of sterile instrument transportation, limiting the comparison of different material handling systems. There is a need for a broader variety of KPIs to evaluate the material handling systems in sterile instrument logistics and to support the analysis of the impact of hospital characteristics on these material handling systems.

### *2.3. Contingency theory and strategic fit*

Contingency theory is a major theoretical lens used to view organisations and support organisations to see the relation between organisational characteristics and contingencies, such as the environment, size and strategy for reaching high performance (Donaldson 2001). This theory provides a substantial basis for investigating fit (Acur, Destan, and Boer 2012) because the concept of strategic fit builds on contingent views of strategy and resources (Venkatraman 1989). Strategic fit describes a situation in which elements both internal and external to the organisation are aligned (Scholz 1987), and this fit between a firm and its environment is crucial to yield desirable performance implications (Zott 2003; Fainshmidt et al. 2019). Therefore, strategic fit has been a powerful tool for managers to match the demand and supply characteristics on a strategic level (Fisher 1997; Christopher, Peck, and Towill 2006; Gligor, Esmark, and Holcomb 2015) because it helps reveal the ideal state towards which a logistics system should be continually directed (Zajac, Kraatz, and Bresser 2000). This concept can be used on a supply chain level (Cannas et al. 2020) and for areas within the supply chain, such as production (Buer et al. 2016) or, as in our study, transportation.

### *2.4. Research gap*

The introduction of AMRs has opened new possibilities for performing services and activities and addressing some current challenges in hospital logistics. Since AMRs have only recently been introduced to hospitals, studies analysing the impact of AMRs on hospital logistics and how to deploy them at the strategic level are lacking. No study has yet evaluated the transportation performance of different material handling systems in sterile instrument logistics. The KPIs for the transportation of sterile instruments and crucial hospital characteristics necessary for such an investigation have not yet been sufficiently detailed. Identifying the ideal states of material handling systems on the strategic level – especially the application of AMRs to achieve high performance in sterile instrument transportation – has also not been sufficiently addressed. Contingency theory can provide support in such investigations to identify hospital characteristics and align them to develop strategic fit. To the best of our knowledge, the existing literature is entirely lacking in this regard.

## 3. Methods

Case research was conducted to achieve the current study's aims and fill the gap in the literature. This research approach is suitable for investigating a real-life phenomenon when the associated variables and complexity are not sufficiently understood (Creswell John 2012). The case study research method has been highly recommended by many researchers as an excellent tool for improving the conceptual and descriptive understanding of phenomena (McCutcheon and Meredith 1993; Barratt, Choi, and Li 2011; Yin 2017). The growing frequency and magnitude of changes in technology and managerial methods in operations management require researchers to apply field-based methods (Lewis 1998), and a case study is among the most powerful research methods in operations management (Fynes et al. 2015). The multiple case study approach allows for a more direct comparison of the similarities and differences between implementation practices in different contexts than other approaches (Dinwoodie and Xu 2008), increases external validity and protects against observer bias (Voss 2010). Since the present study aims to compare different material handling systems regarding performance and understand the impact of contextual factors – in this case, hospital characteristics – contingency theory was chosen as the theoretical lens. The contingency theory focuses on achieving high performance in technology and practice by including and adapting to the organisational context (Donaldson 2001; Sousa and Voss 2008). To do so, three sets of variables should be considered: use of practice, performance and contingency factors.

For the use of practice, the theoretical framework by Tanchoco (1994), which specifies the crucial parts when designing and operating a material handling system in a logistics system, has been applied. KPIs were defined to compare the different material handling systems that involve sterile instrument logistics. Selecting suitable and relevant performance measures is critical when analysing any system precisely. According to Gunasekaran and Kobu (2007), intangibles, such as resource utilisation and flexibility, are difficult to measure but play a major role in the effective management of logistics. Therefore, they advise that KPIs and metrics should be discussed with and tailored to the individual organisations.

For the contingency factors, the current study included hospital characteristics of the general, environmental and operational aspects reflecting the common contingencies of environment, size and strategy. This selection is based on a review of the literature in the field of hospital logistics (Granlund and Wiktorsson 2014; Böhme et al. 2016; Volland et al. 2017; Moons, Waeyenbergh, and Pintelon 2019).

The multiple case study format allowed for building a comprehensive understanding of the findings from different sites and combining them to create a total knowledge area of the critical aspects that helped develop the strategic fit between the case hospitals' characteristics and material handling systems.

### 3.1. Case selection

Case selection is a vital element in the current type of research. When using the traditional approach, a sample of cases is built by selecting cases according to different criteria (Eisenhardt and Graebner 2007). However, for multiple cases that resemble multiple experiments, it is crucial to focus on the replication logic rather than the sampling logic (Yin 2017). Our strategy is based on achieving theoretical replication using information-rich cases that produce diverse results and maximum variation, although for predictable reasons (Bazeley 2013; Voss 2010). The three hospitals selected have implemented three distinct material handling systems – each with different degrees of automation – to supply their CSPDs and point-of-use locations. A material handling system using manual transportation and dedicated elevators, a shared AGV system and a dedicated AMR system both using elevators represent the different degrees of automation in the transportation of sterile instruments. The three hospitals are located in Norway and Denmark and share similarities in how they are structured as organisations and how they provide healthcare.

### 3.2. Data collection and analysis

In case research, triangulation is an essential factor in increasing the research validity: it is the process of corroborating evidence from different individuals and types of data, such as theory, interviews, observations, documents and field notes, to reflect the same phenomenon (Creswell John 2012; Carter et al. 2014). In the current study, multiple semistructured interviews were conducted. The purpose was to interview key personnel who could provide useful information regarding their hospitals' CSPD processes, logistics loops and material handling systems. The interviews were conducted with each hospital's managers, leaders, operators, coordinators and other personnel involved in the day-to-day transportation of sterile instruments to obtain information about decision-making at the operational, tactical and strategic levels. Personnel from different departments were interviewed to ensure the representation of several central stakeholders in the logistics loop (Table 1).

In preparation for the interviews, an interview guide was developed based on the literature review and was adapted to match the subjects' backgrounds and levels of education (Appendix A). This guide supported the discussion with the hospital personnel, leading them to both describe the sterile instrument logistics and express their points of view about applied material handling systems in the case hospitals. Semistructured interviews proved an effective way to collect data, and the interviews were analysed using the recommendations by Mayring (2004) for a content analysis. Several visits were made to conduct observations in different departments (CSPD, ORs, points-of-use, etc.) at all three hospitals. Here, observations were crucial because many occurrences concerning the transportation of goods, such as delays, often go unrecorded. Complex processes inside and outside the CSPD could be observed in their natural setting, allowing the researchers to study actual behaviour. Relevant information was also obtained through the documents, illustrations and reports provided by the participants during the visits and interviews.

**Table 1.** List of interviews conducted.

| Hospital | Interview | Duration |
|---|---|---|
| A | Logistics Manager | 90 min |
| | CSPD Department Manager | 45 min |
| | CSPD Quality Coordinator | 45 min |
| | Operation Room Coordinator | 30 min |
| | Maintenance Operator | 90 min |
| B | CSPD Department Manager | 45 min |
| | CSPD Quality Coordinator | 45 min |
| | Logistics Manager | 45 min |
| | Inventory Control Manager | 90 min |
| | Maintenance Operator | 90 min |
| C | Hospital Director | 30 min |
| | Hospital Planner | 45 min |
| | Logistics Manager | 45 min |
| | CSPD Department Manager | 30 min |
| | Material Handling Supplier | 90 min |

## 4. The case hospitals' sterile instrument logistics and applied material handling systems

The following three subsections provide a detailed description of each case hospital's sterile instrument logistics and applied material handling systems, followed by a description of its closed-loop sterile instrument logistics control model. The general, environmental and operational characteristics of the hospitals are summarised in Table 2.

### 4.1. Hospital A

This hospital's layout follows the principle of serving patients who come for brief visits on the lower floors and patients requiring longer visits on the higher floors. Therefore, outpatient clinics and the emergency department are located on the lower floors and inpatient services on the higher ones. ORs and treatment rooms are located in the left wing and wards in the right wing. The CSPD is located in the basement of the left wing below the ORs and processes reusable instruments for ORs and outpatient clinics. Thus, the surgical department, which uses the largest share (90%) of reusable instruments, is located near the CSPD.

**Table 2:** Case hospitals' key characteristics.

| Hospital characteristics | Hospital A | Hospital B | Hospital C |
|---|---|---|---|
| General | | | |
| Size | 700 beds | 750 beds | 300 beds |
| Type | University hospital | University hospital | Regional hospital |
| Construction year (Last major renovation or addition) | 1961 (2008) | 1902 (2005) | 1988 (expected to be finished in 2024) |
| Environmental | | | |
| Building layout |  | | |
| Building layout | (add the attached figure here) | (add the attached figure here) | (add the attached figure here) |
| Buildings floors | Up to 6 floors | Up to 7 floors | Up to 4 floors |
| Ratio of vertical to horizontal transportation | Vertical 70%, horizontal 30% | Vertical 20%, horizontal 80% | Vertical 30%, horizontal 70% |
| Operational | | | |
| Sterile processing Location | Centralised, in-house | Centralised, in-house | Centralised, in-house |
| Sterile processing Planning horizon | Week | Day | Week |
| Sterile processing Throughput time | 6 h maximum | 24 h maximum | 6 h maximum |
| Inventory Location | Centralised | Decentralised | Centralised |
| Inventory Replenishment method | Kanban | Reorder point policy with periodic review | Kanban |
| Delivery Principle | Just-in-time deliveries with low time buffer | Scheduled deliveries with high time buffer | Just-in-time deliveries with low time buffer |
| Control model | Figure 1 | Figure 2 | Figure 3 |
| Material handling system | | | |
| Method, type | Manual transportation using dedicated elevators | Shared AGV system using shared elevators | AMR using shared elevators |
| Size (length, width, height) | Cart: 860 × 710 × 1500 mm | AGV with cart: 1700 × 860 × 1600 mm | AMR with cart: 890 × 780 × 1600 mm |
| Navigation | Autonomous | Path-guided | Autonomous |
| Transported material types | One – Sterile instruments | Six – Sterile instruments, food, pharmaceuticals, medical supplies, laundry, and waste | One – Sterile instruments |

Since Hospital A is a large university hospital, its CSPD operates 24 h a day, although staffing levels are lower on the weekends. The CSPD's workload is heaviest between 11:00 am and 7:30 pm each weekday, mainly because of the scheduling of surgeries. After the contaminated instruments are returned to the CSPD, the hospital's goal is to wash, inspect, pack, sterilise and return the instruments to storage within 6 h. The carts are washed at the same time in a cart washing machine. Most sterile instruments are stored centrally within the CSPD, which means that it is responsible for cleaning, storing and distributing the hospital's sterile instruments.

The available information technology (IT) system allows sharing information about planned surgeries among all departments involved in the hospital's sterile instrument logistics. The hospital provides information regarding planned surgeries on a weekly basis, allowing the CSPD to plan a week ahead and be quickly updated on changes in surgery schedules. Detailed information about the instruments needed for surgeries can be extracted from the IT system, and the delivery of sterile instruments follows the just-in-time principle. CSPD staff members prepare carts with the instruments needed for a given operation or treatment from central storage. The carts are picked up by porters and delivered to their destinations using elevators and corridors. The CSPD has dedicated clean and soiled elevators. The delivery and return of carts with sterile instruments are both performed manually. After surgery, soiled materials are brought directly to the CSPD's decontamination area. A high level of coordination is required among CSPD personnel, the OR and porters. The control model of the sterile instrument logistics for Hospital A is shown in Figure 1.

### 4.2. Hospital B

This hospital's specialised healthcare services are spread across nine buildings, each containing up to seven floors. The CSPD is in the basement of one of the western buildings. It processes reusable instruments for ORs, the emergency department, outpatient clinics and wards. The orthopaedic clinic and ORs are the CSPD's primary clients. On weekdays, it is staffed 24 h a day, but staffing levels are lower on the weekends. Some equipment and instruments are kept in storage at the CSPD, but the largest share of such items is placed in decentralised storage areas in the hospital's various department levels and ORs. For inventory control, the hospital uses a reorder point policy with periodic review. In every review cycle, if the inventory level is equal to or less than the reorder point, replenishment is triggered to increase inventory to a predefined maximum level. The amount ordered is not constant and depends on the current inventory. All departments use manual requisition forms to indicate their requirements for the next day and, preferably, the specific time at which the items will be needed. These forms are sent electronically to the CSPD each day. The emergency department can order supplies and receive them on the same working day, but departments cannot automatically order what they need for several reasons. Some types of surgery and hospital departments have additional instrument requirements, and some instruments cannot be traced back to their original storage area when they arrive at the CSPD. The instruments are processed according to their priority status: rush orders (as soon as possible), priority orders (within 14 h) and regular orders (within 24 h). Because surgery schedules change frequently, the hospital has decided not to permit placing orders for sterile instruments for more than 24 h in advance. The hospital uses an IT system that can track the flow of sterile reusable instruments in the logistics loop. The items must be scanned manually after they are received, cleaned, inspected, delivered and stored. In some departments, information regarding inventory levels is available.

The AGV system covers the hospital's transportation services to and from the CSPD and other departments. In total, there are 25 AGV pickup and delivery points connected to the sterile instrument logistics (in front of the CSPD and at various point-of-use departments). Personnel must place wagons containing sterile instruments in dedicated areas for pickup by an AGV. When the wagons are delivered to the appropriate department, the hospital personnel are informed via the IT system that the wagons have arrived. In some critical cases and on weekends, manual transportation is used to supply and return sterile instruments. Hospital B's sterile instrument logistics mode is illustrated in Figure 2.

The hospital's AGV system consists of 21 laser-guided AGVs and transports, in addition to sterile instruments, food, linen and clothing, medical supplies, pharmaceutical products and waste. Different priorities and time slots are defined for each group of goods. The AGVs can lift and move wagons within the 4500-m guide-path and access tunnels and elevators, thus reaching many areas of the hospital. The AGVs can communicate with doors and elevators via ultra-wideband. On average, the AGVs transport approximately 50–70 tonnes of goods every week between a total of 114 pickup and delivery points. The remaining 89 points are positioned at goods arrival, kitchen, pharmacy, waste disposal and various departments. The AGVs are cleaned on a regular basis, and each one can operate for 3 h before needing to be charged for an hour.

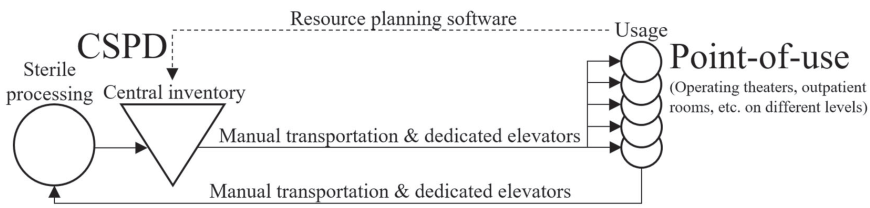



Figure 1. Control model of sterile instrument logistics in Hospital A.

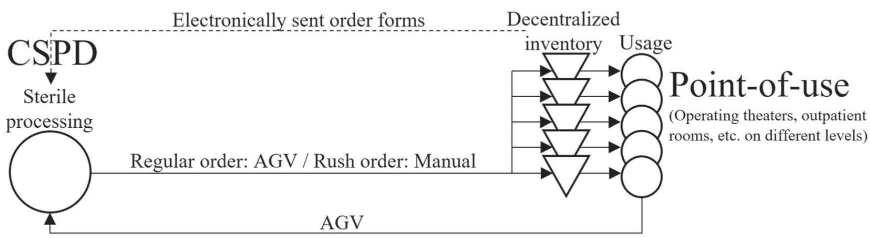



Figure 2. Control model of sterile instrument logistics in Hospital B.

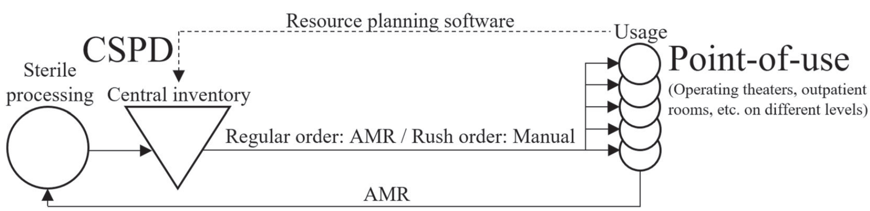



Figure 3. Control model of sterile instrument logistics in Hospital C.

### 4.3. Hospital C

This hospital's healthcare services are spread throughout the building and are arranged by type of patient visit. Outpatient clinics are mainly on the first floor, whereas inpatient wards are on the second. The CSPD is currently in the basement and serves the hospital's operating rooms, outpatient clinics and wards. Elevators and corridors must be used to reach the different departments from the CSPD. Because the hospital has only two floors, more horizontal than vertical transportation is required.

The CSPD is not staffed 24 h a day; it operates from 7:00 am to 10:00 pm on weekdays and 7:00 am to 3:00 pm on weekends. During these hours, it is responsible for washing, maintaining, packing, sterilising and distributing instruments to the hospital's various departments. After a short processing and throughput time of a maximum of 6 h, the instruments are sent to central storage at the CSPD, which is in charge of distributing the instruments and supplies required for surgeries and other treatments. The IT system allows for extracting the information needed to prepare the required sterile goods. The instruments are picked up at the storage area and packed onto a wagon. CSPD staff members send the wagons, with the help of the AMR, from the CSPD to the hospital's various departments (Figure 3). Thus, instruments are delivered according to the just-in-time principle, reducing the need for local storage. Some departments have small local depots with low inventory for special and critical situations. The number and contents in the wagons in operation must be kept up-to-date by the end users in each department. In the past, service assistants delivered the disposable equipment supplies to the departments, which required heavy lifting and considerable physical activity. Today, CSPD personnel can control, monitor and track transports using a tablet computer. There are 10 different pickup and delivery points within the logistics loop. After registering a delivery, the AMR picks up the wagon and delivers it to its destination. It does not have to follow a strict guide-path and, thus, can avoid obstacles and people by autonomously finding alternative paths. This attribute supports the AMR's usefulness in dynamic environments involving human interaction. CSPD personnel can monitor the AMR's path remotely and see if something unusual or wrong is occurring. Communicating via ultra-wideband, the AMR can use elevators and doors; hence, it can access all parts of Hospital C. Because no physical references must be implemented to guide it through the hospital, the costs and implementation time are reduced significantly. The AMR travels 15 km and delivers approximately 60 wagons per day. It can remain in operation for 10 h or travel 20 km before needing to be charged. To prevent and control infection, the AMR is cleaned regularly.

## 5. Performance measures of sterile instrument transportation

Previous studies on material handling systems in sterile instrument logistics have focussed on a few KPIs. The current study identified KPIs that allow for the evaluation of material handling systems not only from the common aspects of costs and productivity, but also flexibility, quality and service.

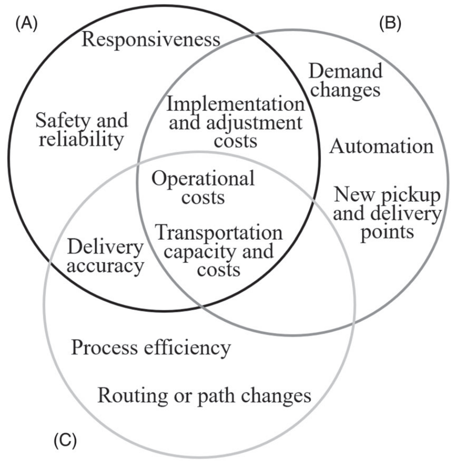



Figure 4. Identified KPIs for sterile instrument transportation in the three case hospitals.

To assess the adequacy and select the appropriate KPIs for sterile instrument transportation, we first determined the main performance areas based on the literature on sterile instrument transportation, as discussed in Section 2. Second, we identified the applied KPIs at each hospital (see Figure 4).

Finally, we selected relevant KPIs and discussed how to evaluate and rate the transportation performance of the hospitals' material handling systems through whole-day workshops at each hospital with hospital planners. Table 3 describes the selected KPIs for sterile instrument transportation.

Three different types of material handling systems – manual transportation with dedicated elevators, a shared AGV system and a dedicated AMR system – that transport sterile instruments in hospitals were analysed by measuring and comparing their performance using several KPIs to assess their applicability in hospitals.

Manual transportation with dedicated elevators was found to be highly flexible, agile and easy to maintain. The level of human involvement, however, reveals its productivity efficiency to be low and that it is an expensive transportation solution because of issues with communication, time management and transportation inefficiency. Since manual transportation is logged less often, it is also difficult to recall errors, delays or miscommunications.

The shared AGV system has standardised processes that enable a high degree of automation. Due to its ability to handle different material flows and heavy loads, the AGV system has been demonstrated to be very efficient and productive. Since the communication system and its interfaces are clearly defined between the personnel and AGVs, the AGV system can immediately register when a wagon must be delivered or returned. However, these positive attributes have drawbacks: there is limited flexibility for making changes and working with large buffers. For example, when changing the pickup and delivery points, the hospital must implement physical reference points, set up new readers for the wagons, establish the new infrastructure information and adapt the guide-path of the AGV's controls. These efforts are

Table 3: KPIs for sterile instrument transportation.

| Performance dimensions | KPI | Description |
|---|---|---|
| Flexibility | Demand changes | The degree of adaptation to changes in demand |
| | Routing or path changes | The degree of adaptation to new paths |
| | Add new pickup and delivery points | The degree of time and effort required to include and integrate new buildings, departments and areas |
| Productivity | Transportation capacity | The number of transported items per delivery |
| | Automation | The ratio of machines to personnel time involved in deliveries |
| | Process efficiency | The ratio of value-added time to non-value-added time |
| Quality/Service | Delivery accuracy | The proportion of correct and on-time deliveries |
| | Responsiveness | The time period for total transportation, including ordering, pickup, and delivery |
| | Safety and reliability | The number of system failures and errors |
| Costs | Implementation and adjustment costs | The costs of setting up and modifying the material handling system |
| | Transportation costs | The costs of single transport run |
| | Operational costs | The costs of operating and maintaining the material handling system |

time-consuming and expensive for hospitals because they require planning the changes and involving all the implementation's external partners.

Due to the low level of effort required for its implementation, the minimal human involvement in its transportation and its modest need for maintenance, the AMR is an affordable material handling system for a single material flow. It facilitates a high degree of responsiveness and the capability of applying lean principles to the supply task, with many small, just-in-time transportations instead of fewer transportations with heavier loads. Reducing the batch sizes and performing on-demand transportation can improve both forward and return logistics. For instance, the washing process performed at the CSPD can form a bottleneck within logistics systems. Supplying the CSPD with soiled instruments in small batches facilitates faster response times, as it allows the washing process to begin earlier, and thus reducing the amount of work in process. Table 4 presents the results of the performance measurements, rated in the ranges of low, middle and high, to differentiate the results.

## 6. Impact of hospital characteristics on material handling systems

### 6.1. Impact of general and environmental hospital characteristics on material handling systems

Whether small or large, regional or university, hospitals have demonstrated favourable productivity, quality, service and cost performance outcomes after applying an automated material handling system for sterile instrument logistics. Even a small regional hospital can implement and use an automated material handling system. In Hospital C, the AMR substituted one full-time employee and amortised costs within two years. It is not the size that is important, but rather the environmental variables, such as the hospital layout and distribution of the pickup and delivery points.

Hospitals have attempted to concentrate their many departments within the sterile instruments loop to reduce transportation times and, thus, costs. Locating the units involved in sterile instrument logistics above one another and using elevators have helped reduce transport times. Therefore, hospital planners aim for a higher ratio of vertical to horizontal transportation when designing a hospital. According to the logistics managers of the case hospitals, this ratio is being challenged by two major identified trends. First, several polyclinical departments increasingly use more complex and reusable instruments and want to be connected to the CSPD. These departments are located throughout hospitals, so relocating them close to the CSPD is nearly impossible in an operating hospital. Second, hospitals are expanding and erecting new buildings, and new departments must be incorporated into the existing sterile instrument logistics. Restructuring and expanding major hospitals while smaller ones are closed has been reported in many Western countries (Giancotti, Guglielmo, and Mauro 2017). The layout of hospitals is changing, and the ratio of vertical to horizontal transportation is decreasing, trending towards a more horizontal approach. Changing the ratio of vertical to horizontal transportation especially affects the productivity and cost performance of the material handling system. As horizontal transportation increases, the economic suitability of AGVs and AMRs also increases because manual transportation reduces the value-added time of hospital personnel, which is associated with higher costs.

### 6.2. Impact of operational characteristics of sterile instrument logistics on material handling systems

In the current study, two logistics system strategies that are typically applied in hospitals were investigated: an efficient one with centralised sterile processing, decentralised storage and scheduled deliveries with a high time buffer and a responsive one with centralised sterile processing, centralised storage and just-in-time deliveries. Both can fulfil the central objective of ensuring the availability of sterile instruments for planned and emergency surgeries, and each one is associated with different trade-offs.

The first strategy relies on decentralised storage areas with high inventory levels in the departments at the point of care responding quickly in critical situations. This allows for longer replenishment lead times, thus reducing the pressure on delivery accuracy. The material handling system can perform deliveries with a high time buffer and low responsiveness. This strategy is convenient for transporting sterile instruments and several other material flows, such as linen, food, waste and so forth with one material handling system, thus reducing the overall transportation costs. The suitable solution for this strategy has been the implementation of AGVs.

Table 4. Results of performance measurements conducted in the three case hospitals.

| KPI | Hospital A | Hospital B | Hospital C |
|---|---|---|---|
| Flexibility | | | |
| Demand changes | *High* – Personnel schedules can be adapted easily | *Low* – The AGV system can adapt to changes, but this may result in longer wait times | *Medium* – The AMR can adapt to changes |
| Routing or path changes | *High* – Personnel can easily make routing or path changes | *Low* – Technical staff must invest many hours adjusting AGV guide paths, sensors, etc. | *High* – The AMR can autonomously find alternatives |
| Add new pickup and delivery points | *High* – New areas can be added easily | *Low* – Technical staff must invest many hours adjusting AGV guide paths, sensors, etc. | *Medium* – New areas can be scanned easily with the AMR to increase the transportation area |
| Productivity | | | |
| Transportation capacity | *Low* – Personnel can only move small carts for a single operation | *High* – AGVs can transport several heavy wagons | *Low* – AMRs can transport a single large wagon |
| Automation | *Low* – Personnel are involved throughout the delivery process | *High* – Personnel only prepare and unload the wagons | *High* – Personnel only prepare and unload the wagons |
| Process efficiency | *Low* – Difficult to combine forward and reverse transportation; many idle periods for personnel without goods transportation | *High* – The AGV system transports many other goods and has a very low number of empty transportations | *Medium* – The AMR can transport both sterile and dirty instruments; nevertheless, some empty transportations are unavoidable |
| Quality/Service | | | |
| Delivery accuracy | High – Applies the just-in-time principle | High – Large time buffers allow the AGVs to make deliveries on time | High – Applies the just-in-time principle |
| Responsiveness | *Medium* – While outgoing instruments are delivered quickly, the return of instruments takes a long time | *Low* – The AGV system must manage several material flows at the same time; ordering and pickup times can both occur during the hospital's core operating hours | *High* – Manages one material flow; the AMR has short wait times and moves rapidly |
| Safety and reliability | *High* – Personnel can make quick decisions and adapt to new challenges | *Low* – AGVs cannot bypass obstacles or errors and depend on technical staff to fix failures and errors | *Medium* – AMRs can handle dynamic areas and bypass obstacles; however, complicated errors must be resolved by personnel |
| Cost | | | |
| Implementation and adjustment costs | Low – Minor costs for equipment and setup; manual transportation can be changed easily at a low cost | High – Physical reference points, the IT structure that must be installed, and high vehicle prices result in high implementation costs; additional adjustments increase costs | *Medium* – Short implementation time, low cost of vehicles and equipment, adjustments can be implemented easily |
| Transportation costs | *High* – High personnel involvement and low transportation capacity result in high transportation costs | *Low* – Electricity and manual preparation of the wagons are incidental costs | *Low* – Electricity and manual preparation of the wagons are incidental costs |
| Operational costs | *High* – High labour costs and low transportation efficiency | *Medium* – Technical staff must maintain the AGVs on a regular basis and are needed during AGV operation to fix problems like removing obstacles from the guide-path | *Low* – Technical staff must maintain the AMRs on a regular basis |

The planner must justify the high implementation costs of incorporating an AGV system into a hospital's design. Including many material flows in the AGV system enables the conversion of a hospital personnel's time from goods transportation to healthcare and value-added activities, as seen in Hospital B's case. This reduces the transportation costs and the hospital's overall operating costs.

This strategy and its corresponding material handling systems are challenged by increased hospital admissions and commensurate material consumption. The rise in material consumption requires increasing either the inventory levels in the decentralised storage areas or transportation frequency to enable shorter reprocessing and replenishment cycles. Increasing inventory levels – thus using more of the hospital's storage area – is costly because the additional space could be used for patient care.

However, increasing the transportation frequency and changing the transportation pattern of AGVs could have a significant impact on the overall material flow in a hospital. The operation or production schedules of ORs, the CSPD, kitchen and other departments must be considered when making even minor changes to an AGV system. Hospital logistics planners are struggling to determine which changes should be made to the AGV system to handle the complexity of several types of material flows (Benzidia et al. 2019). The decentralised planning of the different units complicates the decision-making process when the goal is to improve transportation performance. Therefore, the AGV allows for only minimal adjustments and results in low flexibility.

In contrast, the second strategy aims to achieve high performance regarding flexibility and the provision of high-quality service in deliveries. The inventory is centralised with the purpose of sharing all sterile instruments among different departments. Applying the kanban system allows for keeping inventory levels and costs low. This improves the quality of the services in hospital supply chains, moving away from a push with a high buffer towards a pull with just-in-time deliveries (Papalexi, Bamford, and Dehe 2016).

This strategy requires a material handling system that can easily adapt to changes and be responsive to deliver sterile instruments just in time to the many point-of-use locations throughout the hospital. In the past, it was difficult to find an automated material handling system that could meet these needs, so many hospitals relied on manual transportation. Thanks to recent technological advances, it has been possible to successfully implement AMRs as a material handling system for this strategy.

AMRs can find the shortest path and handle dynamic areas by passing obstacles. This guarantees a high delivery accuracy. Serving only one material flow allows for a high degree of adaptation to the demand changes caused, for instance, by increased surgical operations and responsiveness in the case of an emergency. Furthermore, the AMR can find ideal spots to idle and reduce pickup time. This improves both the outgoing and return logistics of sterile instruments. However, high responsiveness comes with the downside of low utilisation. Therefore, the material handling system results in poor productivity.

## 7. Strategic fit of material handling systems in sterile instrument transportation

A framework can be established for the strategic fit to achieve high performance thanks to the mapping of sterile instrument logistics, the performance measures of sterile instrument transportation and the identification of hospital characteristics impacting the material handling system. The environmental and operational characteristics set the framework dimensions. Thereby, the environmental characteristics are represented by two sets: concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation (E1) and widespread pickup and delivery points and a low ratio of vertical to horizontal transportation (E2). The operational characteristics are represented by the two strategies described in the previous section: centralised sterile processing, decentralised storage and scheduled deliveries with a high time buffer (O1) and centralised sterile processing, centralised storage and just-in-time deliveries (O2).

Although the analysis of sterile instrument transportation positions the material handling systems, the performance measures (low, medium and high) reveal the fit of the material handling systems for sterile instrument transportation (see Figure 5).

The strategic fit framework shows both the advantages and disadvantages of the material handling systems in sterile instrument transportation, thus exposing several interesting trade-offs. High productivity can be achieved with high automation. However, these achievements come with high flexibility and a drop in quality. Furthermore, the logistical setup must be adapted to handle the long delivery times.

Hospitals with concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation can mainly rely on a manual material handling system with low automation (e.g. person elevators) or high automation (e.g. industrial paternoster) support. The investment in automation must be foremost in vertical support systems. Low investment in elevators can form bottlenecks, leading to long waiting times, thus reducing performance quality and flexibility.

However, it is difficult to achieve high productivity with manual material handling systems. Keeping the communication level high with all departments to enable scheduling the personnel responsible for sending and receiving goods requires a highly advanced IT system, which hospitals often do not have. Without the support of such a system, the personnel must make decisions regarding transportation scheduling and routing on their own. Human involvement in this decision-making process can lead to inefficient routing, poor sequencing of transportation, excess transportation and other problems. Some of these transportation inefficiencies have been identified in previous studies (Benzidia et al. 2019;

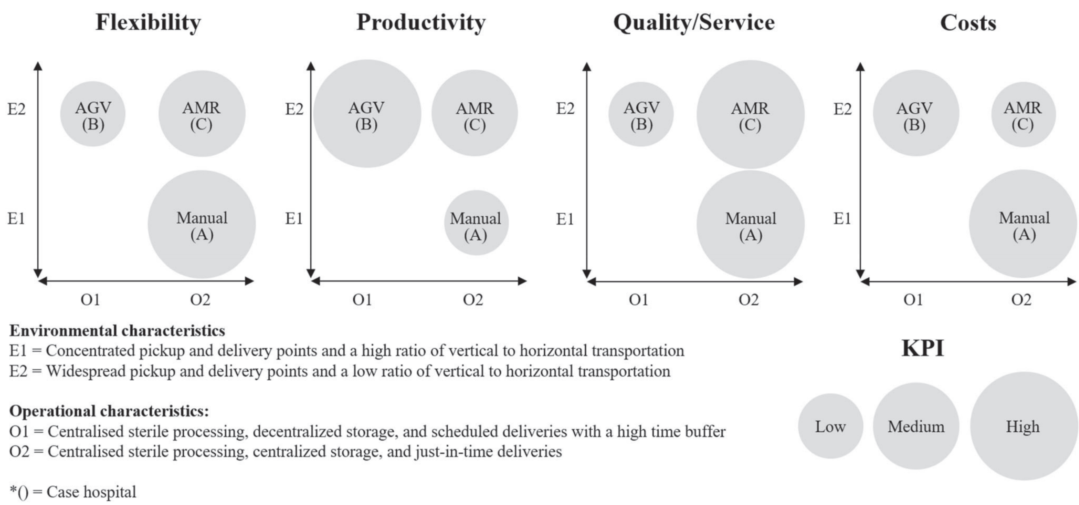



Figure 5. Strategic fit framework of the material handling systems for sterile instrument transportation.

Moons, Waeyenbergh, and Pintelon 2019) and are confirmed in the present one.

Implementing an AGV system in a hospital merely for the sake of automating the material flow will not necessarily bring a positive return on investment or achieve better performance than a manual approach (Chikul, Maw, and Soong 2017). The high implementation costs of an AGV system can only be financially justified when they cover as many material movements in a hospital as possible and reduce overall manual transportation. Achieving high utilisation of AGVs leads to large buffers to handle the different material flows in hospitals. Prioritising single material flows can improve the responsiveness of the system, hence the quality of transportation as well. However, just-in-time deliveries are still rarely feasible. Furthermore, the transportation performance of AGVs in hospitals is vulnerable because of the dynamic environment. Interacting with people and obstacles in narrow hallways can hinder AGVs' performance, as they cannot avoid obstacles and depend on support personnel to address these failures. A recent study confirms that failures caused by dynamic environments result in long queues of AGVs, impairing their transportation performance in hospitals (Fragapane et al. 2019).

One of the strengths of AMRs is their ability to navigate dynamic environments, enabling high flexibility and quality in transportation. Their intelligent navigation system supports maintaining a high level of accuracy when delivering sterile instruments by bypassing obstacles and finding the fastest route. AMRs can be a useful automation alternative to the AGV system. They offer a low-cost solution and just-in-time deliveries. However, in the future, AMRs should improve their decentralised decision-making process to handle several material flows and just-in-time deliveries. This will allow for the achievement of high productivity in transportation and close the gap with AGVs.

Finally, the introduced framework can be especially supportive in the decision-making process on a strategic level. In the planning phase of a new hospital, balancing the previously mentioned trade-offs allows for making better decisions regarding the layout, logistics system setup and the material handling system to achieve high performance. Furthermore, it can support the decision-making process of automating sterile instrument transportation in existing hospitals by indicating which material handling systems are most suitable for the hospitals' characteristics and logistical setup.

## 8. Conclusions

In the present study, the transportation of sterile instruments in three case hospitals was investigated and compared using KPIs to identify the strategic fit between material handling systems and hospital characteristics. AMRs have been shown to be a suitable alternative by providing highly flexible and cost-efficient transportation. The forward and reverse logistics in the closed loop of sterile instrument transportation can produce powerful benefits from such a material handling system. Sterile instruments can be delivered just in time to point-of-use areas while centralising inventory. The rapid return of goods can enable CSPDs to distribute duties more evenly across the workday while avoiding bottlenecks during washing. AMRs might also help reduce throughput times by returning instruments to the CSPD's storage area more quickly, thus reducing inventory levels and providing a buffer against increasing demand.

Due to their size, AGVs are often unable to enter departments, instead delivering only to a predetermined nearby area. However, AMRs can enter departments and deliver materials closer to the point of use because of their intelligent navigation system and smaller size. Integrating AMRs more deeply into the departments, as seen in Hospital C, can help hospitals increase efficiency and meet demand. Currently, the last 50 m, which refers to the innermost area of a hospital department, have not undergone automation. The AMRs' ability to work in dynamic environments alongside patients, nurses, doctors and visitors can lower the need for manual transportation not only in the last 50 m, but also in the entire hospital. The present study and recent study by Fragapane et al. (2020) show that mobile robots have been widely accepted in hospitals and can collaborate with hospital personnel.

The current study contributes to the development of theory by defining the adequate KPIs for assessing sterile instrument transportation. Furthermore, it demonstrates the strengths and weaknesses of different material handling systems, explaining how AMRs can support logistics in hospitals. The strategic fit framework will support practitioners in managing sterile instrument logistics, especially indicating how to automate transportation.

One of the present study's limitations is its exclusive focus on European hospitals. Each facility's layout and its personnel's degree of acceptance of robots have a significant impact on decisions regarding material handling systems in hospitals. Future research should investigate how this innovative AMR technology should be planned and controlled in different types of hospitals and for different material flows. In addition, future research could determine the most suitable ratio of vertical to horizontal transportation for automated material handling systems.

## Acknowledgements

The authors would like to express their gratitude to the Regional Development Fund in Denmark for supporting the project 'Reference architecture and open standards'.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This research received funding from the strategic research area of NTNU Health in 2020 at NTNU, the Norwegian University of Science and Technology.

## Notes on contributors

***Giuseppe Fragapane*** is a PhD candidate in the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU). He holds an M.Sc. in Business Administration and Engineering from Beuth University of Applied Sciences in Berlin, Germany, and a B.Eng. in Mechanical Engineering from the Pforzheim University of Applied Sciences, Germany. His main research interests are in the area of logistics and material handling, about which he has published research articles in peer-reviewed international conferences and journals. In addition to research activities, he is also assisting in lecturing, configuring layouts, warehousing, scheduling and conducting experimental research with autonomous mobile robots in the Logistics 4.0 Lab.

***Hans-Henrik Hvolby*** is a Full Professor at the Centre for Logistics, Aalborg University in Denmark and a visiting professor at the Norwegian University of Science and Technology and at the University of Tasmania, Australia. For seven years, he was a visiting professor at the University of South Australia. He holds a PhD in Manufacturing Information Systems, has published more than 150 peer-reviewed papers and serves as an editorial board member of several international journals. For over two decades, he has been the project manager or partner in larger research projects raising national and European research funding. His research areas include manufacturing information systems (MRP, ERP, APS and VMI), logistics, supply chain planning, supply chain integration, value chain management and order management (BPR).

***Fabio Sgarbossa*** has been a Full Professor of Industrial Logistics at the Department of Mechanical and Industrial Engineering at NTNU, Norway, since October 2018. He was an Associate Professor at the University of Padova (Italy), where he also received his PhD in Industrial Engineering in 2010. He is working in the Production Management Group at MTP and is responsible for the Logistics 4.0 Lab at NTNU. He has been involved in several Europeans and national projects and is the author and co-author of about 90 publications in relevant international journals on industrial logistics, material handling, materials management and supply chain. He is a member of the organising and scientific committees of several international conferences and served as a guest editor of several special issues of relevant international journals, such as Omega.

***Jan Ola Strandhagen*** is a Full Professor of Production Management in the Department of Mechanical and Industrial Engineering at NTNU, Norway. He holds a PhD in Manufacturing Logistics. For three decades, he has been working with the research organisation SINTEF as a researcher and research manager. He now holds a full professorship at NTNU doing research in and teaching manufacturing strategy, production planning and control, and logistics and sustainability and has supervised 10 PhD students.

## ORCID

Giuseppe Fragapane http://orcid.org/0000-0001-8915-509X
Hans-Henrik Hvolby http://orcid.org/0000-0002-5574-5216
Fabio Sgarbossa http://orcid.org/0000-0002-9541-3515
Jan Ola Strandhagen http://orcid.org/0000-0003-3741-9000

## References

Acur, Nuran, Kandemir Destan, and Harry Boer. 2012. "Strategic Alignment and New Product Development: Drivers and Performance Effects." *Journal of Product Innovation Management* 29 (2): 304–318. doi:10.1111/j.1540-5885.2011.00897.x.

Ahmadi, Ehsan, Dale T. Masel, Ashley Y. Metcalf, and Kristin Schuller. 2019. "Inventory Management of Surgical Supplies and Sterile Instruments in Hospitals: A Literature Review." *Health Systems (Basingstoke, England)* 8 (2): 134–151. doi:10.1080/20476965.2018.1496875.

Barratt, Mark, Thomas Y. Choi, and Mei Li. 2011. "Qualitative Case Studies in Operations Management: Trends, Research Outcomes, and Future Research Implications." *Journal of Operations Management* 29 (4): 329–342. doi:10.1016/j.jom.2010.06.002.

Bazeley, Patricia. 2013. *Qualitative Data Analysis: Practical Strategies*. London: Sage Publications.

Behn, Robert D. 2003. "Why Measure Performance? Different Purposes Require Different Measures." *Public Administration Review* 63 (5): 586–606. doi:10.1111/1540-6210.00322.

Benzidia, Smail, Blandine Ageron, Omar Bentahar, and Julien Husson. 2019. "Investigating Automation and AGV in Healthcare Logistics: A Case Study Based Approach." *International Journal of Logistics Research and Applications* 22 (3): 273–293. doi:10.1080/13675567.2018.1518414.

Böhme, Tillmann, Sharon J. Williams, Paul Childerhouse, Eric Deakins, and Denis Towill. 2016. "Causes, Effects and Mitigation of Unreliable Healthcare Supplies." *Production Planning & Control* 27 (4): 249–262. doi:10.1080/09537287.2015.1105396.

Buer, Sven-Vegard, Jo Wessel Strandhagen, Jan Ola Strandhagen, and Erlend Alfnes. 2016. "Strategic Fit of Planning Environments: Towards an Integrated Framework." International Conference on Information Systems, Logistics and Supply Chain, 77–92. Cham: Springer.

Cannas, Violetta G., Jonathan Gosling, Margherita Pero, and Tommaso Rossi. 2020. "Determinants for Order-Fulfilment Strategies in Engineer-to-Order Companies: Insights from the Machinery Industry." *International Journal of Production Economics* 228: 107743. doi:10.1016/j.ijpe.2020.107743.

Carter, Nancy, Denise Bryant-Lukosius, Alba DiCenso, Jennifer Blythe, and Alan J. Neville. 2014. "The Use of Triangulation in Qualitative Research." *Oncology Nursing Forum* 41 (5): 545–547. doi:10.1188/14.ONF.545-547.

Čerić, Vlatko. 1990. "Simulation Study of an Automated Guided-Vehicle System in a Yugoslav Hospital." *Journal of the Operational Research Society* 41 (4): 299–310. doi:10.1057/jors.1990.51.

Chikul, Mittal, Hsann Yin Maw, and Yang Kok Soong. 2017. "Technology in Healthcare: A Case Study of Healthcare Supply Chain Management Models in a General Hospital in Singapore." *Journal of Hospital Administration* 6 (6): 63–70. doi:10.5430/jha.v6n6p63.

Chobin, Nancy, and Karen Swanson. 2012. "Putting Patient Safety First: The Sterile Processing Department and Healthcare Technology Management." *Biomedical Instrumentation & Technology* 46 (sp12): 27–31. doi:10.2345/0899-8205-12.1.27.

Christopher, Martin, Helen Peck, and Denis Towill. 2006. "A Taxonomy for Selecting Global Supply Chain Strategies." *The International Journal of Logistics Management* 17 (2): 277–287. doi:10.1108/09574090610689998.

Costa, Luana Bonome Message, and Moacir Godinho Filho. 2016. "Lean Healthcare: Review, Classification and Analysis of Literature." *Production Planning & Control* 27 (10): 823–836. doi:10.1080/09537287.2016.1143131.

Creswell John, W. 2012. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*. 4th ed. Boston: Pearson.

Di Mascolo, Maria, and Alexia Gouin. 2013. "A Generic Simulation Model to Assess the Performance of Sterilization Services in Health

Establishments." *Health Care Management Science* 16 (1): 45–61. doi: 10.1007/s10729-012-9210-2.

Dinwoodie, John, and Jingjing Xu. 2008. "Case Studies in Logistics: A Review and Tentative Taxonomy." *International Journal of Logistics Research and Applications* 11 (5): 393–408. doi:10.1080/13675560802389130.

Donaldson, Lex. 2001. *The Contingency Theory of Organizations*. Thousand Oaks, CA: Sage Publications.

Eisenhardt, Kathleen M., and Melissa E. Graebner. 2007. "Theory Building from Cases: Opportunities and Challenges." *Academy of Management Journal* 50 (1): 25–32. doi:10.5465/amj.2007.24160888.

Fainshmidt, Stav, Lucas Wenger, Amir Pezeshkan, and Mark R. Mallon. 2019. "When Do Dynamic Capabilities Lead to Competitive Advantage? The Importance of Strategic Fit." *Journal of Management Studies* 56 (4): 758–787. doi:10.1111/joms.12415.

Fisher, Marshall L. 1997. "What is the Right Supply Chain for Your Product?" *Harvard Business Review* 75: 105–117.

Fogliatto, Flavio S., Michel J. Anzanello, Leandro M. Tonetto, Daniela S. S. Schneider, and Ana Maria Muller Magalhães. 2020. "Lean-Healthcare Approach to Reduce Costs in a Sterilization Plant Based on Surgical Tray Rationalization." *Production Planning & Control* 31 (6): 483–495. doi:10.1080/09537287.2019.1647366.

Fragapane, Giuseppe, Hans-Henrik Hvolby, Fabio Sgarbossa, and Jan Ola Strandhagen. 2020. "Autonomous Mobile Robots in Hospital Logistics." IFIP International Conference on Advances in Production Management System. Cham: Springer.

Fragapane, Giuseppe, Cevin Zhang, Fabio Sgarbossa, and Jan Ola Strandhagen. 2019. "An Agent-Based Simulation Approach to Model Hospital Logistics." *International Journal of Simulation Modelling* 18 (4): 654–665. doi:10.2507/IJSIMM18(4)497.

Fragapane, Giuseppe, René de Koster, Fabio Sgarbossa, and Jan Ola Strandhagen. 2021. "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda." *European Journal of Operational Research*. doi:10.1016/j.ejor.2021.01.019.

Fynes, Brian, Paul Coughlan, Harry Boer, Matthias Holweg, Martin Kilduff, Mark Pagell, Roger Schmenner, and Chris Voss. 2015. "Making a Meaningful Contribution to Theory." *International Journal of Operations & Production Management* 35 (9): 1231–1252. doi:10.1108/IJOPM-03-2015-0119.

Giancotti, Monica, Annamaria Guglielmo, and Marianna Mauro. 2017. "Efficiency and Optimal Size of Hospitals: Results of a Systematic Search." *PLoS One* 12 (3): e0174533 doi:10.1371/journal.pone.0174533.

Gligor, David M., Carol L. Esmark, and Mary C. Holcomb. 2015. "Performance Outcomes of Supply Chain Agility: When Should You Be Agile?" *Journal of Operations Management* 33-34 (1): 71–82. doi:10.1016/j.jom.2014.10.008.

Granlund, Anna, and Magnus Wiktorsson. 2014. "Automation in Internal Logistics: Strategic and Operational Challenges." *International Journal of Logistics Systems and Management* 18 (4): 538–558. doi:10.1504/IJLSM.2014.063984.

Gunasekaran, Angappa, and Bulent Kobu. 2007. "Performance Measures and Metrics in Logistics and Supply Chain Management: A Review of Recent Literature (1995–2004) for Research and Applications." *International Journal of Production Research* 45 (12): 2819–2840. doi: 10.1080/00207540600806513.

Hammami, Sondes, Ruiz Angel, Pierre Ladet, and Atidel B. Hadj Alouane. 2006. "Supplying the Operating Theatre: Cyclic and Supply Chain Approaches." *IFAC Proceedings Volumes* 39 (3): 713–718. doi:10.3182/20060517-3-FR-2903.00361.

Hichri, B., J. C. Fauroux, L. Adouane, I. Doroftei, and Y. Mezouar. 2019. "Design of Cooperative Mobile Robots for Co-Manipulation and Transportation Tasks." *Robotics and Computer-Integrated Manufacturing* 57: 412–421. doi:10.1016/j.rcim.2019.01.002.

Ketokivi, Mikko, and Roger Schroeder. 2004. "Manufacturing Practices, Strategic Fit and Performance." *International Journal of Operations & Production Management* 24 (2): 171–191. doi:10.1108/01443570410514876.

Landry, Sylvain, and Martin Beaulieu. 2010. "Achieving Lean Healthcare by Combining the Two-Bin Kanban Replenishment System with RFID Technology." *International Journal of Health Management and Information* 1 (1): 85–98.

Le-Anh, Tuan, and M. B. M. De Koster. 2006. "A Review of Design and Control of Automated Guided Vehicle Systems." *European Journal of Operational Research* 171 (1): 1–23. doi:10.1016/j.ejor.2005.01.036.

Lewis, Marianne W. 1998. "Iterative Triangulation: A Theory Development Process Using Existing Case Studies." *Journal of Operations Management* 16 (4): 455–469. doi:10.1016/S0272-6963(98)00024-2.

Lin, Feng, Mark Lawley, Charlie Spry, Kelly McCarthy, Patricia G. Coyle-Rogers, and Yuehwern Yih. 2008. "Using Simulation to Design a Central Sterilization Department." *AORN Journal* 88 (4): 555–567. doi: 10.1016/j.aorn.2008.03.015.

Marques, Leonardo, Marina Martins, and Cláudia Araújo. 2020. "The Healthcare Supply Network: Current State of the Literature and Research Opportunities." *Production Planning & Control* 31 (7): 590–609. doi:10.1080/09537287.2019.1663451.

Mayring, Philipp. 2004. "Qualitative Content Analysis." In *A Companion to Qualitative Research*, edited by Uwe Flick, Ernst von Kardorff, and Ines Steinke, 159–176. London: Sage Publications.

McCutcheon, David M., and Jack R. Meredith. 1993. "Conducting Case Study Research in Operations Management." *Journal of Operations Management* 11 (3): 239–256. doi:10.1016/0272-6963(93)90002-7.

Moons, Karen, Geert Waeyenbergh, and Liliane Pintelon. 2019. "Measuring the Logistics Performance of Internal Hospital Supply Chains–A Literature Study." *Omega* 82: 205–217. doi:10.1016/j.omega.2018.01.007.

Nikolova, Silviya, Mark Harrison, and Matt Sutton. 2016. "The Impact of Waiting Time on Health Gains from Surgery: Evidence from a National Patient-reported Outcome Dataset." *Health Econ* 25 (8): 955–968. doi: 10.1002/hec.3195.

Ozturk, Onur, Mehmet A. Begen, and Gregory S. Zaric. 2014. "A Branch and Bound Based Heuristic for Makespan Minimization of Washing Operations in Hospital Sterilization Services." *European Journal of Operational Research* 239 (1): 214–226. doi:10.1016/j.ejor.2014.05.014.

Papalexi, Marina, David Bamford, and Benjamin Dehe. 2016. "A Case Study of Kanban Implementation within the Pharmaceutical Supply Chain." *International Journal of Logistics Research and Applications* 19 (4): 239–255. doi:10.1080/13675567.2015.1075478.

Pedan, Marko, Milan Gregor, and Dariusz Plinta. 2017. "Implementation of Automated Guided Vehicle System in Healthcare Facility." *Procedia Engineering* 192: 665–670. doi:10.1016/j.proeng.2017.06.115.

Scholz, Christian. 1987. "Corporate Culture and Strategy—The Problem of Strategic Fit." *Long Range Planning* 20 (4): 78–87. doi:10.1016/0024-6301(87)90158-0.

Siciliani, Luigi, Valerie Moran, and Michael Borowitz. 2014. "Measuring and Comparing Health Care Waiting Times in OECD Countries." *Health Policy* 118 (3): 292–303. doi:10.1016/j.healthpol.2014.08.011.

Soremekun, Olanrewaju A., James K. Takayesu, and Stephen J. Bohan. 2011. "Framework for Analyzing Wait Times and Other Factors That Impact Patient Satisfaction in the Emergency Department." *The Journal of Emergency Medicine* 41 (6): 686–692. doi:10.1016/j.jemermed.2011.01.018.

Sousa, Rui, and Christopher A. Voss. 2008. "Contingency Research in Operations Management Practices." *Journal of Operations Management* 26 (6): 697–713. doi:10.1016/j.jom.2008.06.001.

Tanchoco, Jose Mario Azaña. 1994. *Material Flow Systems in Manufacturing*. Boston: Springer.

Tlahig, Houda, Aida Jebali, Hanen Bouchriha, and Pierre Ladet. 2013. "Centralized versus Distributed Sterilization Service: A Location–Allocation Decision Model." *Operations Research for Health Care* 2 (4): 75–85. doi:10.1016/j.orhc.2013.05.001.

Tortorella, Guilherme Luz., Flávio Sanson Fogliatto, Alejandro Mac Cawley Vergara, Roberto Vassolo, and Rapinder Sawhney. 2020. "Healthcare 4.0: Trends, Challenges and Research Directions." *Production Planning & Control* 31 (15): 1245–1216. doi:10.1080/09537287.2019.1702226.

Ullrich, Günter. 2015. *Automated Guided Vehicle Systems*. Heidelberg: Springer.

van de Klundert, Joris, Philippe Muls, and Maarten Schadd. 2008. "Optimizing Sterilization Logistics in Hospitals." *Health Care Management Science* 11 (1): 23–33. doi:10.1007/s10729-007-9037-4.

Venkatraman, Nenkat. 1989. "The Concept of Fit in Strategy Research: Toward Verbal and Statistical Correspondence." *Academy of Management Review* 14 (3): 423–444. doi:10.5465/amr.1989.4279078.

Villarreal, Bernardo, Jose Arturo Garza-Reyes, Edgar Granda-Gutiérrez, Vikas Kumar, and Samantha Lankenau-Delgado. 2018. "A Lean Transportation Approach for Improving Emergency Medical Operations." *Production Planning & Control* 29 (11): 928–942. doi:10.1080/09537287.2018.1494343.

Volland, Jonas, Andreas Fügener, Jan Schoenfelder, and Jens O. Brunner. 2017. "Material Logistics in Hospitals: A Literature Review." *Omega* 69: 82–101. doi:10.1016/j.omega.2016.08.004.

Voss, C. 2010. *Case Research in Operations Management. Researching Operations Management*. London: Routledge.

Wubben, I., Jeanette Gabrielle van Manen, B. J. Van den Akker, S. R. Vaartjes, and Willem H. van Harten. 2010. "Equipment-Related Incidents in the Operating Room: An Analysis of Occurrence, Underlying Causes and Consequences for the Clinical Process." *Quality and Safety in Health Care* 19 (6): e64–e64.

Yin, Robert K. 2017. *Case Study Research and Applications: Design and Methods*. Beverly Hills, CA: Sage Publications.

Zajac, Edward J., Matthew S. Kraatz, and Rudi K. F. Bresser. 2000. "Modeling the Dynamics of Strategic Fit: A Normative Approach to Strategic Change." *Strategic Management Journal* 21 (4): 429–453. doi:10.1002/(SICI)1097-0266(200004)21:4<429::AID-SMJ81>3.0.CO;2-#.

Zott, Christoph. 2003. "Dynamic Capabilities and the Emergence of Intraindustry Differential Firm Performance: Insights from a Simulation Study." *Strategic Management Journal* 24 (2): 97–125. doi:10.1002/smj.288.

## Appendix A

*Semistructured interview guide:*

A. Background
- Please introduce yourself (position and responsibilities, career background and years of employment)

B. **General and environmental information about the hospital**
- When was the hospital built, and what main changes have been made until now?
- What kind of hospital is it, and what does it specialise in?
- How many beds does the hospital have?
- How are the departments distributed in the hospital?

C. **Sterile processing**
- Where is the sterile processing department located?
- How are the resources for washing, inspection, packaging and sterilisation planned?
- What are the minimum, maximum and average process times for washing, inspection, packaging and sterilisation?
- How are the carts and material handling equipment washed and checked?

D. **Inventory**
- Is the storage centralised or decentralised?
- Where is the storage area located?
- Describe the inventory control and refill process.
- Describe the process from receiving an order until sending the cart.

E. **Material handling and transportation**
- What type of material handling system and equipment is used in the hospital?
- When was the material handling system implemented?
- How many pickups and delivery points are there in the hospital? How are they distributed?
- Explain the pickup and delivery process.
- Who is responsible for the loading and unloading activities? How are the employees informed when the carts arrive at the department?
- How is the communication carried out between the material handling system and employees, doors, elevators, etc.?
- How is the human interaction with the material handling equipment? How is the collaboration and acceptance between employees and the automated material handling system?
- Are elevator bottlenecks in the hospital?
- What problems or disturbances have occurred regarding the material handling system and transportation of sterile instruments?
- Describe the maintenance of the material handling equipment.
- What is the infection control process of the material handling equipment? How do you clean the material handling equipment?

F. **Point of use**
- Describe the ordering process of sterile instruments.
- How many people are involved from the pickup and delivery points at the department level to the point of use?
- Who is responsible for picking up the carts at the department level, preparing the return of soiled instruments and sending carts back?
- How are the sterile instruments received and checked for completeness or right of order?

# Paper 5

Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021).
Planning and control of autonomous mobile robots for intralogistics:
Literature review and research agenda.
*European Journal of Operational Research.*

*This is an accepted manuscript of an article published in*
*European Journal of Operational Research.*
*The final authenticated version is available online at:*
https://doi.org/10.1016/j.ejor.2021.01.019

European Journal of Operational Research 294 (2021) 405–426

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Invited Review

# Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda

Giuseppe Fragapane[a,*], René de Koster[b], Fabio Sgarbossa[a], Jan Ola Strandhagen[a]

[a] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Rotterdam School of Management, Erasmus University Rotterdam, the Netherlands

ARTICLE INFO

*Article history:*
Received 12 June 2020
Accepted 8 January 2021
Available online 17 January 2021

*Keywords:*
Logistics
Autonomous mobile robots
Planning and control
Literature review
Research agenda

ABSTRACT

Autonomous mobile robots (AMR) are currently being introduced in many intralogistics operations, like manufacturing, warehousing, cross-docks, terminals, and hospitals. Their advanced hardware and control software allow autonomous operations in dynamic environments. Compared to an automated guided vehicle (AGV) system in which a central unit takes control of scheduling, routing, and dispatching decisions for all AGVs, AMRs can communicate and negotiate independently with other resources like machines and systems and thus decentralize the decision-making process. Decentralized decision-making allows the system to react dynamically to changes in the system state and environment. These developments have influenced the traditional methods and decision-making processes for planning and control. This study identifies and classifies research related to the planning and control of AMRs in intralogistics. We provide an extended literature review that highlights how AMR technological advances affect planning and control decisions. We contribute to the literature by introducing an AMR planning and control framework to guide managers in the decision-making process, thereby supporting them to achieve optimal performance. Finally, we propose an agenda for future research within this field.



## 1. Introduction

In recent decades, the technology in materials handling has advanced rapidly. One major development is the evolution of automated guided vehicles (AGV) into autonomous mobile robots (AMR). Since 1955, when the first AGV was introduced (Muller, 1983), the guiding system that forms the core part of AGV material handling systems has evolved along various stages of mechanical, optical, inductive, inertial, and laser guidance into today's vision-based system (Fig. 1). This vision-based system uses ubiquitous sensors, powerful on-board computers, artificial intelligence (AI) and simultaneous location and mapping (SLAM) technology, enabling the device to understand its operating environment and to navigate in facilities without the need to define and implement reference points in advance. This has opened a new dimension in navigational flexibility.

Conventional AGVs can only follow fixed paths and move to predefined points on the guide path (Fig. 1(a)–((f)). By contrast, AMRs can move to any accessible and collision-free point within a given area (Fig. 1(g)). Small changes due to, for example, a machine layout change would typically take substantial time for most AGV guidance systems, cause periods of inactivity, and risk economic losses and decreases in productivity. AMRs, however, can adapt quickly to changes in the operating environment.

The need for more flexibility has driven the development of AMRs, not only in navigational ability but also in the services they can provide. Compared to AGVs, which have been characterized as computer-controlled, wheel-based load carriers for horizontal transportation without the need for an onboard operator or driver (Le-Anh & De Koster, 2006) to be used for repeated transport patterns, AMRs can provide many services beyond mere transport and material handling operations, such as patrolling and collaborating with operators. Combined with the ability to take autonomous decisions, these mobile platforms can offer flexible solutions. The autonomy of AMR vehicles implies continuous decision-making about how to behave in an operating environment consistent with prevailing rules and constraints. A substantial challenge lies in the complete absence of a human supervisor who knows the system's limits. An AMR must, therefore, monitor its own state autonomously, spot potential system faults and react appropriately.

The AMR's hardware and control software facilitate advanced capabilities for autonomous operation, not only for navigation and

* Corresponding author.
*E-mail address:* giuseppe.fragapane@ntnu.no (G. Fragapane).

https://doi.org/10.1016/j.ejor.2021.01.019

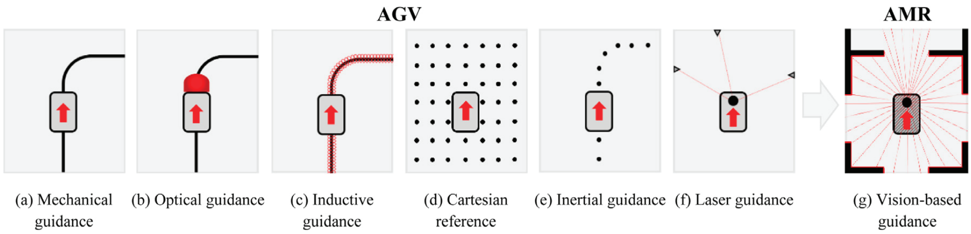



**Fig. 1.** Guiding systems for AGVs and AMRs (top view of the system).

object recognition but also for object manipulation in unstructured and dynamic environments (Hernández *et al.*, 2018). These developments have led to the decentralization of decision-making processes. Compared to an AGV system in which a central unit takes control decisions such as routing and dispatching for all AGVs, AMRs can communicate and negotiate independently with other resources like machines and systems such as enterprise resource planning or material handling assessment and control software (Fig. 2), and take decision themselves. This reduces the need for centralized, external control (Furmans & Gue, 2018). The goal of the AMR decentralized decision-making is to react dynamically to demand or changes and allow each vehicle to continuously optimize itself.

The AMR concept is not new. The first generic AMR patent was issued in 1987 (Mattaboni, 1987). Since then, it has been discussed mainly in the fields of robotics and information technology, but it has recently emerged in logistics applications and its importance is expected to increase significantly in the near future. In fact, it has been estimated that more than 13,000 AGV and AMR systems have been installed globally (Bechtsis *et al.*, 2017). Currently, hundreds of suppliers worldwide supply autonomous robots. Through the use of generic components, e.g. sensors, driving and steering systems, batteries, manipulating equipment and processing devices, basic vehicles can be assembled at a fairly low cost. Traditionally, the main sectors with AGV applications were manufacturing systems, warehouses and container terminals (Le-Anh *et al.*, 2006), but their areas of application and the services they can provide have increased significantly. AMRs can now be found in industrial, healthcare, hotel, security and domestic settings, performing a wide range of tasks.

Besides machine loading and transportation tasks, AMRs can be used as assistive systems as they can interact with humans as coworkers (Fig. 3(c)). In automotive car assembly, AMRs with manipulators can assist workers and together mount heavy parts of a car body at different stages along the assembly line (Angerer *et al.*, 2012), thus increasing both productivity and quality while simultaneously reducing fatigue levels among workers.

In warehouses, AMRs collaborate with operators in order picking (Fig. 3(p)). AMRs carry a few small containers inside the picking areas and stop in front of the location where the operator must pick the next item. They then move to the next location independently. When all items in a given order have been collected, the AMR autonomously travels to the packing and consolidation area, where it is emptied and reassigned to a new set of orders (Meller *et al.*, 2018; Azadeh *et al.*, 2019a). This technique enables a zone-picking strategy that optimizes operator and AMR picking and traveling efficiency.

The strength of AMRs is especially well demonstrated in narrow-aisle, high-traffic environments like those found in warehouses and hospitals. AGVs do not enter wards or departments for safety and delivery performance reasons; instead, they deliver goods close to the entrance. AMRs, by contrast, have greater access

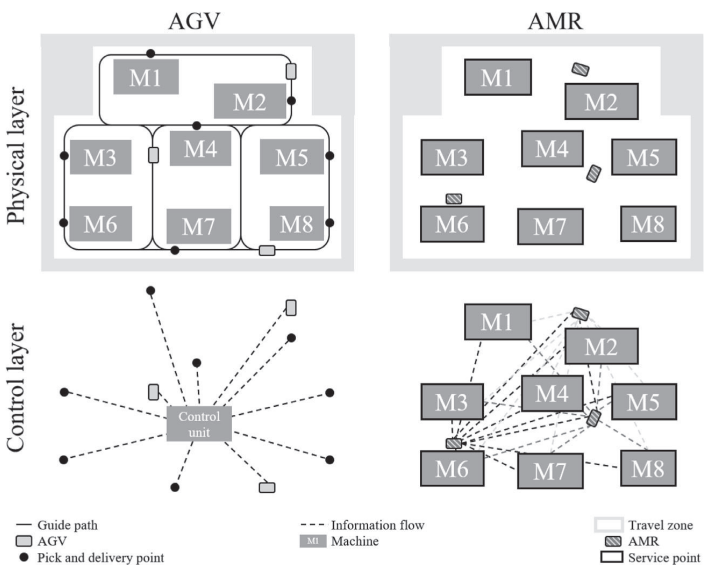



**Fig. 2.** Centralized AGV control and decentralized AMR control.

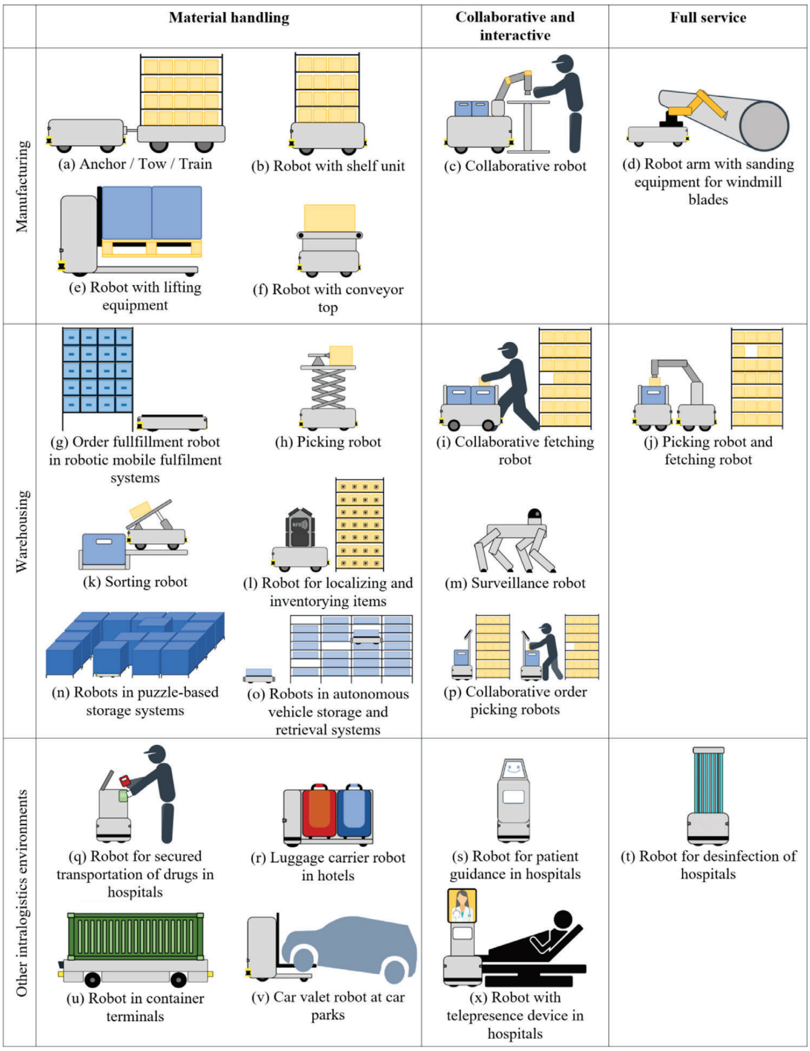



**Fig. 3.** Types of AMRs and examples of applications.

to nearly all departments and can be used for critical and just-in-time deliveries like cancer medicines or radioactive therapeutic and diagnostic medicines of which the correct dose decays rapidly (Fig. 3(q)). In addition to transport tasks, they can provide services, such as disinfecting rooms, telemedicine or guidance assistance (Fig. 3(s, t, x)) (Fragapane *et al.*, 2020a). AMRs can effectively reduce manual material handling in hospitals, providing more time for patient-related activities and increasing value-added time for direct-care staff.

The activities performed characterize and divide AMRs into three main groups. They provide (I) material handling (retrieve, move, transport, sort, etc.), (II) collaborative and interactive activities and (III) full-service activities (Fig. 3). They come with the following attributes (Hernández *et al.*, 2018; Indri *et al.*, 2019):

- Decentralized control: applying methodologies and technologies of intelligent, cognitive and behavior-based control to maximize flexibility and productivity performance.
- Platform operation: providing a platform to extend an AMR's capabilities and application possibilities beyond common material handling activities.
- Collaborative operation: working together with humans or other AMRs in a swarm.
- Ease of integration: integrating fast and cost-efficient AMRs into a factory or other facility.
- Scalability: increasing or decreasing the number of AMRs without being hindered by structural change.
- Robustness: providing resilience, i.e. systems that can recover after failure.

To summarize, the authors propose and use the following definition in this study:

*Autonomous mobile robots are industrial robots that use a decentralized decision-making process for collision-free navigation to provide a platform for material handling, collaborative activities, and full services within a bounded area.*

The increasing ability of AMRs to take over tasks and activities and the fact that AMRs navigate, operate and interact with humans and machines differently than AGVs requires a new decision structure. Managers need guidance during decision making in order to achieve optimal performance. For instance, at the strategic decision level, it is essential to define the degree of control decentralization of assistive material handling activities for AMRs in car manufacturing. At the tactical level in warehouses, work zones must be determined for collaborative AMRs. At the operational level in hospitals, safe and low contagion-risk AMR travel paths must be planned.

The literature on AMRs is fragmented and has a largely technological focus. The lack of a unified, accepted definition among practitioners and researchers has also hampered research in this field. AGVs have dominated the literature on vehicle planning and control systems. Vis (2006) and Le-Anh *et al.* (2006) distinguish key decision areas, such as guide path design and determining the number and locations of pick-up and delivery points, while Bechtsis *et al.* (2017) provide a literature review focusing on sustainability aspects in AGV planning and control. The greater degree of autonomy, applicability, and flexibility provided by AMRs result in a large number of different decisions on strategic, tactical and operational level that must be taken, and this number continues to grow. However, since their applications are not yet abundant, AMRs have not been investigated sufficiently from an academic perspective. The current methods of AGV planning and control remain to be analyzed, and it is worthwhile to assess whether they can be transferred, extended, or modified for AMRs.

Starting with the literature on AGVs, the present study identifies and classifies research related to the planning and control of AMRs and proposes an agenda for future research in this field. The focus is on the main elements of autonomy (i.e. decision-making), mobility (i.e. free navigation) and robotics (i.e. providing services). We examine the following research questions:

- How do the technological advances of AMRs affect planning and control decisions?
- What are the dominant approaches and methods in the literature on AMR planning and control?
- What future research is needed in AMR planning and control?

To answer these questions, we carried out a literature study that inventoried articles in refereed journals; English-language sources from online databases like ScienceDirect, Web of Science and Google Scholar were included. The following keywords (and their variants) were used: 'Automated Guided Vehicle', 'Autonomous Intelligent Vehicle', 'Autonomous Mobile Robot', 'Mobile Robotic Fulfilment', 'Collaborative Mobile Robot', 'Mobile Service Robot' and 'Puzzle Based Storage System'. We then narrowed down our search. First, we focused only on articles published in the last 15 years. Older material on AGVs has been adequately covered in two literature reviews by Le-Anh *et al.* (2006) and Vis (2006), which describe the main methods and approaches before 2006. Second, we excluded conference proceedings, professional journals, book chapters and doctoral dissertations, since we assume that important research has eventually appeared in refereed academic journals. Third, we focused on high-impact journals and included only articles published in journals with a Scimago Journal Rank higher than 0.5. Next, we manually screened the titles and abstracts of all 302 remaining articles. Only papers with full texts in English and related to either AMRs or AGVs (if relevant and applicable for AMRs) were included. In the final step, all the remaining articles were full-text screened to confirm their relevance to the planning and control of AMRs. Examining the reference lists, some highly relevant articles, cited multiple times but not identified previously, have also been added. A total of 108 articles were included in the final review.

The rest of the paper is organized as follows. Section 2 presents the crucial technological advances of AMRs and explains how they have affected the AGV decision areas and decisions. In Section 3, we introduce a decision-making framework for AMRs indicating the main changes compared to AGV decisions. Section 4 describes the planning and control decisions and the operational research methods applied. In Section 5, we quantify and summarize the current approaches to identify the gaps in literature, and present detailed recommendations for future research areas. We conclude in Section 6.

## 2. Technological advances impacting AMRs

The evolution of AGVs into AMRs has become possible due to new hardware (Section 2.1) and software (Section 2.2) technologies.

### 2.1. Hardware

#### 2.1.1. Sensors

AMRs are typically equipped with a wide array of small, low-cost, and power-efficient sensing technologies providing input data for autonomous navigation. Integrated laser scanners such as Light Detection and Ranging (LiDAR), 3D cameras, accelerometers, gyroscopes, and wheel encoders, which provide information on wheel positions to calculate the distance that the robot has driven or turned, and capture and transmit enormous amounts of data about the AMR's immediate, extended and anticipated environments, along with its internal condition (De Silva *et al.*, 2018). While LiDAR laser scanners provide a very precise distance point cloud relative to the AMR in its environment, 3D cameras provide wide-angle support that enables the visual recognition of obstacles. These technologies have become popular due to their easy dynamic usage and speedy rendering of results. Compared to AGVs, AMRs are not 'blind', but have full recognition of the environment. This affects decisions about guide path choice, collision and deadlock prediction and avoidance, and failure management. Sensing the environment allows an AMR to assist, collaborate and interact with humans and machines, which means more decisions to make.

#### 2.1.2. Robot locomotion mechanism

The locomotion mechanism of a robot has a strong impact on its stability, manoeuvrability, and kinematics. Most AGVs have either one steerable traction wheel in the front with supporting wheels in the back or two independently driven wheels with several, omnidirectional supporting wheels, thus providing a cost-efficient and low complexity trade-off against the above-mentioned factors. Different combinations, configurations, and arrangements of AMR wheels or legs exist. A high level of manoeuvrability can be achieved by powering Swedish or spherical wheels or increasing the number of legs, thus allowing the robot to move at any time in any direction along the ground plane regardless of the orientation of the robot (Siegwart *et al.*, 2011). Since many intralogistics activities require a high level of stability, wheeled AMRs are typically the first choice. However, movement in rough terrain is typically attempted with legged AMRs. Several companies have presented legged AMRs for activities in intralogistics; examples include SPOT by Boston Dynamics (https://www.bostondynamics.com/) and ANYmal C by ANYbotics (https://www.anybotics.com/). The increased flexibility in the movement and positioning of AMRs requires appropriate path planning methods, and the service points should be correctly determined.

#### 2.1.3. Batteries

Higher energy capacity and improvements in charging methods, ranging from conventional plug-in connector power supplies to wireless power transfer, have a significant impact on the battery management of AMRs. Studies indicate that wireless power transfer can be applied in many cases, eliminating the need for wired connections (Huang *et al.*, 2018). A limited battery capacity and long charging times were weak points of AGVs and reduce performance, utilization, and computational power. In addition, traditional lead-acid high-capacity batteries required increased vehicle size. The new high-capacity batteries (e.g.lithium-ion) enable longer operational time and provide more power for the calculations needed for autonomous navigation and operations. They also allow the AMRs to be smaller (this also holds for the newest AGVs) and thus to be deployed in narrow-aisle areas, or even directly underneath multiple loads stored closely in deep lanes (Lamballais *et al.*, 2017). With these technological improvements, the importance of battery management has declined somewhat, although it may still be relevant in 24/7 operations (Zou *et al.*, 2018). By contrast, reliable system operations, including battery management, have gained research interest. In addition, the increased battery power encourages more intensive scheduling decisions.

#### 2.1.4. Manipulating equipment

By combining AMRs with different manipulating equipment into a single unit, new services and material handling operations can be performed. Robotic manipulators enable AMRs not only to lift unit loads but also to pick single items (Shah *et al.*, 2018). AMRs can collaborate with humans and other AMRs, to carry out transportation tasks jointly (Lee & Murray, 2019; Machado *et al.*, 2019). The extended range of operations that AMRs offer must be planned over both the short and long term. This includes making new decisions on how to provide these services, developing methods on how AMRs can collaborate, and integrating their scheduling with production schedules to ensure collaboration at the right time and place.

#### 2.1.5. Processing devices

The AMR's ability to navigate and operate in a dynamic environment results from its capacity to make real-time decisions. Previously, intelligent decision-making capabilities in mobile robots were limited because of the significant computational power required. With the introduction of ultra-low-power AI processors, real-time decision-making for AMRs became possible (Kim *et al.*, 2017). Today, powerful AI-focused processor architectures such as the Intel Nervana, NVIDIA Xavier and Kneron AI SoC are widely available for vision recognition of face, body, gesture, object, or scene. This development especially affects the operational level of decision-making in AMRs. Enabling calculations of complex decisions allows new ways of dynamic routing and scheduling, navigating and classifying, and reacting to obstacles appropriately.

### 2.2. Software

#### 2.2.1. Simultaneous localization and mapping

SLAM, which is a supportive technology for real-time navigation, encompasses the two activities of creating detailed area maps of the environment and calculating the position of an AMR on a map (Bloss, 2008). The mapping process converts 3D point clouds retrieved from the scanning sensors to a reference map while filtering the dynamic obstacles. Combining the sensing information to accurately determine the AMR's location at any time has proven to be a difficult challenge. In recent years, a breakthrough was made through the application of Kalman filter technology. Estimations from different sensor sources must be combined to generate a probability distribution over all possible robot locations and to predict a robot's position and orientation (Bloss, 2008). The Kalman filter uses a recursive algorithm to correct the prediction over time. Using several measurement sources, measurement noise and sensor inaccuracy issues can be overcome (Pratama *et al.*, 2016). For high accuracy and reliability, SLAM can be supported indoors by real-time location systems using ultra-wideband technology, and outdoors by global positioning systems using network satellites placed in orbit. Applying trilateration and multilateration allows the identification of the exact positions of the AMRs.

#### 2.2.2. Motion planning

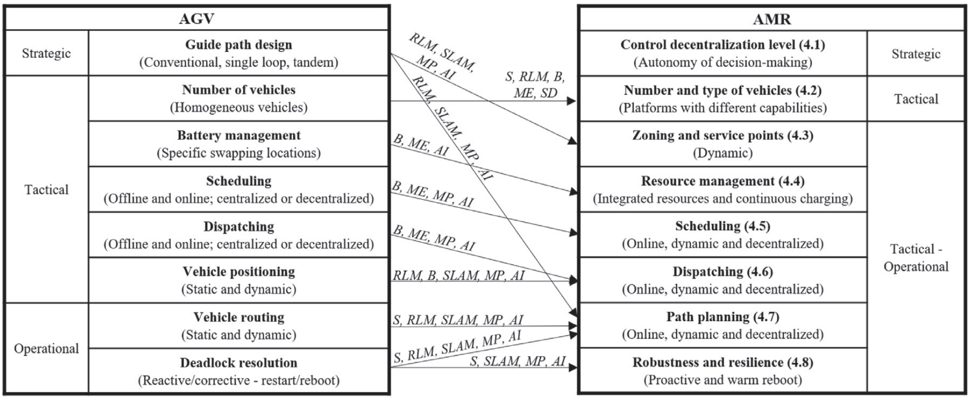
Motion planning is an essential part of the vision-based guidance systems and manipulation of equipment. Using the input of the environmental representation, the motion planner can calculate the robot's size and dynamics and a feasible, collision-free path from the initial point to the final position (Karaman & Frazzoli, 2011). Further, the motion planning algorithms provide speed and turning commands to the vehicle actuators such as wheels or manipulator to reach the set of guidance points along the path. Sensors and the SLAM technology allow the AMR trajectory to be tracked and provide feedback to correct its position. In dynamic environments, the motion planner allows the AMR to adapt to traffic or congestion by reducing speed, or even by stopping the vehicle. If planned paths are no longer feasible due to an emerging obstacle, a new collision-free path will be generated. Decisions that must be made about the guide path, routing, and obstacle avoidance are all taken by the AMR itself. Several open source platforms provide codes for the control of AMRs (and other robots). Examples include Robotics and Autonomous Systems by Intel (https://01.org/robotics-autonomous-systems), the Robot Operating System (https://www.ros.org/), Yet Another Robot Platform (https://www.yarp.it/) and the Mobile Robot Programming Toolkit (https://www.mrpt.org/).

#### 2.2.3. Artificial intelligence

Facilitated by hardware developments, AI techniques can be applied to support AMRs in both navigation and providing services. Compared to AGVs, for which most situations and tasks are predictable and therefore solvable by predefined decision rules, AMRs navigate autonomously in a dynamic and unpredictable environment. AI techniques such as vision systems and machine learning (ML) enable the identification and classification of obstacles. Fuzzy logic, neural networks and neuro-fuzzy and genetic algorithms are examples of well-known fusion techniques that help move the robot from the starting point to the target, while avoiding collisions with any obstacles along its path (Almasri *et al.*, 2016; Dias *et al.*, 2018). These techniques are inspired by the ability of the human brain to perform complex tasks by reasoning about, and adapting and responding to changes in the environment. Such behavior-based learning methods can be used to solve complex control problems that autonomous robots encounter in an unfamiliar, real-world environment. Without these techniques, AMRs would react to all obstacles in the same way. The introduction of AI affects all decision areas by opening new approaches to making decisions. The AI branches of vision, ML and planning, have been found to be very promising. As AI continues to advance, the ability to interact and collaborate with AMRs will increase. For example, in warehouses in which a human in the picking role and an AMR in the fetching role collaborate in order picking (Fig. 3 (i)), the human picker can use speech or gesture instead of tactile communication to confirm that picking tasks have been completed or to ask for help in finding items.

## 3. Planning and control framework for AMRs

The new developments and possibilities of AMRs, compared to AGV systems, require a new decision-making framework for planning and control.




*Hardware* - *S: Sensors, RLM: Robot Locomotion Mechanism, B: Battery, ME: Manipulating Equipment, SD: Semiconductor Devices.*
*Software* - *SLAM: Simultaneous Location And Mapping, MP: Motion Planner, AI: Artificial Intelligence.*

**Fig. 4.** Impact of technological developments on planning and control decision areas for AMRs.

The central hierarchical system has been challenged by large fleet sizes or fleet swarms, collaborative robots, and an increased variety of services provided. System performance is reduced by a centralized control hierarchy since it must take and simultaneously communicate many decisions in a short period. For instance, in robotic mobile fulfilment (RMF) systems (Fig. 3 (g)), there can be hundreds of mobile robots forming a large system (Wang *et al.*, 2020). The largest Amazon warehouses control thousands of mobile robots. Such systems are often divided into modules that consist of pods positioned in a grid structure, picking and replenishment stations, and vehicles (Lamballais *et al.*, 2020). The system can easily be scaled up by adding vehicles or modules. In such intralogistics environments, decentralized control of navigation and task allocation can help to handle the high number and density of vehicles by reducing elevated levels of traffic and congestion. The degree of decentralization of operations and the responsibility of the AMRs must be decided at the strategic level.

Depending on specific tasks and applications, the number of AMRs, including equipment such as manipulators, must be determined. Methods need to be developed for deciding and evaluating the fleet's size and equipment in terms of flexibility, productivity, quality, and costs. However, due to the short implementation times of systems, once they are available, vehicles can be added on the spot.

AMR vehicles are no longer tied to a fixed guide path, but instead can plan their path themselves and so freely move in predefined travel zones. The design of a guide path is therefore no longer necessary, but new decisions such as defining zones in which AMRs can operate autonomously must be taken (Fig. 2). These zones can be defined and changed on a daily or weekly basis, or dynamically in a decentralized manner by the AMR. The speedy establishment and easy change of zones enables operational flexibility that keeps AMR responsiveness high. Within these zones, service positions for tasks such as picking items or collaborating with humans can simply be added, assigned, or configured on a short-term basis. The zones can provide travel directions, traffic levels and other relevant information to reduce congestion and the risk of accidents. Both the service zone and service point locations have a strong impact on travel times and lead times. The increased flexibility requires new principles for scheduling and dispatching and how to allocate idle AMRs for maximum responsiveness.

The robot's locomotion mechanism and equipment enable the AMRs to follow paths and handle materials that AGVs cannot. AMRs can coordinate with multiple robots to reduce traffic (e.g. in a RMF system), to climb shelves (e.g. in some Autonomous Vehicle Storage and Retrieval (AVS/R) systems, see Fig. 6(o)), or to remove blocking loads (e.g. in Puzzle-Based Storage (PBS) systems, see Fig. 3(n)) to retrieve or store unit loads. This navigation flexibility must be incorporated in path planning approaches.

Like all intralogistics vehicles, AMRs must adhere to many standards, e.g. safety standards, before they can be brought to market. They must also be robust and reliable. Currently, AGV systems cannot work without human surveillance and support. Their sensitivity to a dynamic environment forces strong focus on error and failure management by humans. AI can support the recovery of AMRs after failures and find strategies to overcome such errors, making them more robust.

Changes in the planning and control environment from hardware and software developments have changed the traditional AGV decision areas to the following ones for AMRs (Fig. 4): (i) the control decentralization level, (ii) the number and type of vehicles, (iii) zoning and service points, (iv) resource management, (v) scheduling, (vi) dispatching, (vii) path planning and (viii) robustness and resilience.

The emerging planning and control framework with its decision areas is presented in the next section. In each section, first, we explain the shift from AGVs to AMRs and the corresponding decision problem. Second, we present and discuss the modeling approaches for AMRs and the AGV methods applicable for AMRs as per the literature.

## 4. Methods for planning and controlling AMRs

### 4.1. Control decentralization level

Problem

The level of control decentralization is a fundamental strategic decision. Determining which parts of a system should be controlled in a centralized or decentralized manner plays a crucial role in defining the interfaces between AMRs and their operating environment.

Centralized control structures are deeply rooted in the industry and can access global information to achieve optimal single-objective performance for small-scale, simple systems. Decentralized control can often access only local information and find local optimal solutions for systems with multiple objectives, that

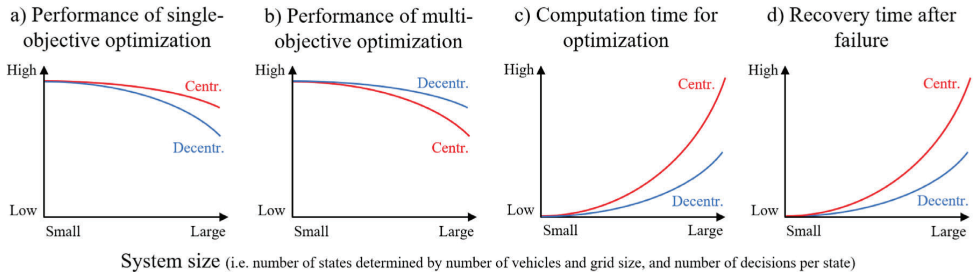



**Fig. 5.** Centralized versus decentralized control in small and large systems (partly based on Fauadi 2012).

are globally suboptimal (Fig. 5a). However, large-scale, complex systems require decentralized systems (De Ryck *et al.*, 2020a).

With a greater variety of operations and a more unstructured environment, decentralized control can achieve high performance, since multiple criteria are included in the optimization (Fig. 5b). Large systems with many vehicles imply a large number of decision states to be considered in the optimization approaches. The computation time is significantly lower in decentralized than in centralized control, since the decision making is distributed among multiple AMRs taking only local factors into consideration (Fig. 5c). This also allows further reduction of the recovery time after failure (Fig. 5d). Centralized control on the other hand requires a long time to evaluate the state of every single AMR after failure and to coordinate the entire fleet to recovery. Therefore, it is crucial, at the strategic decision level, to provide methods to determine the most suitable control decentralization level for the different decisions area such as scheduling, zoning or path planning.

Methods

AMRs with varying degrees of decentralization have been introduced and discussed in existing studies. Wan *et al.* (2017) introduce a cloud-based decision-making engine with centralized scheduling (i.e. task allocation) and decentralized navigation (i.e. map processing) that can be shared among AMRs. The small system size facilitates more central control of AMRs and decisions can be made by the cloud-based system. The study emphasizes that applying simple AMRs, and outsourcing the decision making to the cloud can keep overall costs low, while simultaneously using simulation modeling based on the AMRs' statuses and locations can improve their energy performance.

Simulations and computational experiments have been used to analyze the pertinence and feasibility of hierarchical control of AMRs (Demesure *et al.*, 2017; Zhang *et al.*, 2017). Kousi *et al.* (2019) apply discrete event simulation to analyze the performance of an assembly line in the automotive industry. Under their approach, centralized cloud-based systems can detect material supply requirements, trigger material supply operations, schedule them, and communicate schedules to the AMRs. This reduces the frequency of parts depletion and limits vehicle travel distance, leading to increased assembly line productivity and efficient resource utilization. In high-density, PBS systems, mobile robots can autonomously move storage loads from input points to the storage area or retrieval loads from storage to output points (Gue & Kim, 2007; Alfieri *et al.*, 2012; Gue *et al.*, 2014). These systems do not have travel aisles: the robots must collaborate to move loads out of the way to create paths. The robots negotiate and divide the transportation tasks to move items quickly and deadlock-free.

A few studies have investigated the decentralization of control areas beyond path planning. AMRs can be a cost-effective alternative compared to other material handling systems and allow quick implementations. De Ryck *et al.* (2020a) describe a decentralized task allocation in which AMRs can negotiate with or bid against other machines for task assignments. Fragapane *et al.* (2020b) use mathematical modeling and parametrical analysis to determine optimal configurations and the associated throughput performance impact of the AMR in production networks when compared to traditionally balanced lines. The control of connecting workstations during workstation downtime within a production network relies on AMRs.

The studies by Maniya and Bhatt (2011) and Hellmann *et al.* (2019) offer further support by using new methodologies to consider and select centralized or decentralized control systems. Maniya *et al.* (2011) propose a modified grey relational analysis method combined with an analytical hierarchy approach for multi-attribute selection processes. Hellmann *et al.* (2019) introduce a novel framework that integrates failure modes and effects analysis and analytic hierarchy processes to support decision-making for AMR design, operation, and control policies.

In the analysis of centralized and decentralized control structures, the prime objectives are to maximize resource utilization and throughput while reducing costs. The most common trend is to decentralize decision-making for navigation, but several other decision areas can also be decentralized and thus increase the autonomy of AMRs. Every application area has unique needs and requires a tailored mix of centralized and decentralized control. The degree of autonomy in AMRs must be analyzed and determined at the strategic level to establish a reliable basis for the number of vehicles and other relevant requirements.

### *4.2. Number and type of vehicles*

Problem

Combining the analysis of both the distances in the fixed guide path and the number of trips with AGV characteristics traditionally supported decisions on fleet size. However, due to the navigational flexibility of AMRs, travel distances and times between service points are highly variable or even uncertain. While AGV routing only has a limited number of possibilities to connect two points within the guide path, the autonomous path finding mechanism that AMRs use means the possibilities are effectively endless. AMRs currently operate in application areas in which humans, such as hospital visitors, may be unfamiliar with AMR tasks. Congestion and high traffic are unavoidable, which will hinder AMR performance and increase travel time. Thus, new methods are needed to calculate the right number of vehicles. The flexible platform also enables different types of AMRs that vary by equipment, size, or function within a single fleet. The number of vehicles and the type of equipment must also be determined at the tactical level.

Methods

*Mathematical modeling and simulation*

Simulation and mathematical modeling can be used to determine the optimal number of vehicles in manufacturing. Ji and Xia (2010) apply discrete event simulation to find the number of vehicles required for high utilization and to guarantee the stability of a system with a varying number of depots. Singh *et al.* (2011) use discrete event simulation to find the minimum number of vehicles needed to meet the entire material distribution requirement in a manufacturing system. To investigate different layout configurations in warehouses, Vivaldini *et al.* (2016) and Ribino *et al.* (2018) employ discrete event simulation and agent-based simulation to analyze throughput performance and to derive the optimal number of vehicles. Gharehgozli *et al.* (2017) apply simulation in a game theoretic setting to allow decision makers to understand the relationship between costs, throughput time, and waiting time when determining the optimal number of autonomous vehicles for transport between container terminals.

To ensure low traffic volumes, Małopolski (2018) and Lyu *et al.* (2019) model manufacturing environments and apply simulation to determine the optimal number of vehicles by simultaneously considering scheduling, path planning, and conflict-free vehicle routing. Draganjac *et al.* (2020) analyze the impact of traffic conflict negotiation in industrial logistics on throughput performance in a simulation model to determine the right number of vehicles.

A different approach is offered by mathematical programming models. Pjevcevic *et al.* (2017) propose a data envelopment analysis decision-making approach to simultaneously determine vehicle numbers, reduce operating delay costs, and increase equipment utilization rates in container terminals. Most studies focus on homogenous fleets, but the AMR's flexible platform allows for heterogenous fleets in which AMRs have different or exchangeable equipment. Collaborating pickers and fetchers (mounted on the same vehicle base) in a warehouse context offer an example. A recent study by Lee *et al.* (2019) proposes a mixed-integer linear programming (MILP) approach and numerical analysis to determine the number and type of vehicles needed to minimize the time required to pick and transport all items on a pick list from the warehouse to the packing station.

*Queuing network modeling*

In queuing network modeling, a customer arrives in a queue and goes through several service processes in a network, according to some routing mechanism, until he exits the system. The AMRs can be modelled as a server (open queuing network) or customer (closed queuing network) or to connect to a customer for specific tasks (semi-open queuing network). The different models have different application possibilities. While open queuing networks can be used at the operational decision level to estimate waiting and throughput times. Closed queuing networks assume the system is the bottleneck and as such they are fit to estimate throughput capacity of a given configuration at design decision level. Semi-open queuing networks can do both, but the (approximate) analysis is somewhat more involved.

Fukunari and Malmborg (2008) use an open queuing network model to estimate the cycle time and resource utilization for AVS/R systems. Performance is estimated using an iterative computational scheme considering random storage assumptions. Yuan and Gong (2017) determine the optimal number and velocity of robots and provide design rules for RMF. Wang *et al.* (2020) apply analytical models, including a bottleneck-based model and an open queuing network model, to simulate robotic mobile fulfilment system layout configurations and to identify the optimal number of vehicles. Zhang *et al.* (2020) use open queuing networks and discrete event simulation to investigate the influence of robot capacity on the performance of a flexible flow shop with random and state-dependent batch transport. Open queuing networks cannot model a joint capacity constraint set by the AMRs involved in multiple processes.

Limiting the number of resources, as in closed queuing network, allows to focus on the population constraint. Fukunari and Malmborg (2009) propose a closed queuing network approach for estimating resource utilization in AVS/R systems. Hoshino *et al.* (2007) propose using closed queuing network model and simulation to analyze the transportation system within container terminals. The suitable number of vehicles can be determined that minimizes total investment cost. Choobineh *et al.* (2012) propose an analytical multi-class closed queuing network model, extended with simulation, to determine the optimal number of vehicles and the ratio between loaded and empty travel times to maximize system throughput in a manufacturing or distribution environment. Roy *et al.* (2016) also apply a closed queuing network model with simulation to investigate the effect of traffic on the number of vehicles in container terminals. Roy *et al.* (2020) use open, closed, and semi-open queues to determine the numbers of vehicles with different capabilities in automated container terminals. The results of these studies indicate that vehicle congestion and speed depend heavily on the number and type of vehicles and throughput.

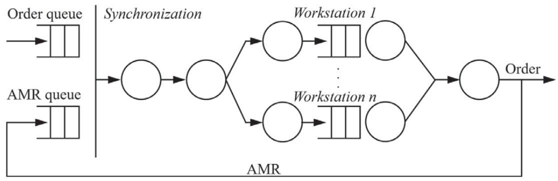



**Fig. 6.** Semi-open queuing network model with AMRs.

Semi-open queuing network modeling combines the advantages of open queuing networks (external queue to accommodate jobs whose entrance is delayed) and closed queuing networks (inner network with a population constraint). Using a synchronization station, incoming customers waiting at an external queue can be paired with available resources in the resource queue (Fig. 6).

This modeling approach allows to capture the external waiting time and precisely estimate the throughput time. The network is typically aggregated to a single synchronization station plus one station with queue, representing the remaining network, with a load dependent service rate. The continuous-time Markov chain of this network is analyzed. After determining the generator matrix

$$Q = \begin{Bmatrix} B_0 & C_0 & 0 & 0 & \dots \\ A_1 & B_1 & C_1 & 0 & \dots \\ 0 & A_2 & B_1 & C_1 & \dots \\ 0 & 0 & A_2 & B_1 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{Bmatrix}$$

which is nearly block-tridiagonal and which includes a repetitive pattern of the matrices A, B, and C, the matrix-geometric method can be applied to solve for the state probability vector $\pi$ of the system (solving for $\pi Q = 0$ with $\pi 1 = 1$) and from that performance measures can be calculated. To solve for $\pi$ the so-called rate matrix $R$ must be calculated from the equation

$$C_1 + RB_1 + R^2 A_2 = 0,$$

which includes the repetitive part of the generator matrix $Q$. $R$ can be calculated iteratively (Neuts, 1981), and the rate matrix at the n-th iteration is given by $R_{(n)} = -(C_1 + R^2_{(n-1)}A_2)B_1^{-1}$. The iteration process stops when the difference of two consecutive iterates is less than a given tolerance of $||R_{(n)} - R_{(n-1)}|| < \varepsilon$. This rate matrix $R$ allows one to obtain all the stationary probability vectors, facilitating the network analysis with relative high accuracy.

The studies by Ekren *et al.* (2013, 2014) demonstrate that AVS/R systems can be modelled efficiently as a semi-open queuing network. The performance of the external queue length as well as the average number of transactions in the network (including waiting for service, average number of vehicles in the vehicle pool, and average waiting time in the external queue) can be evaluated by applying the matrix-geometric method and the proposed extended algorithm (Ekren and Heragu 2010). The study by Zou *et al.*

(2016) applies semi-open queuing networks to estimate the system throughput time and cost and determines the number of robots which have transport and lifting capabilities and can move on the grid roof of a compact warehouse.

In sum, mathematical optimization, simulation, and queuing networks have all shown to be suitable methods to model the industrial environment with its specific constraints, to analyze operating systems and to evaluate the number of vehicles, with maximizing system throughput as main objective and workload distribution, minimizing throughput time, travel time, and costs as additional objectives.

### 4.3. Zoning and service points

Problem

The transition from providing services along fixed guide paths to flexible areas requires decisions to be made regarding the design of zones and service points. In some AMR application areas, the number and location of service points can be decided dynamically. Examples include guidance assistance in hospitals or shopping malls and RMF systems or collaborating fetchers in warehouses. Dividing the service areas into several zones with single or multiple vehicles can improve cost and productivity performance. Limiting the operating area for each vehicle improves the overall responsiveness of the system, since only short trips are performed, and vehicles are available more quickly. Therefore, zoning comprises the activities and decisions involving (I) analyzing the area in which the service must be provided, (II) determining fixed and/or dynamic service points, (III) configuring zones (adding, removing, dividing or overlaying zones, and defining flow direction) and (IV) determining the number of vehicles in each zone. The sequence of these steps can vary.

Methods

Several studies suggest designing zones in loops or blocks and co-locating picking and delivery points to improve performance within manufacturing systems. Shalaby *et al.* (2006) investigate zone partitioning and the selection of a tandem transportation system, using a heuristic algorithm to meet several objectives: minimizing total flow distance and total handling cost, achieving maximum workload, and limiting the number of between-zone trips. Asef-Vaziri *et al.* (2007) develop exact optimization, decomposition, and heuristic procedures to design a unidirectional flow loop. A binary integer programming model and a neighborhood search heuristic method support maximizing loaded-vehicle trips and minimizing empty vehicle trip distances. Farahani *et al.* (2007) investigate the flow path layout and develop a genetic algorithm to determine the optimal location of the loop and the picking and delivery stations, with the goal of minimizing the total distance travelled. ElMekkawy and Liu (2009) use a memetic algorithm in a computational experiment techniques to optimize the partitioning problem in a tandem AGV system, by minimizing overall workload, balancing the workload across zones, and preventing bottlenecks. Hamzeei *et al.* (2013) propose a cutting-plane algorithm to model and design the flow path and the location of pickup and delivery points. Asef-Vaziri and Kazemi (2018) investigate the traveling salesman problem of the shortest loop covering at least one edge of each workstation. Their proposed evolutionary algorithm achieves robust loop design solutions that maximize loaded and minimize empty vehicle travel.

Analyzing different layouts and zone configurations simultaneously can yield additional performance improvements. Using a simulated annealing approach, Tubaileh (2014) analyzes different manufacturing systems with simulations to find the optimal locations for machines in all feasible layouts. The objective of the study is to minimize travel times in a material handling system. Qi *et al.* (2018) investigate warehouse layouts and develop zones according to task density. Their simulation supports minimizing total traveling time, total distance traveled, and total waiting time. They recommend an even storage distribution of fast-selling or frequently transported goods to improve system performance. According to Lee *et al.* (2019), zoning in warehouses can significantly reduce costs. Different warehouse layouts, zone and service point configurations for order-picking robots are analyzed using MILP and numerical analysis with the goal of minimizing the time needed to deliver all items from a pick list to the packing station. Lamballais *et al.* (2017) and Roy *et al.* (2019) use queuing network models and simulation to analyze zone assignment strategies in RMF systems to improve system throughput, average order cycle time, and robot utilization. To analyze the preferred number of service points in such systems, Lamballais *et al.* (2020) use a semi-open queueing network with simulation to determine the optimal number of pods, and picking and replenishment stations. With regard to AVS/R systems, Roy *et al.* (2012) propose a semi-open queueing network approach to investigate the impact of vehicle locations and zones within a tier using multiple vehicle classes and class switching probabilities in terms of throughput performance. Azadeh *et al.* (2020) use a closed two-phase server queuing network, embedded in a Markov decision process, to dynamically adjust the number of zones in a human-robot collaborative picking system. They show that dynamically adjusting the number of zones can lead to higher throughput capacity in multichannel warehouses with varying numbers of large and small orders.

Differences in zoning and in the number of vehicles per zone can influence overall traffic. Reducing congestion between vehicles – by reducing the time that vehicles spend negotiating complex traffic situations and removing bottlenecks in high-traffic areas – helps to decrease overall travel time and increase system responsiveness. Ho and Liao (2009) propose a dynamic zone strategy that includes zone partition design and dynamic zone control. Their simulation results show a reduction in vehicle congestion and an increase in load balance between vehicles in different zones. Azadeh *et al.* (2019b) use closed-queuing network models to compare different zoning schemes and access control rules to estimate the throughput impact on vehicle blocking. To maximize throughput, Singh *et al.* (2011) suggest using discrete event simulation and a scheme for partitioning the entire area into exclusive zones for individual vehicles in an automotive manufacturing plant. Małopolski (2018) offers a method that divides the layout into a rectangular grid and then uses both linear programming and simulation to improve transportation performance for unidirectional, bidirectional, and multiple-lane flow path systems in a manufacturing environment.

The main objectives when designing zones and service points are to minimize travel distance, traffic, and throughput time while distributing the workload throughout the system, to increase and – ideally - maximize system throughput and resource utilization. Dynamic zones with multiple and varying service points increases the AMR modeling complexity and limits the application of earlier AGV-based approaches. When service point positions change dynamically, they impact the workload and service demands. This increases the number of variables in mathematical models, with negative consequences for feasibility and on computation time. Evolutionary approaches and simulation seem to be most suitable in these cases. Another promising approach has been used to model the assignment of mobile robots in warehousing. In warehouses, the service points (picking locations) are numerous and they change according to the orders to be fulfilled. Queuing network modeling (to estimate performance) and Markov decision processes (to assign vehicles dynamically) are a promising combination of methods able to solve complex and dynamic problems in an accurate way and with acceptable computation time. They can be applied also in other application areas, such as manufacturing, hospitals or shopping malls, adjusting the definition of the service points to the application context. These methods are also suitable to dynamically manage large amounts of input data. Further extensions will be to integrate the traffic modeling into these methods in order to consider blocking and congestion and their impact on the performance of the system.

### 4.4. Resource management

Problem

Current AGVs can only provide few handling activities (e.g. lifting and moving), since they are equipped with only a single handling unit (e.g. lifting unit). However, in robotics and flexible manufacturing, it is common to exchange equipment. AMRs can load, use, unload, exchange equipment, and charge or exchange batteries. The AMR's platform allows a wide range of resources to be used and shared. The decision-making processes of location planning, scheduling, and dispatching these resources are essential to their optimal utilization and thus to high AMR productivity performance.

Methods

Even though the energy density of batteries is increasing, it is still necessary to decide where charging stations should be located. Boysen *et al.* (2018) investigate the influence of battery capacity, the number and location of charging stations, and charging periods on makespan performance. They propose a genetic algorithm and computational experiments to identify the optimal charging locations in terminals. A study by Kabir and Suzuki (2019) explores how the four heuristics of (I) selecting the nearest battery station, (II) selecting a battery station that will cause minimum delay considering both travel time and waiting time in a queue, (III) selecting the nearest battery station on the current route and (IV) selecting the farthest reachable battery station on the current route, can affect performance in terms of total travel distance and waiting time at a battery station. Their simulation reveals that a higher frequency of decision-making about battery swapping helps to increase the productivity of a manufacturing system. Zou *et al.* (2018) evaluate battery charging and swapping strategies in an RMF system. Applying a semi-open queuing network and simulation allows the comparison of different strategies in terms of cost and throughput time performance. The study emphasizes that throughput time performance can be significantly affected by the battery recovery policy that is selected, and that inductive charging offers the best performance. De Ryck *et al.* (2020b) propose a decentralized charging approach in which an AMR can independently choose when to visit a charging station and how long to charge. Their approach is modeled as an extension of the traveling salesman problem in manufacturing systems and solved by a general constrained optimization algorithm. They investigate different charging schemes and charging station choices to increase resource efficiency.

In the near future, the efficient management of resources will play a greater role in planning and controlling AMRs. While AGVs employ a narrow range of handling equipment, AMRs will have access to and use a wide variety of equipment, which requires efficient management and use. Fully decentralizing resource management to the AMRs, without some form of coordination, will lead to suboptimal results at the system level. Iterating the decentral optimization decisions for all AMRs and sharing the results between multiple units are essential to achieve a near global optimum. Using the results of the decentralized decisions in operational level to take tactical decisions such as location planning of battery stations or equipment storage areas can yield in performance such as short travel time. New modeling approach for AMRs are needed to solve these decisions simultaneously or iteratively. Predictive analytics can further support in deciding when to charge batteries or when to exchange the mounted equipment to a time period with lowest risk of conflict. None of the current studies are providing methods which consider the operational information exchange for such decisions.

### 4.5. Scheduling

Problem

A substantial body of literature has been developed to support the decision-making process in scheduling material handling systems simultaneously with machines, humans, equipment, parts, and containers. In manufacturing, most studies consider a low number (fewer than 50) of vehicles under centralized, hierarchical control applying mixed integer programming models with heuristic algorithms. Mathematical modeling and optimization approaches have been widely developed to solve scheduling problems, mostly in manufacturing since the number and type of tasks are typically higher than in a warehouse. Some of the papers have also integrated simulation models to validate and generalize their results. A new stream of research uses AI techniques, such as evolutionary algorithms, which is now possible due to the advances in computational power. However, decentralized scheduling methods in which AMRs negotiate or bid for tasks are still scarce.

Methods

*Mathematical modeling for scheduling of transportation activities*

The scheduling of 'only' vehicles has been studied by analyzing the impact on the performance of the manufacturing system. Few papers have focused on container terminals and warehousing, since solving dispatching problems seems to be predominant in these application areas.

In manufacturing systems, decomposition methods (Corréa *et al.*, 2007) and mathematical and statistical models (Ghasemzadeh *et al.*, 2009) have been used to solve and analyze the interaction between conflict-free vehicle routing and scheduling policies and the impact on the production delays. Other authors have studied the impact on makespan, cycle time deviations, and vehicle earliness and tardiness, through two-step algorithms to cluster the solution space and next to find the optimal solution (Fazlollahtabar *et al.*, 2015; Bakshi *et al.*, 2019). For more complex problems with heterogeneous and multiple-load vehicles, simulation is used to evaluate different scheduling policies (Ho & Chien, 2006; Bocewicz *et al.*, 2019). In container terminals, scheduling transportation activities has been modeled by a minimum cost flow model solved by an extended simplex algorithm and greedy vehicle search (Rashidi & Tsang, 2011). Polten and Emde (2020) focus on warehouses with very narrow aisles and address the multi-aisle access scheduling problem by proposing two access policies: exclusive and parallel access. A MILP and a large neighborhood search algorithm analyze and optimize the robot task allocation problem.

*Methods for joint scheduling of vehicles and machines*

The simultaneous scheduling of jobs in machine centers and vehicles is relevant to obtain high overall efficiency in the manufacturing system. The main objectives are to minimize the makespan, waiting times, and transportation costs. Due to the complexity of the problem, general heuristics, decomposition algorithms, adaptive genetic or memetic algorithms, and simulated annealing approaches are mainly applied (Jerald *et al.*, 2006; Deroussi *et al.*, 2008; Nishi *et al.*, 2011; Lacomme *et al.*, 2013; Zheng *et al.*, 2014; Baruwa, 2016; Lei *et al.*, 2019). Fazlollahtabar (2016) and Fazlollahtabar and Hassanli (2018) apply a mathematical cost flow model and modified network simplex algorithm, while Lyu *et al.* (2019) use simulation to investigate the impact of scheduling policies on makespan and vehicles utilization. In the context of a container terminal, Yang *et al.* (2018) analyze simultaneous scheduling of multiple cranes and vehicles at a container yard to minimize the makespan of container loading and unloading by using a genetic algorithm. Chen *et al.* (2020) propose a multicommodity network flow model to deal with inter-robot constraints that accurately reflect the complex interactions among container terminal agents. Using a genetic algorithm, the average makespan of the system and the average resource transfer times of all robots can be minimized.

*AI-based methods for multi-objectives or constraint problems*

Due to advances in computational power and the application of AI techniques, the use of multi-objective or constraint scheduling models has become more feasible, in particular in complex environments, such as manufacturing with multiple jobs and machine centers. Some authors have developed genetic and ant colony optimization algorithms (Udhayakumar & Kumanan, 2010; Saidi-Mehrabad *et al.*, 2015), or a sheep flock heredity algorithm (Anandaraman *et al.*, 2012), hybrid evolutionary or genetic algorithms, particle swarm optimization (Gen *et al.*, 2017; Mousavi *et al.*, 2017; Rahman *et al.*, 2020), and a whale optimization algorithm (Petrović *et al.*, 2019). The whale optimization algorithm is inspired by humpback whale hunting. It first explores the 'ocean' looking for 'prey' (exploration phase). This corresponds to agents searching the state space by changing their locations while attempting to find global optima. When a location near a global optimum is found, they stop. After the first phase, the whales start diving in a spiral shape in order to trap the prey. This is called exploitation phase. In the algorithm, the agents follow a 'leader' and change their locations according to a shrinking encircling mechanism, while updating their location data, until the final location. These methods perform well for solving multi-objective problems, combining e.g. minimization of makespan, travel time, and tardiness, with maximization of battery charging efficiency and vehicle utilization.

*Methods for decentralized scheduling and task allocation*

Current information sharing and computing technologies provide a new information processing method for online machine and vehicle scheduling, enabling new dimensions of agility and flexibility. High levels of connectivity and communication are needed when decentralizing task allocation. Zeng *et al.* (2018) propose a collaborative and distributed scheduling approach for decentralizing task allocation, based on dynamic communication between vehicles and machines, using a hormone-regulation mechanism. A new promising approach in decentralized scheduling is offered by auction-based methods where an announcer (machine) and bidder (AMR) cooperate to achieve high performance in task allocation. De Ryck *et al.* (2020a) classify different auction-based methods for task allocation in single, bundled, and combined items offered and bid on these in sequential or parallel auctions. The bid calculation is a crucial element since it reflects the cost for the AMR to perform the specific task, and therefore for scheduling and task allocation. Even while executing a given task, AMRs can bid on new tasks and thus locally optimize the task list and use this information to calculate the next bid. Bids can be calculated based on the cost to perform the tasks by the AMRs, or on the marginal cost considering also the other tasks in the list. Each type of calculation has its most suitable bidding algorithm. For the first type of cost CNET, OCA-Alloc, CBAA and CBBA are used, while marginal cost is used in Prim Allocation, SIT- and SET-MASR algorithms (see De Ryck *et al.* 2020a for an overview). These action-based methods overcome the limitations of previous OR approaches, and extend to large vehicle fleets, while introducing flexibility and scalability. The computation is distributed, so it can be applied to very complex problems with many constraints. The collateral effect is the increase in demand for computational power for each single AMR, with negative impact on battery consumption. Further opportunities for improving these methods will be in the integration of this decision area with resource management and dispatching.

### *4.6. Dispatching*

Problem

Smart dispatching methods, that allow AMRs to be close to the point of demand before an actual need is announced, can increase performance. The increased flexibility of accessing a wide area and of free positioning due to autonomous navigation, enable new opportunities for positioning and for cruising while an AMR is idle. Centralizing the decision-making processes of distributing and dispatching AMRs requires a system that analyzes the AMR positions and the demand data. ML and big data analysis of demand can support the optimization of vehicle distribution over the system. However, large-scale AMR systems need high computational power to analyze and communicate in real time. Decentralizing this process will decrease the need for high-power cloud computing. Each AMR will optimize its available time based on historical data and on data shared with neighboring AMRs. Continuous communication and negotiations will optimize the AMR's ability to react quickly to demand.

Methods

Various multi-attribute dispatching rules have been developed to allocate tasks to the appropriate AMRs, using mainly mathematical modeling, queuing networks, and simulation to evaluate them. They have been mostly applied in manufacturing, and only few implementations can be found in warehousing and container terminals.

Several mathematical approaches have been developed to model the dispatching problem in its complexity, including path layouts, vehicle capacity and restrictions as constraints, and single or multiple objectives, such as minimizing makespan, travel time, and delay. Ventura and Rieksts (2009) develop a dynamic programming algorithm to solve idle vehicle positioning in a single loop AGV system. Ventura *et al.* (2015) extend the problem to a general guide-path layout, solved by a genetic algorithm. Bozer and Eamrungroj (2018) present an analytic model to assess the throughput performance and device utilization of various dispatching rules, by varying layout configurations in trip-based systems. In case of more complex problems, with multi-objectives and more constraints, heuristics like genetic and evolutionary algorithms have been implemented (Lin *et al.*, 2006; Umar *et al.*, 2015; Miyamoto & Inoue, 2016; Gen *et al.*, 2017).

While queuing network modeling is less often applied to manufacturing systems, it is commonly used in warehousing, in particular for RMF systems. An extended review of closed queuing network models by Smith (2015) analyzes optimal workload allocation in manufacturing systems with multiple transportation servers, infinite-capacity workstations, and a finite capacity state. Zou *et al.* (2017) apply semi-open queuing networks and a two-phase approximate approach to estimate the performance of RMF systems in terms of retrieval throughput time. An assignment rule based on the handling speeds of workstations is proposed and managed by a neighborhood search algorithm to find a nearly optimal assignment. He *et al.* (2018) introduce a differentiated probabilistic queuing policy and use an alternating minimization method with simulated annealing to minimize the weighted latency of all customer orders.

Simulation has been used to explore various scenarios to extract general guidelines and results to support decision makers, especially in manufacturing where the problems are complex. Some authors focus on evaluating the impact of several multi-attributes dispatching rules (Bilge *et al.*, 2006; Guan & Dai, 2009; Singh *et al.*, 2011; Confessore *et al.*, 2013; Zamiri & Choobineh, 2014). These rules can typically include attributes such as travel time or distance to pick up location, input and output buffer size, use of single or multiple-load vehicles, and waiting time. Demand characteristics and constraints from the operating environment have a significant impact on the responsiveness of AMRs. Simulation has shown to be a powerful tool for multi-scenario analysis that can be integrated with big data analytics and ML techniques.

### 4.7. Path planning

Problem

Path planning is the task of finding a continuous, deadlock-free path, with little congestion delay for the AMR from the start to the goal position so that it can navigate autonomously between locations, potentially within a large swarm. Compared to AGV routing, which uses a guide path as input, path finding for AMRs uses a representation of the environment to mathematically find the shortest and conflict-free path. An AMR always creates a new, unique path when moving from one point to another. Constraints of static and dynamic obstacles, feasible curvature, robot size, lane dimensions, and speed may be included to find the optimal path with single or combined objectives. In static environments, the path planning is often performed only once, but dynamic environments can require repeating the process of finding a collision-free path multiple times, for multiple vehicles to bypass or to remove the obstacles.

Methods

The methods for path finding can be grouped into those for a single vehicle, for multiple vehicles, and for multiple vehicles with unit load accessibility constraints (i.e. obstacles need to be removed).

*Methods for a single vehicle*

De Ryck *et al.* (2020a) explain the graph representations of the environment and graph search algorithms for a single AMR. Their study highlights that the A* and D*Lite algorithms, modifications of Dijkstra's algorithm, are the most popular graph search algorithms to find a shortest path.

Compared to Dijkstra's algorithm which allows to prioritize directions (favoring lower cost paths, e.g. lower costs to encourage moving along straight lines, or higher costs to avoid U-turns) to explore and find the shortest path, the A* algorithm uses a heuristic that prioritizes paths that seem to lead closer to a goal. A* selects the path that minimizes

$$f(n) = g(n) + h(n),$$

where $g(n)$ is the length of the path from the start node to the node n, and $h(n)$ is the heuristic cheapest distance (Manhattan, Euclidean, or Chebyshev) of the current node n to the goal state. Compared to the previous mentioned approaches, the D*Lite algorithm works in the opposite direction which is from the goal to the start and is especially useful to find the shortest path in large and complex areas.

According to Liaqat *et al.* (2019), simulation is currently not able to properly reproduce the AMR paths and behavior in dynamic environments. In a dynamic environment, many situations occur in which moving obstacles can temporarily block the AMR's path. In their study, experiments support the AMR motion planning reaction to avoid obstacles. They provide protocols that improve the accuracy and quality of path planning simulation in dynamic environments.

*Methods for multiple vehicles*

In intralogistics systems with multiple vehicles, the shortest path does not necessarily result in the shortest travel time due to constraints such as congestion or deadlock. Several studies use mathematical modeling to introduce conflict-free or deadlock-free strategies to find the shortest path (Wu & Zhou, 2007; Saidi-Mehrabad *et al.*, 2015; Yang *et al.*, 2018), and to solve combinatorial scheduling (Corréa *et al.*, 2007; Ghasemzadeh *et al.*, 2009; Nishi *et al.*, 2011), dispatching (Miyamoto *et al.*, 2016), number of vehicles (Vivaldini *et al.*, 2016), and routing problem. The study by Nishi *et al.* (2009) applies Lagrangian relaxation to solve the routing problem. It enables the inclusion of various constraints such as loading, unloading, buffering, or coordination with other material handling machines. According to Joseph and Sridharan (2011), routing flexibility has a strong impact on the overall flexibility of a manufacturing system. The study applies simulation and fuzzy logic to analyze the routing flexibility and its effect on efficiency and versatility for a manufacturing system. They provide decision support methods to improve the vehicle routing. The studies by Zhang *et al.* (2018) and Lyu *et al.* (2019) apply an improved Dijkstra algorithm to predetermine the initial route of each task. Comparing every route of each vehicle to the given transportation time window, potential congestion can be detected and prevented by suggesting alternative paths. Digani *et al.* (2019) present an optimization strategy to coordinate a vehicle fleet in automated warehouses to reduce the time mobile robots spend negotiating in complex traffic patterns. A quadratic optimization program, representing a centralized coordination strategy is compared with a decentralized strategy that relies on local negotiations for shared resources. The simulation shows that the coordination strategy can maximize vehicle throughput and minimize the time vehicles spend negotiating traffic under different scenarios. Mohammadi and Shirazi (2020) introduce a tandem-queue-link with a look-ahead approach to enable flexible, collision-free routing in manufacturing systems. Applying simulation, different scenarios are evaluated for congestion, travel time, utilization, and system throughput. Draganjac *et al.* (2020) propose a decentralized control algorithm that allows each vehicle to plan its own shortest feasible path and to resolve conflict situations with other vehicles by negotiating priority. They use simulation to analyze the intralogistics system for travel distance, system throughput, and energy costs. Fransen *et al.* (2020) propose a dynamic approach to avoid congestion for large, dense grid-based vehicle systems. Since most approaches in the literature are not rapid enough for real-time control, the introduced method can solve this issue by using a graph representation of the grid system layout with vertex weights that are updated over time. An extensive discrete event simulation allows the proposed path planning approach to significantly increase the throughput and enable recovery from deadlock situations.

*Methods for multiple vehicles with obstacle removal*

Obstacles (e.g. stored unit loads) can block the AMR paths to fulfill the material handling task. Compared to AGVs, AMRs are not helpless in deadlock situations. For instance, to obtain access to a specific pallet in a truck trailer or to retrieve a unit load in a PBS system, the AMR can move the unit loads that are in front of it or can request support from other AMRs.

For such cases, Gue *et al.* (2007) investigate the sequencing of movements for retrieving an item from a PBS system with a single 'escort' (i.e. a single open storage space: all other spaces are occupied). Each load has its own vehicle that can lift and move it to a neighboring escort. At each time step, it must be decided which load to move and in which direction. The presented single-escort algorithm finds the optimal path to move an item to the retrieval point, minimizing retrieval time. Alfieri *et al.* (2012) extend the work of Gue *et al.* (2007) to systems with multiple empty slots, where multiple vehicles (but fewer than the number of loads) perform the transportation tasks. The proposed heuristic algorithm for conflict avoidance regulates how vehicles should behave in different traffic situations. Mirzaei *et al.* (2017) extend this to systems where multiple loads must be retrieved and multiple vehicles must be coordinated, with a single escort. They provide an optimal method for two loads and a heuristic method for retrieving more than two loads. Yalcin *et al.* (2019) propose an exact and heuristic solution algorithm for the single-item retrieval problem in PBS systems with multiple escorts. Their algorithm is based on the A* algorithm and can be used to plan minimum energy movements for unit loads. The study by Gue *et al.* (2014) introduces a decentralized control method for PBS systems that follow an Assess-Negotiate-Convey cycle. The heuristic algorithm allows it to assess its current state and the states of its neighbors for each load at each step, and then to move it according to the conveying policy.

In sum, mathematical modeling and simulation modeling have been applied and heuristic algorithms have been proposed to avoid conflicts and deadlocks and to integrate decision variables such as scheduling multiple loads and vehicles. AMRs can find short paths by moving obstacles. However, this capability has hardly been considered in finding the shortest paths, except in PBS systems.

### 4.8. Robustness and resilience

Problem

A crucial attribute of AMRs is the ability to operate without human surveillance or interference and to recover after failure, guaranteeing a robust and resilient system. Thus, it is necessary to study the internal and external factors that affect system reliability and to introduce decision-making methods that support AMR planning and control abilities.

Methods

The increased navigational flexibility of AMRs can actually lead to increased uncertainty in travel time. Fazlollahtabar and Olya (2013) propose a heuristic statistical technique to compute total stochastic material handling time and develop a cross-entropy approach to model the problem. To ensure system stability, Tavana *et al.* (2014) introduce an optimization model that uses both time and cost measures to analyze the reliability of a manufacturing system. Bi-objective stochastic programming helps determine optimal reliable production time and cost in a manufacturing system.

Only a few studies have evaluated the ability of AMRs to respond to reliability issues. Yan *et al.* (2017) apply a failure modes effects and criticality analysis and Yan *et al.* (2018) propose predictive maintenance strategies for the long-term reliability and stability of the system. To guarantee uninterrupted system performance, Petrović *et al.* (2019) recommend balancing the utilization and activities of AMRs. Their proposed regulatory measure can increase the AMR life cycle and improve maintenance efficiency.

Dynamic interactions by humans is often neglected in simulation studies. Fragapane *et al.* (2019) introduce an agent-based simulation model for the use of vehicles in a hospital, using historical material handling data. This facilitates the analysis of the impact of the dynamic environment on performance decline during core business hours and periods of high traffic. Agent-based simulation is especially useful in simulating complex logistics networks and understanding real-world systems with many individual decision making units. The increasing number and density of vehicles in grid-based systems prompted Fransen *et al.* (2020) to propose a dynamic path planning approach that supports the recovery of AMRs from deadlock situations and increases the robustness of the system.

Widespread acceptance of decentralizing the decision-making process and assigning decisions to AMRs will depend on the overall reliability of the system. Robust systems with stable and predictive results are needed. All AMR risks must be analyzed to discover, refine, and propose methods so that AMRs can achieve reliable performance in various different environments.

## 5. Research agenda for AMRs

### 5.1. Approaches and methods used in the planning and control of AMRs

Based on Section 4, we have classified and grouped all 108 reviewed articles on the decision area, prime objectives, methods, and application area. A detailed description of each reviewed article is provided in Table 1a (covering Sections 4.1–4.4) and Table 1b (covering Sections 4.5–4.8). Articles discussed and referred to in multiple decision areas are mentioned multiple times. The following paragraphs highlight the insights of the tables for each decision area. An overview and summary of all decision areas can be found at the end of the section (Table 2).

Decentralized decision-making (Section 4.1) has received increasing research interest. However, few studies have investigated when decentralized control of material handling is profitable or results in higher performance than centralized control. System throughput and throughput time are the decisive performance measures when analyzing and deciding on the control decentralization level, and thus simulation modeling has so far been the favored method (6/11 papers). Most studies have been conducted in manufacturing rather than in other intralogistics areas (7/11 papers), which might be traced back to the strong promotion of Industry 4.0 to decentralize material handling (Furmans *et al.*, 2018). Thus, more studies are needed that investigate and compare centralized vs. decentralized control and global vs. local optimization and that analyze different degrees of autonomy in decision-making. Further, more research is needed to investigate how decentralized control affects the profit, resource efficiency, responsiveness, delay, and system robustness and reliability.

Due to the high variety of AMRs (see Fig. 3), different types of equipment and levels of decentralization are required. Simulation modeling and queuing networks have supported decision-making on determining the number and types of AMRs (Section 4.2), by analyzing the intralogistics system with system throughput and throughput time as prime objectives, followed by waiting time, utilization and cost. While most studies treat manufacturing and warehousing equally, container terminals have received the highest level of attention in this decision area. Most of the reviewed studies investigate AMRs with lifting or carrying equipment. Methods for analyzing, optimizing, and providing decision-making support for the wide range of equipment and heterogonous fleets are still lacking.

In the decision area of zoning and service points (Section 4.3), mathematical modeling has been applied almost exclusively to analyze the intralogistics systems in manufacturing to improve the distribution of workload and to increase the utilization of AMRs. In contrast, queuing networks have mainly been used for warehousing to increase system throughput and decrease travel time, and thus retrieval time. Flexibility in zoning and the location of service points require dynamic approaches. However, only two studies have proposed dynamic approaches. Ho *et al.* (2009) apply heuristics/meta-heuristics and a simulated annealing approach for load balancing and traffic reduction, and Azadeh *et al.* (2020) use a closed two-phase server queuing network, embedded in a Markov decision process, to increase throughput capacity. More dynamic methods are needed to adjust quickly to service location fluctuations such as product demand changes in warehousing or treatment demand changes in hospitals. AI algorithms that have rarely been considered in this decision area can facilitate optimization methods to improve the responsiveness, resource consumption, and reliability that are currently lacking. Further, decentralized methods can support AMRs to negotiate zones or request support to handle the demand change when needed.

Only four studies have investigated resource management (Section 4.4). These studies provide optimization methods and decision support to improve a variety of performance measures in manufacturing and warehousing. The current studies mainly focus on scheduling battery charging and positioning charging stations or inductive charging lines, while the management of the equipment mounted on top of the vehicle has received little attention.

**Table 1a**
List of 56 reviewed articles for decision areas in Sections 4.1–4.4.

| Author | Year | Decision area | Prime objective | | | | | | | | Method | | | | | Application area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cost/ profit | Energy/ resource consumption | System throughput | Throughput time/travel time/travel distance/ makespan | Utilization rate/ workload distribution /bottleneck analysis | Work in process/ waiting time/ congestion and traffic /waste | Responsiv-eness/ tardiness/ lateness/ delay and penalty cost | Robustness/ reliability | Mathematical modelling | Queuing network modeling | Simulation modeling | Optimization methods | Decision science approach (sensitivity/ scenario analysis,...) | Manufacturing | Warehousing | Container terminals | Other intralogistics environ-ments | Not specified |
| Gue *et al.* | 2007 | 4.1, 4.7 | | | √ | √ | | | | | √ | | | Ex+H/MH | √ | | √ | | | |
| Maniya *et al.* | 2011 | 4.1 | √ | | | | | | | | | | | | √ | √ | | | | |
| Alfieri *et al.* | 2012 | 4.1, 4.7 | | | √ | √ | | | | | √ | | √ | H/MH | | | √ | | √ | |
| Gue *et al.* | 2014 | 4.1, 4.7 | | | √ | √ | | | | | | | √ | | √ | | √ | | | |
| Demesure *et al.* | 2017 | 4.1 | | | | √ | | | | | | | √ | | | √ | | | | |
| Wan *et al.* | 2017 | 4.1 | √ | √ | | | | | | | | | √ | | | √ | | | | |
| Zhang *et al.* | 2017 | 4.1 | | | | √ | | √ | | | | | √ | | | √ | | | | |
| Hellmann *et al.* | 2019 | 4.1 | √ | | √ | | √ | √ | | | | | | | √ | √ | | | | |
| Kousi *et al.* | 2019 | 4.1 | | | | √ | √ | | | | | | √ | | | √ | | | | |
| Fragapane *et al.* | 2020 | 4.1 | | | √ | | √ | | | | √ | | | | √ | √ | | | | |
| De Ryck *et al.* | 2020a | 4.1, 4.5, 4.7 | | | √ | | | | | | | | | | √ | √ | | | | |
| *Total 11 articles* | | *4.1* | *3* | *1* | *6* | *6* | *3* | *2* | *0* | *0* | *3* | *0* | *6* | *2* | *6* | *8* | *3* | *0* | *1* | *0* |
| Hoshino *et al.* | 2007 | 4.2 | √ | | | | | | | | | √ | √ | | | | | √ | | |
| Fukunari *et al.* | 2008 | 4.2 | √ | | | √ | √ | √ | | | | √ | √ | | | | √ | | | |
| Fukunari *et al.* | 2009 | 4.2 | | | | | √ | | | | | √ | √ | | | | √ | | | |
| Ji *et al.* | 2010 | 4.2 | | | | | √ | | | | √ | | √ | | | √ | | | √ | |
| Singh *et al.* | 2011 | 4.2, 4.3, 4.6 | | | √ | | | | | | √ | | √ | | √ | √ | | | | |
| Choobineh *et al.* | 2012 | 4.2 | | | √ | | √ | | | | | √ | √ | | | √ | | | | |
| Ekren *et al.* | 2010 | 4.2 | | | √ | | | | | | | √ | √ | | | | √ | | | |
| Ekren *et al.* | 2013 | 4.2 | | | √ | | √ | √ | | | | √ | √ | | | | √ | | | |
| Ekren *et al.* | 2014 | 4.2 | | | √ | | √ | √ | | | | √ | √ | | | | √ | | | |
| Roy *et al.* | 2016 | 4.2 | | | √ | | | √ | | | | √ | | | √ | | | √ | | |
| Vivaldini *et al.* | 2016 | 4.2, 4.7 | | | | √ | | | | | | | √ | | | | √ | | | |
| Zou *et al.* | 2016 | 4.2 | √ | | √ | | | | | | | √ | | | √ | | √ | | | |
| Gharehgozli *et al.* | 2017 | 4.2 | √ | | | √ | | √ | | | √ | | √ | | √ | | | √ | | |
| Pjevcevic *et al.* | 2017 | 4.2 | | | | | √ | | √ | | √ | | √ | | | | | √ | | |
| Yuan *et al.* | 2017 | 4.2 | | | √ | √ | | | | | | √ | | | √ | | √ | | | |
| Małopolski | 2018 | 4.2, 4.3 | | | | √ | | √ | √ | | √ | | √ | | | √ | | | | |
| Ribino *et al.* | 2018 | 4.2 | | | | √ | | | | | | | √ | | | | √ | | | |
| Lee *et al.* | 2019 | 4.2, 4.3 | | | | √ | | | | | √ | | | Ex | | | √ | | | |
| Lyu *et al.* | 2019 | 4.2, 4.5, 4.7 | | | | √ | | √ | √ | | √ | | | GA | √ | √ | | | | |
| Draganjac *et al.* | 2020 | 4.2, 4.7 | √ | √ | √ | | | | | | | | √ | | √ | √ | √ | | | |
| Roy *et al.* | 2020 | 4.2 | | | √ | √ | | √ | | | | √ | | | | | | √ | | |
| Wang *et al.* | 2020 | 4.2 | | | √ | √ | | | | | | √ | √ | | | | √ | | | |
| Zhang *et al.* | 2020 | 4.2 | | | √ | | | | | | | √ | √ | | √ | √ | | | | |
| *Total 23 articles* | | *4.2* | *5* | *1* | *12* | *10* | *7* | *8* | *3* | *0* | *7* | *13* | *17* | *2* | *8* | *7* | *12* | *5* | *1* | *0* |
| Shalaby *et al.* | 2006 | 4.3 | √ | | | | √ | √ | | | √ | | √ | H/MH | | √ | | | | |
| Asef-Vaziri *et al.* | 2007 | 4.3 | | | √ | | √ | | | | √ | | | Ex+H/MH | | √ | | | | |
| Farahani *et al.* | 2007 | 4.3 | | | | √ | | | | | √ | | | GA | | √ | | | | |
| ElMekkawy *et al.* | 2009 | 4.3 | | | | | √ | | | | √ | | | MA | | √ | | | | |
| Ho *et al.* | 2009 | 4.3 | | | | | √ | √ | | | | | √ | H/MH+SA | | √ | | | | |
| Singh *et al.* | 2011 | 4.2, 4.3, 4.6 | | | √ | | | | | | √ | | √ | | √ | √ | | | | |
| Roy *et al.* | 2012 | 4.3 | | | √ | √ | √ | | | | | √ | √ | | | | √ | | | |
| Hamzeei *et al.* | 2013 | 4.3 | | | | √ | √ | | | | √ | | | Ex+SA | | √ | | | | |
| Tubaileh | 2014 | 4.3 | | | | √ | | | | | √ | | √ | SA | | √ | | | | |
| Lamballais *et al.* | 2017 | 4.3 | | | √ | | √ | | | | | √ | | | √ | | √ | | | |
| Asef-Vaziri *et al.* | 2018 | 4.3 | | | | | √ | | | | √ | | | EA | | √ | | | | |
| Małopolski | 2018 | 4.2, 4.3 | | | | √ | | √ | √ | | √ | | √ | | | √ | | | | |
| Qi *et al.* | 2018 | 4.3 | | | | √ | | √ | | | | | √ | | | | √ | | | |
| Azadeh *et al.* | 2019b | 4.3 | | | √ | | | | | | | √ | | | √ | | √ | | | |
| Lee *et al.* | 2019 | 4.2, 4.3 | | | | √ | | | | | √ | | | Ex | | | √ | | | |
| Roy *et al.* | 2019 | 4.3 | | | √ | | √ | | | | | √ | | | √ | | √ | | | |
| Azadeh *et al.* | 2020 | 4.3 | | | √ | | | | | | | √ | | | √ | | √ | | | |
| Lamballais *et al.* | 2020 | 4.3 | | | √ | | | | | | | √ | √ | | √ | | √ | | | |
| *Total 18 articles* | | *4.3* | *1* | *0* | *8* | *7* | *9* | *4* | *1* | *0* | *10* | *6* | *8* | *9* | *6* | *10* | *8* | *0* | *0* | *0* |
| Boysen *et al.* | 2018 | 4.4 | | | | | | | √ | | √ | | | GA | | | | | | √ |
| Zou *et al.* | 2018b | 4.4 | √ | | √ | | | | | | | √ | | | | | √ | | | |
| Kabir *et al.* | 2019 | 4.4 | | | | √ | √ | | | | | | √ | | √ | √ | | | | |
| De Ryck *et al.* | 2020b | 4.4 | | √ | | | √ | | | | √ | | | H/MH+PSO | | √ | | | | |
| *Total 4 articles* | | *4.4* | *1* | *1* | *1* | *1* | *2* | *0* | *1* | *0* | *2* | *1* | *1* | *2* | *1* | *2* | *1* | *0* | *0* | *1* |

AC: Ant Colony Approach, AT: Auction Theory, EA: Evolutionary Algorithm, Ex: Exact Optimization, GA: Genetic Algorithm, H/MH: Heuristics/Meta-Heuristics, MA: Memetic Algorithm, PSO: Particle Swarm Optimization, SA: Simulated Annealing, SFHA: Sheep Flock Heredity Algorithm, WA: Whale Optimization Algorithm.

**Table 1b**
List of 74 reviewed articles for decision areas in Sections 4.5–4.8.

| Author | Year | Decision area | Prime objective | | | | | | | | Method | | | | | Application area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cost/ profit | Energy/ resource consumption | System throughput | Throughpu time/travel time/travel distance /makespan | Utilization rate /workloaddi- stribution /bottleneck analysis | Work in process /waiting time /congestion and traffic /waste | Respon- siveness- /tardiness /lateness /delay and penalty cost | Robustness /reliability | Mathematical modelling | Queuing network modeling | Simulation modeling | Optimization methods | Decision science approach (sensitivity /scenario analysis,...) | Manufacturing | Warehousing | Container terminals | Other intralogistics environments | Not specified |
| Ho *et al.* | 2006 | 4.5 | | | √ | | | | √ | | | | √ | | √ | √ | | | | |
| Jerald *et al.* | 2006 | 4.5 | | | | | | √ | √ | | √ | | | GA | | √ | | | | |
| Corréa *et al.* | 2007 | 4.5, 4.7 | | | | | | √ | √ | | √ | | | H/MH | | √ | | | | |
| Deroussi *et al.* | 2008 | 4.5 | | | | √ | | | √ | | √ | | | H/MH+SA | | √ | | | | |
| Ghasemzadeh *et al.* | 2009 | 4.5, 4.7 | | | | | | √ | √ | | √ | | | H/MH | | √ | | | | |
| Udhayakumar *et al.* | 2010 | 4.5 | | | | | √ | √ | | | √ | | | GA+AC | | √ | | | | |
| Nishi *et al.* | 2011 | 4.5, 4.7 | | | | | | | √ | | √ | | | H/MH | | √ | | | | |
| Rashidi *et al.* | 2011 | 4.5 | | | | √ | | √ | √ | | √ | | | Ex+H/MH | | | | √ | | |
| Anandaraman *et al.* | 2012 | 4.5 | | | | √ | | | √ | | √ | | | SFHA | | √ | | | | |
| Lacomme *et al.* | 2013 | 4.5 | | | | √ | | | | | √ | | | MA | | √ | | | | |
| Zheng *et al.* | 2014 | 4.5 | | | | √ | | | | | √ | | | H/MH | | √ | | | | |
| Fazlollahtabar *et al.* | 2015 | 4.5 | | | | | | | √ | | √ | | | H/MH | | √ | | | | |
| Saidi-Mehrabad *et al.* | 2015 | 4.5, 4.7 | | | | √ | | | | | √ | | | AC | | √ | | | | |
| Baruwa | 2016 | 4.5 | | | | √ | | | √ | | | | √ | H/MH | | √ | | | | |
| Fazlollahtabar | 2016 | 4.5 | | | | √ | | | | | √ | | | H/MH | | √ | | | | |
| Gen *et al.* | 2017 | 4.5, 4.6 | | | | √ | | | √ | | √ | | | GA | | √ | | | | |
| Mousavi *et al.* | 2017 | 4.5 | | | | √ | | | | | √ | | | GA+PSO | | √ | | | | |
| Fazlollahtabar *et al.* | 2018 | 4.5 | √ | | | √ | | | | | √ | | | Ex | | √ | | | | |
| Yang *et al.* | 2018 | 4.5, 4.7 | | | | √ | | | | | √ | | | GA | | | | √ | | |
| Zeng *et al.* | 2018 | 4.5 | | | | √ | √ | | | | √ | | | AT | | √ | | | | |
| Bakshi *et al.* | 2019 | 4.5 | | | | √ | | | | | √ | | | H/MH | | √ | | | | |
| Bocewicz | 2019 | 4.5 | | | √ | | | | √ | | √ | | √ | Ex | | √ | | | | |
| Lei *et al.* | 2019 | 4.5 | | | | | | √ | | | √ | | | MA | | √ | | | | |
| Lyu *et al.* | 2019 | 4.2, 4.5, 4.7 | | | | √ | | √ | √ | | √ | | | GA | | √ | | | | |
| Petrović *et al.* | 2019 | 4.5, 4.8 | | | | √ | √ | √ | | | √ | | | WA | | √ | | | | |
| Chen | 2020 | 4.5 | | | √ | | | | | | √ | | | GA | | | | √ | | |
| De Ryck *et al.* | 2020a | 4.1, 4.5, 4.7 | | | √ | | | | | | | | | | √ | √ | | | | |
| Polten *et al.* | 2020 | 4.5 | | | | | √ | | | | √ | | | H/MH | √ | | √ | | | |
| Rahman *et al.* | 2020 | 4.5 | | | √ | | | | √ | | √ | | | H/MH+PSO | | √ | | | | |
| *Total 29 articles* | | *4.5* | *1* | *0* | *5* | *16* | *4* | *8* | *14* | *0* | *26* | *0* | *3* | *27* | *3* | *25* | *1* | *3* | *0* | *0* |
| Bilge *et al.* | 2006 | 4.6 | | | √ | | | | √ | | | | √ | | √ | √ | | | | |
| Lin *et al.* | 2006 | 4.6 | | | | √ | | | | | | | √ | GA | | √ | | | | |
| Guan *et al.* | 2009 | 4.6 | | | √ | | | √ | √ | | | | √ | | √ | √ | | | | |
| Ventura *et al.* | 2009 | 4.6 | | | | | √ | | √ | | √ | | | H/MH | | √ | | | | |
| Singh *et al.* | 2011 | 4.2, 4.3, 4.6 | | | √ | | | | | | √ | | √ | | √ | √ | | | | |
| Confessore *et al.* | 2013 | 4.6 | | | | √ | √ | | | | | | √ | | √ | √ | | | | |
| Zamiri *et al.* | 2014 | 4.6 | | | | | √ | | | | | | √ | | √ | √ | | | | |
| Smith | 2015 | 4.6 | | | | | √ | √ | | | | √ | | | √ | √ | | | | |
| Umar *et al.* | 2015 | 4.6 | | | | √ | | | √ | | √ | | | GA | | √ | | | | |
| Ventura *et al.* | 2015 | 4.6 | | | | | | | √ | | √ | | | GA | | √ | | | | |
| Miyamoto *et al.* | 2016 | 4.6, 4.7 | | | | √ | | | √ | | √ | | | H/MH | | √ | | | | |
| Gen *et al.* | 2017 | 4.5, 4.6 | | | | √ | | | √ | | √ | | | GA | | √ | | | | |
| Zou *et al.* | 2017 | 4.6 | | | | √ | | | | | | √ | √ | | √ | | √ | | | |
| Bozer *et al.* | 2018 | 4.6 | | | | √ | √ | | | | √ | | √ | | √ | √ | | | | |
| He *et al.* | 2018 | 4.6 | | | | √ | | | √ | | | √ | | H/MH+SA | | | √ | | | |
| *Total 15 articles* | | *4.6* | *0* | *0* | *3* | *8* | *5* | *2* | *8* | *0* | *7* | *3* | *8* | *7* | *8* | *13* | *2* | *0* | *0* | *0* |

(*continued on next page*)

**Table 1b** (*continued*)

| Author | Year | Decision area | Prime objective | | | | | | | | Method | | | | | Application area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cost/ profit | Energy/ resource consumption | System throughput | Throughpu time/travel time/travel distance /makespan | Utilization rate /workloaddi-stribution /bottleneck analysis | Work in process /waiting time /congestion and traffic /waste | Respon-siveness- /tardiness /lateness /delay and penalty cost | Robustness /reliability | Mathematical modelling | Queuing network modeling | Simulation modeling | Optimization methods | Decision science approach (sensitivity /scenario analysis,...) | Manufacturing | Warehousing | Container terminals | Other intralogistics environments | Not specified |
| Corréa *et al.* | 2007 | 4.5, 4.7 | | | | | | √ | √ | | √ | | | H/MH | | √ | | | | |
| Gue *et al.* | 2007 | 4.1, 4.7 | | | √ | √ | | | | | √ | | | Ex + H/MH | √ | | √ | | | |
| Wu *et al.* | 2007 | 4.7 | | | | √ | | | | | √ | | | H/MH | | √ | | | | |
| Ghasemzadeh *et al.* | 2009 | 4.5, 4.7 | | | | | | √ | √ | | √ | | | H/MH | | √ | | | | |
| Nishi *et al.* | 2009 | 4.7 | √ | | | | | | | | √ | | | H/MH | | | | | | √ |
| Nishi *et al.* | 2011 | 4.5, 4.7 | | | | | | | √ | | √ | | | H/MH | | √ | | | | |
| Joseph *et al.* | 2011 | 4.7 | | | | √ | √ | √ | | | √ | | √ | | | | | | | |
| Alfieri *et al.* | 2012 | 4.1, 4.7 | | | √ | √ | | | | | √ | | √ | H/MH | | | √ | | √ | |
| Gue *et al.* | 2013 | 4.1, 4.7 | | | √ | √ | | | | | | | √ | | √ | | √ | | | |
| Saidi-Mehrabad *et al.* | 2015 | 4.5, 4.7 | | | | √ | | | | | √ | | | AC | | √ | | | | |
| Miyamoto *et al.* | 2016 | 4.6, 4.7 | | | | √ | | | √ | | √ | | | H/MH | | √ | | | | |
| Vivaldini *et al.* | 2016 | 4.2, 4.7 | | | | √ | | | | | | | √ | | | | √ | | | |
| Mirzaei *et al.* | 2017 | 4.7 | | | √ | √ | | | | | √ | | √ | Ex + H/MH | | | √ | | | |
| Yang *et al.* | 2018 | 4.5, 4.7 | | | | √ | | | | | √ | | | GA | | | | √ | | |
| Zhang *et al.* | 2018 | 4.7 | | | | | | √ | | | | | √ | H/MH | √ | | √ | | | |
| Digani *et al.* | 2019 | 4.7 | | | | √ | | √ | | | | | √ | | | | √ | | | |
| Liaqat *et al.* | 2019 | 4.7 | | | | √ | | √ | | | √ | | √ | | | √ | | | | |
| Lyu *et al.* | 2019 | 4.2, 4.5, 4.7 | | | | √ | | √ | √ | | √ | | | GA | | √ | | | | |
| Yalcin *et al.* | 2019 | 4.7 | | | √ | √ | | | | | √ | | √ | Ex + H/MH | | | √ | | | |
| De Ryck *et al.* | 2020a | 4.1, 4.5, 4.7 | | | √ | | | | | | | | | | √ | √ | | | | |
| Draganjac *et al.* | 2020 | 4.2, 4.7 | √ | √ | √ | | | | | | | | √ | | √ | √ | √ | | | |
| Fransen *et al.* | 2020 | 4.7, 4.8 | | | | √ | | √ | | √ | | | √ | | | | | | √ | |
| Mohammadi *et al.* | 2020 | 4.7 | | | | √ | √ | √ | | | | | √ | H/MH | | √ | | | | |
| *Total 23 articles* | | *4.7* | *2* | *1* | *7* | *16* | *2* | *9* | *5* | *1* | *15* | *0* | *12* | *15* | *5* | *11* | *9* | *1* | *2* | *1* |
| Fazlollahtabar *et al.* | 2013 | 4.8 | | | | √ | | | | √ | √ | | | H/MH | | √ | | | | |
| Tavana *et al.* | 2014 | 4.8 | √ | | | √ | | | | √ | √ | | | Ex | | √ | | | | |
| Yan *et al.* | 2017 | 4.8 | | | | | | | | √ | | | √ | | √ | | | | | √ |
| Yan *et al.* | 2018 | 4.8 | | | | | | | | √ | | | √ | | √ | | | | | √ |
| Fragapane *et al.* | 2019 | 4.8 | | | | √ | √ | √ | | √ | | | √ | | | | | | √ | |
| Petrović *et al.* | 2019 | 4.5, 4.8 | | | | √ | √ | √ | | | √ | | | WA | | √ | | | | |
| Fransen *et al.* | 2020 | 4.7, 4.8 | | | | √ | | √ | | √ | | | √ | | | | | | √ | |
| *Total 7 articles* | | *4.8* | *1* | *0* | *0* | *5* | *2* | *3* | *0* | *6* | *3* | *0* | *4* | *3* | *2* | *3* | *0* | *0* | *2* | *2* |

AC: Ant Colony Approach, AT: Auction Theory, EA: Evolutionary Algorithm, Ex: Exact Optimization, GA: Genetic Algorithm, H/MH: Heuristics/Meta-Heuristics, MA: Memetic Algorithm, PSO: Particle Swarm Optimization, SA: Simulated Annealing, SFHA: Sheep Flock Heredity Algorithm, WA: Whale Optimization Algorithm.

**Table 2**
Number of papers per decision area, prime objectives, methods used in the decision-making process, and application areas.

| Decision area | Articles | Prime objective | | | | | | | | Method | | | | | Application area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost/profit | Energy /resource consumption | System throughput | Throughput time/travel time/travel distance/ makespan | Utilization rate/workload distribution/ bottleneck analysis | Work in process/ waiting time/ congestion and traffic/waste | Responsiveness /tardiness/ lateness/ delay and penalty cost | Robustness/ reliability | Mathematical modelling | Queuing network modeling | Simulation modeling | Optimization methods | Decision science approach (sensitivity/ scenario analysis,…) | Manufacturing | Warehousing | Container terminals | Other intralogistics environments | Not specified |
| 4.1 Control decentralization level | 11 | 3 | 1 | 6 | 6 | 3 | 2 | 0 | 0 | 3 | 0 | 6 | 2 | 6 | 8 | 3 | 0 | 1 | 0 |
| 4.2 Number and type of vehicles | 23 | 5 | 1 | 12 | 10 | 7 | 8 | 3 | 0 | 7 | 13 | 17 | 2 | 8 | 7 | 12 | 5 | 1 | 0 |
| 4.3 Zoning and service points | 18 | 1 | 0 | 8 | 7 | 9 | 4 | 1 | 0 | 10 | 6 | 8 | 9 | 6 | 10 | 8 | 0 | 0 | 0 |
| 4.4 Resource management | 4 | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 0 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 0 | 0 | 1 |
| 4.5 Scheduling | 29 | 1 | 0 | 5 | 16 | 4 | 8 | 14 | 0 | 26 | 0 | 3 | 27 | 3 | 25 | 1 | 3 | 0 | 0 |
| 4.6 Dispatching | 15 | 0 | 0 | 3 | 8 | 5 | 2 | 8 | 0 | 7 | 3 | 8 | 7 | 8 | 13 | 2 | 0 | 0 | 0 |
| 4.7 Path planning | 23 | 2 | 1 | 7 | 16 | 2 | 9 | 5 | 1 | 15 | 0 | 12 | 15 | 5 | 11 | 9 | 1 | 2 | 1 |
| 4.8 Robustness and resilience | 7 | 1 | 0 | 0 | 5 | 2 | 3 | 0 | 6 | 3 | 0 | 4 | 3 | 2 | 3 | 0 | 0 | 2 | 2 |
| *Total* | *130* | *14* | *4* | *42* | *69* | *34* | *36* | *32* | *7* | *73* | *23* | *59* | *67* | *39* | *79* | *36* | *9* | *6* | *4* |

*Articles included in several decision areas appear multiple times.

Future studies will have to provide decision support for positioning the storage of sharing equipment and multi-objective optimization methods for scheduling the sharing of equipment among a fleet. Optimization methods for battery and equipment could increase AMR availability, thus reducing costs and increasing productivity.

Scheduling vehicles and loads (Section 4.5) has received the most attention in literature, with 29 articles. Most applications can be found in manufacturing (25/29 papers), with a focus on makespan and delay optimization. Mathematical modeling and a wide variety of optimization techniques have been introduced and investigated (26/29 papers). Compared to other decision areas, AI-based techniques methods such as evolutionary algorithms, genetic algorithms, memetic algorithms and, furthermore, swarm intelligence-based methods such as the ant colony approach, particle swarm optimization, sheep flock heredity algorithms, and the whale optimization algorithm have been widely applied. In comparison to scheduling, dispatching (Section 4.6) has focused more on queuing network and simulation modeling to improve the main objectives of makespan and responsiveness. Scheduling is used in container terminals, while dispatching methods are more commonly used in warehousing. However, optimization methods for scheduling and dispatching focused on resource consumption and reliability are still lacking. Optimization methods for scheduling and dispatching in other intralogistics systems are also lacking.

The decision area of path planning (Section 4.7) has received increasing interest in recent years. While there has been a greater focus on reducing traffic, congestion and conflict, more recent studies highlight the potential of finding paths by moving unit loads that are blocking the shortest path. Mathematical modeling and simulation have supported analyses of warehousing and manufacturing and introduced heuristics improving the overall objectives of travel distance, travel time, traffic, and system throughput. While path planning with obstacle removal has been investigated in especially compact warehouses, studies for manufacturing and other intralogistics systems are still lacking. The increased level of decentralized control and flexibility in path planning and equipment require methods to establish robust and resilient systems (Section 4.8). However, few studies have provided methods aiming at stable and reliable systems. The reviewed studies have applied mathematical modeling and simulation to optimize robustness, reliability, and throughput time. New methods are needed to support autonomous material handling systems to react appropriately in case of failures and to work independently without human surveillance. These methods would enable proactive work environments that can reduce failures and reboot autonomously instead of requiring a cold restart in times of failure.

Overall, the prime objectives have been throughput time, travel time, travel distance, and makespan minimization and system throughput and utilization maximation (see Table 2). Mathematical modeling is the most frequently applied method for long-term decisions in decision support and for short-term decisions for optimization purposes. Queuing modeling has been found to be useful in modeling warehousing and container terminals, and simulation modeling has found great interest and applicability in overall intralogistics systems. Few articles focus on decision-making at the strategic level (control decentralization level, Section 4.1). Instead, most of the reviewed articles focus on decision-making at the tactical–operational level. Scheduling is the most strongly represented method (22% of all reviewed articles), followed by path planning (18%), determining the number and types of vehicles (18%), zoning and service points (14%), dispatching (12%), control decentralization (8%), robustness and resilience (5%), and resource management (3%).

Several studies see strong potential to improve performance yields by addressing multiple decision variables simultaneously, such as determining the number of vehicles, determining zoning and service point locations (Singh *et al.*, 2011; Małopolski, 2018), or simultaneous scheduling and path planning (Corréa *et al.*, 2007; Ghasemzadeh *et al.*, 2009; Nishi *et al.*, 2011; Petrović *et al.*, 2019). This allows us to understand how the different decisions interact and to evaluate them to make more balanced decisions. For instance, research on the number and types of vehicles and resource management can support reduced costs and increased utilization by analyzing how to share the equipment mounted on top of the vehicle. This influences the number of required vehicles. Moreover, dispatching, path planning, and robustness and resilience can help to increase the uptime of an intralogistics system. Analyzing these decision areas simultaneously makes it possible to investigate how swarm behavior can be used to dispatch and navigate other AMRs in case of an AMR breakdown and thus guarantee a robust and resilient intralogistics system. Further, the decision areas of zoning and scheduling or zoning and dispatching should be investigated simultaneously. In current studies, the output of one decision area is the input data for the other. Optimizing these decision areas simultaneously would result in a larger variety of possibilities and enable the identification and achievement of a new optimum. AI techniques can support to solve multi-objective optimization (Petrović *et al.*, 2019) and are especially useful for integrating decision areas, such as zoning and dispatching, with objectives related to cost, resource consumption, responsiveness, system throughput, and travel time.

Manufacturing and warehousing applications have dominated the research on AMRs in intralogistics. Other intralogistics applications have received little attention (Table 2). However, the use of AMRs in other intralogistics areas is growing rapidly, offering opportunities for modelling and optimization.

In hospitals and nursing homes, AMRs can fill the gap in transporting critical, on-demand materials through narrow hallways, high traffic areas and dynamic environments. Agent-based simulations can support modeling different traffic scenarios with human interaction and analyze different path planning approaches to increase safety, quality, and transportation performance. Further, semi-open queuing network modeling can support determining the number of vehicles, while minimizing customer waiting times and improving the utilization and cost performance of AMRs mounted with hospital equipment shared among departments.

In agriculture, for handling delicate materials, AMRs with sensing and picking equipment can benefit from methods developed for warehouses with pick-and-fetch robots. Picking fruits or flowers is challenging since they are prone to damage during the harvesting process. As the AI branches of vision and ML evolve, sensing and picking delicate materials is becoming more feasible. The uncertainty in forecasting the harvest time period is a challenge for labour planning. Quickly upscaling an AMR fleet when needed can increase quality and productivity in agriculture, and reduce food waste.

In restaurants, automated delivery of dishes is not new (e.g. conveyors in sushi bars). However, unidirectional conveyors that do not stop allow for less flexibility in terms of layout and transportation variety. AMRs enable free navigation and on-demand transportation from the kitchen to the customer and vice versa. The rich knowledge of modeling in manufacturing can help decrease manual transportation and human fatigue in restaurants, and support rapid adjustment to customer arrival rates and volumes by increasing or decreasing the AMR fleet.

### 5.2. Research agenda

Based on the analyses in the previous sections, we can draw conclusions on the future research agenda for planning and control of AMRs. The objective should be to operate a cost-efficient, flexible, scalable, proactive, and robust system. The future research agenda should include the following:

- More studies are needed in assisting and deciding which operations should be centralized and decentralized and what degree of autonomy should be given to the AMR, and under which circumstances performance benefits. Multi-scenario analyses and agent-based simulations are promising methods that can help refine the decision-making process, especially in new AMR application areas. Agent-based simulation makes use of self-regulating, self-governing resource units that follow a series of predefined rules to achieve their objectives whilst interacting with each other and their environment system. This method allows integrating different levels of decentralization.
- New approaches are needed to evaluate the number of vehicles, since AMRs are entering new intralogistics environments and provide more services. Methods are needed that include the uncertainties of a dynamic environment like traffic, varying travel paths and distances, variable service points within a zone and different service activities, to determine the optimal number of vehicles. Moreover, methods are needed to find the optimal ratio of different types of AMRs within a fleet. Simulation modeling in combination with big data, machine learning, and predictive analytics can support this. Also, queuing, flow, and traffic theory can assist in analyzing overall obstacle avoidance as a factor in assessing performance improvement or degradation.
- New decision models for the management of AMR equipment are needed. AMR equipment will play a crucial role in integrated scheduling of manufacturing and warehousing operations, but also in new application areas. Think of models where vehicles with different equipment collaborate, or where equipment or tools can be swapped to carry out specific tasks. New methods are needed to support decision-making on how to plan and optimally share equipment in intralogistics systems.
- AMRs can be integrated rapidly into new environments. This, however, calls for efficient and fast methods for designing work zones and finding handover point positions. Work zones can also become dynamic, as they are mainly software embedded, and the number and size of zones can rapidly be adapted to the workload or work composition. New methods are needed to distribute AMRs within zones to ensure high response and performance. Big data and predictive analytics can help identify where AMRs should idle while awaiting their next request. AMRs can further share demand patterns and negotiate with each other for smart, decentralized distribution.
- Large-scale AMR systems (e.g. Amazon warehouses with thousands of interacting AMRs) will inevitably rely on decentralized scheduling. Therefore, new methods and approaches besides auction-based task allocation should be proposed. New optimization models for both large-scale systems and multi-objective optimization are needed. AI-based algorithms for multi-objective optimization can offer support to such investigations.
- Methods inspired by nature such as swarm optimization, ant colony optimization, and firefly algorithms can inject intelligence into path planning. New simulation methods are needed to integrate AMR behavior in dynamic environments. Furthermore, methods for path planning with unit load accessibility constraints should be investigated in manufacturing and other intralogistics systems.
- Finally, more research on system robustness and reliability is needed. New simulation models may support the autonomous decision-making processes when AMRs fail. AI techniques such as ML can support AMRs to react dynamically and independently without human surveillance in case of failures. New predictive methods for e.g. maintenance will support AMRs to work proactively to reduce the number failures.

## 6. Conclusion

The technological advances of AMRs have significantly helped to achieve operational flexibility and to increase performance in productivity, quality and (sometimes) cost efficiency. Taking decisions autonomously thanks to AI promotes the decentralization of activities involving AMRs. The systems can often be implemented rapidly, particularly in those application areas where suppliers have developed expertise in past implementation projects. However, it is still difficult to estimate the benefits that AMRs will bring and to determine how they should be deployed to reap maximum benefits. This literature study has detailed the crucial technological developments and identified decision areas for the planning and control of AMRs. We have structured and analyzed the literature, have given a definition of AMRs, and have proposed a planning and control framework. Based on the literature, decision areas with applied objectives and approaches have been identified. In summary, most studies in this field have focused on manufacturing and warehousing, and thus, research on many other intralogistics application areas is still lacking. Only a few studies have investigated the conditions under which decentralized control is more profitable compared to centralized control, or results in higher performance. Addressing multiple decision variables simultaneously, such as determining the number of vehicles, determining zoning and service point locations or simultaneous scheduling and path planning, improves the understanding of how different decisions interact and allows their evaluation to provide more balanced decisions. AI techniques are especially useful for integrating decision areas since they can support solving multiple objectives. We conclude that, although research is growing rapidly, several research areas have still received little attention, leading to a future research agenda.

## Acknowledgments

This research received funding from the strategic research area of NTNU Health in 2020 at NTNU, the Norwegian University of Science and Technology.

## References

Alfieri, A., Cantamessa, M., Monchiero, A., & Montagna, F. (2012). Heuristics for puzzle-based storage systems driven by a limited set of automated guided vehicles. *Journal of Intelligent Manufacturing, 23*(5), 1695–1705.

Almasri, M., Elleithy, K., & Alajlan, A. (2016). Sensor fusion based model for collision free mobile robot navigation. *Sensors, 16*(1), 24.

Anandaraman, C., Vikram, A., Sankar, M., & Natarajan, R. (2012). Evolutionary approaches for scheduling a flexible manufacturing system with automated guided vehicles and robots. *International Journal of Industrial Engineering Computations, 3*(4), 627–648.

Angerer, S., Strassmair, C., Staehr, M., Roettenbacher, M., & Robertson, N. M. (2012). Give me a hand—The potential of mobile assistive robots in automotive logistics and assembly applications. In *Proceedings of the IEEE international conference on technologies for practical robot applications* (pp. 111–116).

Asef-Vaziri, A., & Kazemi, M. (2018). Covering and connectivity constraints in loop-based formulation of material flow network design in facility layout. *European Journal of Operational Research, 264*(3), 1033–1044.

Asef-Vaziri, A., Laporte, G., & Ortiz, R. (2007). Exact and heuristic procedures for the material handling circular flow path design problem. *European Journal of Operational Research, 176*(2), 707–726.

Azadeh, K., De Koster, R., & Roy, D. (2019a). Robotized and automated warehouse systems: Review and recent developments. *Transportation Science, 53*(4), 917–945.

Azadeh, K., Roy, D., & De Koster, R. (2019b). Design, modeling, and analysis of vertical robotic storage and retrieval systems. *Transportation Science, 53*(5), 1213–1234.

Azadeh, K., Roy, D., & De Koster, R. (2020). *Dynamic human-robot collaborative picking strategies*. Erasmus University working paper.

Bakshi, S., Feng, T., Yan, Z., & Chen, D. (2019). Fast scheduling of autonomous mobile robots under task space constraints with priorities. *Journal of Dynamic Systems, Measurement, and Control, 141*(7), Article 071009.

Baruwa, O. T., & Piera, M. A. (2016). A coloured Petri net-based hybrid heuristic search approach to simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Research, 54*(16), 4773–4792.
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*, 3970–3984.
Bilge, Ü., Esenduran, G., Varol, N., Öztürk, Z., Aydın, B., & Alp, A. (2006). Multi-attribute responsive dispatching strategies for automated guided vehicles. *International Journal of Production Economics, 100*(1), 65–75.
Bloss, R. (2008). Simultaneous sensing of location and mapping for autonomous robots. *Sensor Review, 28*(2), 102–107.
Bocewicz, G., Banaszak, Z., & Nielsen, I. (2019). Multimodal processes prototyping subject to grid-like network and fuzzy operation time constraints. *Annals of Operations Research, 273*(1-2), 561–585.
Boysen, N., Briskorn, D., & Emde, S. (2018). Scheduling electric vehicles and locating charging stations on a path. *Journal of Scheduling, 21*(1), 111–126.
Bozer, Y. A., & Eamrungroj, C. (2018). Throughput analysis of multi-device trip-based material handling systems operating under the modified-FCFS dispatching rule. *International Journal of Production Research, 56*(4), 1486–1503.
Chen, X., He, S., Zhang, Y., Tong, L. C., Shang, P., & Zhou, X. (2020). Yard crane and AGV scheduling in automated container terminal: A multi-robot task allocation framework. *Transportation Research Part C: Emerging Technologies, 114*, 241–271.
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), 3222–3235.
Confessore, G., Fabiano, M., & Liotta, G. (2013). A network flow based heuristic approach for optimising AGV movements. *Journal of Intelligent Manufacturing, 24*(2), 405–419.
Corréa, A. I., Langevin, A., & Rousseau, L.-M. (2007). Scheduling and routing of automated guided vehicles: A hybrid approach. *Computers & Operations Research, 34*(6), 1688–1707.
De Ryck, M., Versteyhe, M., & Debrouwere, F. (2020a). Automated guided vehicle systems, state-of-the-art control algorithms and techniques. *Journal of Manufacturing Systems, 54*, 152–173.
De Ryck, M., Versteyhe, M., & Shariatmadar, K. (2020b). Resource management in decentralized industrial automated guided vehicle systems. *Journal of Manufacturing Systems, 54*, 204–214.
De Silva, V., Roche, J., & Kondoz, A. (2018). Robust fusion of LiDAR and wide-angle camera data for autonomous mobile robots. *Sensors, 18*(8), 2730.
Demesure, G., Defoort, M., Bekrar, A., Trentesaux, D., & Djemai, M. (2017). Decentralized motion planning and scheduling of AGVs in an FMS. *IEEE Transactions on Industrial Informatics, 14*(4), 1744–1752.
Deroussi, L., Gourgand, M., & Tchernev, N. (2008). A simple metaheuristic approach to the simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Research, 46*(8), 2143–2164.
Dias, L. A., de Oliveira Silva, R. W., da Silva Emanuel, P. C., Ferrus Filho, A., & Bento, R. T. (2018). Application of the fuzzy logic for the development of automnomous robot with obstacles deviation. *International Journal of Control, Automation and Systems, 16*(2), 823–833.
Digani, V., Hsieh, M. A., Sabattini, L., & Secchi, C. (2019). Coordination of multiple AGVs: a quadratic optimization method. *Autonomous Robots, 43*(3), 539–555.
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*, Article 101915.
Ekren, B. Y., & Heragu, S. S. (2010). Approximate analysis of load-dependent generally distributed queuing networks with low service time variability. *European Journal of Operational Research, 205*(2), 381–389.
Ekren, B. Y., Heragu, S. S., Krishnamurthy, A., & Malmborg, C. J. (2013). An approximate solution for semi-open queueing network model of an autonomous vehicle storage and retrieval system. *IEEE Transactions on Automation Science and Engineering, 10*(1), 205–215.
Ekren, B. Y., Heragu, S. S., Krishnamurthy, A., & Malmborg, C. J. (2014). Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. *Computers & Industrial Engineering, 68*, 78–86.
ElMekkawy, T., & Liu, S. (2009). A new memetic algorithm for optimizing the partitioning problem of tandem AGV systems. *International Journal of Production Economics, 118*(2), 508–520.
Farahani, R. Z., Karimi, B., & Tamadon, S. (2007). Designing an efficient method for simultaneously determining the loop and the location of the P/D stations using genetic algorithm. *International Journal of Production Research, 45*(6), 1405–1427.
Fauadi, M. H. F. M (2012). *Agent-based material transportation scheduling of AGV systems and its manufacturing applications (Doctoral dissertation*. Waseda University.
Fazlollahtabar, H. (2016). Parallel autonomous guided vehicle assembly line for a semi-continuous manufacturing system. *Assembly Automation, 36*(3), 262–273.
Fazlollahtabar, H., & Hassanli, S. (2018). Hybrid cost and time path planning for multiple autonomous guided vehicles. *Applied Intelligence, 48*(2), 482–498.
Fazlollahtabar, H., & Olya, M. H. (2013). A cross-entropy heuristic statistical modeling for determining total stochastic material handling time. *The International Journal of Advanced Manufacturing Technology, 67*(5-8), 1631–1641.
Fazlollahtabar, H., Saidi-Mehrabad, M., & Balakrishnan, J. (2015). Mathematical optimization for earliness/tardiness minimization in a multiple automated guided vehicle manufacturing system via integrated heuristic algorithms. *Robotics and Autonomous Systems, 72*, 131–138.
Fragapane, G., Hvolby, H. H., Sgarbossa, F., & Strandhagen, J. O. (2020a). Autonomous mobile robots in hospital logistics. In *Proceedings of the* IFIP international conference on advances in production management systems (pp. 672–679). Springer.
Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., & Strandhagen, J. O. (2020b). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research*, 1–19.
Fragapane, G., Zhang, C., Sgarbossa, F., & Strandhagen, J. O. (2019). An Agent-based simulation approach to model hospital logistics. *International Journal of Simulation Modelling (IJSIMM), 18*(4), 654–665.
Fransen, K. J. C., van Eekelen, J. A. W. M., Pogromsky, A., Boon, M. A. A., & Adan, I. J. B. F (2020). A dynamic path planning approach for dense, large, grid-based automated guided vehicle systems. *Computers & Operations Research, 123*, Article 105046.
Fukunari, M., & Malmborg, C. J. (2008). An efficient cycle time model for autonomous vehicle storage and retrieval systems. *International Journal of Production Research, 46*(12), 3167–3184.
Fukunari, M., & Malmborg, C. J. (2009). A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems. *European Journal of Operational Research, 193*(1), 152–167.
Furmans, K., & Gue, K. R. (2018). A framework for modeling material handling with decentralized control. In *Proceedings of the* 15th IMHRC (Savannah, Georgia. USA – 2018) (p. 17).
Gen, M., Zhang, W., Lin, L., & Yun, Y. (2017). Recent advances in hybrid evolutionary algorithms for multiobjective manufacturing scheduling. *Computers & Industrial Engineering, 112*, 616–633.
Gharehgozli, A. H., de Koster, R., & Jansen, R. (2017). Collaborative solutions for inter terminal transport. *International Journal of Production Research, 55*(21), 6527–6546.
Ghasemzadeh, H., Behrangi, E., & Azgomi, M. A. (2009). Conflict-free scheduling and routing of automated guided vehicles in mesh topologies. *Robotics and Autonomous Systems, 57*(6-7), 738–748.
Guan, X., & Dai, X. (2009). Deadlock-free multi-attribute dispatching method for AGV systems. *The International Journal of Advanced Manufacturing Technology, 45*(5-6), 603.
Gue, K. R., Furmans, K., Seibold, Z., & Uludağ, O. (2014). GridStore: a puzzle-based storage system with decentralized control. *IEEE Transactions on Automation Science and Engineering, 11*(2), 429–438.
Gue, K. R., & Kim, B. S. (2007). Puzzle-based storage systems. *Naval Research Logistics (NRL), 54*(5), 556–567.
Hamzeei, M., Farahani, R. Z., & Rashidi-Bejgan, H. (2013). An exact and a simulated annealing algorithm for simultaneously determining flow path and the location of P/D stations in bidirectional path. *Journal of Manufacturing Systems, 32*(4), 648–654.
He, Z., Aggarwal, V., & Nof, S. Y. (2018). Differentiated service policy in smart warehouse automation. *International Journal of Production Research, 56*(22), 6956–6970.
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. *The International Journal of Advanced Manufacturing Technology, 101*(1-4), 815–824.
Hernández, C., Bermejo-Alonso, J., & Sanz, R. (2018). A self-adaptation framework based on functional knowledge for augmented autonomy in robots. *Integrated Computer-Aided Engineering, 25*(2), 157–172.
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), 4193–4222.
Ho, Y.-C., & Liao, T.-W. (2009). Zone design and control for vehicle collision prevention and load balancing in a zone control AGV system. *Computers & Industrial Engineering, 56*(1), 417–432.
Hoshino, S., Ota, J., Shinozaki, A., & Hashimoto, H. (2007). Hybrid design methodology and cost-effectiveness evaluation of AGV transportation systems. *IEEE Transactions on Automation Science and Engineering, 4*(3), 360–372.
Huang, S.-J., Lee, T.-S., Li, W.-H., & Chen, R.-Y. (2018). Modular on-road agv wireless charging systems via interoperable power adjustment. *IEEE Transactions on Industrial Electronics, 66*(8), 5918–5928.
Indri, M., Lachello, L., Lazzero, I., Sibona, F., & Trapani, S. (2019). Smart sensors applications for a new paradigm of a production line. *Sensors, 19*(3), 650.
Jerald, J., Asokan, P., Saravanan, R., & Rani, A. D. C. (2006). Simultaneous scheduling of parts and automated guided vehicles in an FMS environment using adaptive genetic algorithm. *The International Journal of Advanced Manufacturing Technology, 29*(5-6), 584–589.
Ji, M., & Xia, J. (2010). Analysis of vehicle requirements in a general automated guided vehicle system based transportation system. *Computers & Industrial Engineering, 59*(4), 544–551.
Joseph, O., & Sridharan, R. (2011). Evaluation of routing flexibility of a flexible manufacturing system using simulation modelling and analysis. *The International Journal of Advanced Manufacturing Technology, 56*(1-4), 273–289.
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), 624–641.
Karaman, S., & Frazzoli, E. (2011). Sampling-based algorithms for optimal motion planning. *The International Journal of Robotics Research, 30*(7), 846–894.
Kim, Y., Shin, D., Lee, J., Lee, Y., & Yoo, H.-J. (2017). A 0.55V 1.1mW artificial intelligence processor with on-chip PVT compensation for autonomous mobile robots. *IEEE Transactions on Circuits and Systems I: Regular Papers, 65*(2), 567–580.
Kousi, N., Koukas, S., Michalos, G., & Makris, S. (2019). Scheduling of smart intra—factory material supply operations using mobile robots. *International Journal of Production Research, 57*(3), 801–814.

Lacomme, P., Larabi, M., & Tchernev, N. (2013). Job-shop based framework for simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Economics, 143*(1), 24–34.

Lamballais, T., Roy, D., & De Koster, M. (2017). Estimating performance in a robotic mobile fulfillment system. *European Journal of Operational Research, 256*(3), 976–990.

Lamballais, T., Roy, D., & De Koster, R. B. (2020). Inventory allocation in robotic mobile fulfillment systems. *IISE Transactions, 52*(1), 1–17.

Le-Anh, T., & De Koster, M. (2006). A review of design and control of automated guided vehicle systems. *European Journal of Operational Research, 171*(1), 1–23.

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

Lei, C., Zhao, N., Ye, S., & Wu, X. (2019). Memetic algorithm for solving flexible flow-shop scheduling problems with dynamic transport waiting times. *Computers & Industrial Engineering*, Article 105984.

Liaqat, A., Hutabarat, W., Tiwari, D., Tinkler, L., Harra, D., Morgan, B., & Tiwari, A. (2019). Autonomous mobile robots in manufacturing: Highway Code development, simulation, and testing. *The International Journal of Advanced Manufacturing Technology, 104*(9-12), 4617–4628.

Lin, L., Shinn, S. W., Gen, M., & Hwang, H. (2006). Network model and effective evolutionary approach for AGV dispatching in manufacturing system. *Journal of Intelligent Manufacturing, 17*(4), 465–477.

Lyu, X.-F., Song, Y.-C., He, C.-Z., Qi, L., & Guo, W.-F. (2019). Approach to integrated scheduling problems considering optimal number of automated guided vehicles and conflict-free routing in flexible manufacturing systems. *IEEE Access, 7*, 74909–74924.

Machado, T., Malheiro, T., Monteiro, S., Erlhagen, W., & Bicho, E. (2019). Attractor dynamics approach to joint transportation by autonomous robots: theory, implementation and validation on the factory floor. *Autonomous Robots, 43*(3), 589–610.

Małopolski, W. (2018). A sustainable and conflict-free operation of AGVs in a square topology. *Computers & Industrial Engineering, 126*, 472–481.

Maniya, K., & Bhatt, M. (2011). A multi-attribute selection of automated guided vehicle using the AHP/M-GRA technique. *International Journal of Production Research, 49*(20), 6107–6124.

Mattaboni, P. J. (1987). *Autonomous mobile robot*. Google Patents.

Meller, R. D., Nazzal, D., & Thomas, L. M. (2018). Collaborative bots in distribution centers. In *Proceedings of the* 15th IMHRC proceedings (savannah, georgia. USA – 2018) (p. 17).

Mirzaei, M., De Koster, R. B., & Zaerpour, N. (2017). Modelling load retrievals in puzzle-based storage systems. *International Journal of Production Research, 55*(21), 6423–6435.

Miyamoto, T., & Inoue, K. (2016). Local and random searches for dispatch and conflict-free routing problem of capacitated AGV systems. *Computers & Industrial Engineering, 91*, 1–9.

Mohammadi, E. K., & Shirazi, B. (2020). Toward high degree flexible routing in collision-free FMSs through automated guided vehicles' dynamic strategy: A simulation metamodel. *ISA Transactions, 96*, 228–244.

Mousavi, M., Yap, H., Musa, S., & Dawal, S. (2017). A fuzzy hybrid GA-PSO algorithm for multi-objective AGV scheduling in FMS. *International Journal of Simulation Modelling (IJSIMM), 16*(1), 58–71.

Muller, T. (1983). *Automated guided vehicles*. Kempston England: IFS Ltd..

Neuts, M. (1981). *Matrix-geometric solutions in stochastic models*. Baltimore: The Johns Hopkins University Press.

Nishi, T., Hiranaka, Y., & Grossmann, I. E. (2011). A bilevel decomposition algorithm for simultaneous production scheduling and conflict-free routing for automated guided vehicles. *Computers & Operations Research, 38*(5), 876–888.

Nishi, T., Shimatani, K., & Inuiguchi, M. (2009). Decomposition of Petri nets and Lagrangian relaxation for solving routing problems for AGVs. *International Journal of Production Research, 47*(14), 3957–3977.

Petrović, M., Miljković, Z., & Jokić, A. (2019). A novel methodology for optimal single mobile robot scheduling using whale optimization algorithm. *Applied Soft Computing, 81*, Article 105520.

Pjevcevic, D., Nikolic, M., Vidic, N., & Vukadinovic, K. (2017). Data envelopment analysis of AGV fleet sizing at a port container terminal. *International Journal of Production Research, 55*(14), 4021–4034.

Polten, L., & Emde, S. (2020). Scheduling automated guided vehicles in very narrow aisle warehouses. *Omega*, Article 102204.

Pratama, P. S., Gulakari, A. V., Setiawan, Y. D., Kim, D. H., Kim, H. K., & Kim, S. B. (2016). Trajectory tracking and fault detection algorithm for automatic guided vehicle based on multiple positioning modules. *International Journal of Control, Automation and Systems, 14*(2), 400–410.

Qi, M., Li, X., Yan, X., & Zhang, C. (2018). On the evaluation of AGVS-based warehouse operation performance. *Simulation Modelling Practice and Theory, 87*, 379–394.

Rahman, H. F., Janardhanan, M. N., & Nielsen, P. (2020). *An integrated approach for line balancing and AGV scheduling towards smart assembly systems*. Assembly Automation.

Rashidi, H., & Tsang, E. P. (2011). A complete and an incomplete algorithm for automated guided vehicle scheduling in container terminals. *Computers & Mathematics with Applications, 61*(3), 630–641.

Ribino, P., Cossentino, M., Lodato, C., & Lopes, S. (2018). Agent-based simulation study for improving logistic warehouse performance. *Journal of Simulation, 12*(1), 23–41.

Roy, D., Gupta, A., & De Koster, R. B. (2016). A non-linear traffic flow-based queuing model to estimate container terminal throughput with AGVs. *International Journal of Production Research, 54*(2), 472–493.

Roy, D., Koster, R. D., & Bekker, R. (2020). Modeling and design of container terminal operations. *Operations Research, 68*(3), 686–715. Retrieved from https://pubsonline.informs.org/doi/abs/10.1287/opre.2019.1920 . https://doi.org/10.1287/opre.2019.1920.

Roy, D., Krishnamurthy, A., Heragu, S. S., & Malmborg, C. J. (2012). Performance analysis and design trade-offs in warehouses with autonomous vehicle technology. *IIE Transactions, 44*(12), 1045–1060.

Roy, D., Nigam, S., de Koster, R., Adan, I., & Resing, J. (2019). Robot-storage zone assignment strategies in mobile fulfillment systems. *Transportation Research Part E: Logistics and Transportation Review, 122*, 119–142.

Saidi-Mehrabad, M., Dehnavi-Arani, S., Evazabadian, F., & Mahmoodian, V. (2015). An Ant Colony Algorithm (ACA) for solving the new integrated model of job shop scheduling and conflict-free routing of AGVs. *Computers & Industrial Engineering, 86*, 2–13.

Shah, M., Bostelman, R., Legowik, S., & Hong, T. (2018). Calibration of mobile manipulators using 2D positional features. *Measurement, 124*, 322–328.

Shalaby, M., El Mekkawy, T., & Fahmy, S. (2006). Zones formation algorithm in tandem AGV systems: a comparative study. *International Journal of Production Research, 44*(3), 505–521.

Siegwart, R., Nourbakhsh, I. R., & Scaramuzza, D. (2011). *Introduction to autonomous mobile robots*. MIT press.

Singh, N., Sarngadharan, P., & Pal, P. K. (2011). AGV scheduling for automated material distribution: a case study. *Journal of Intelligent Manufacturing, 22*(2), 219–228.

Smith, J. M. (2015). Optimal workload allocation in closed queueing networks with state dependent queues. *Annals of Operations Research, 231*(1), 157–183.

Tavana, M., Fazlollahtabar, H., & Hassanzadeh, R. (2014). A bi-objective stochastic programming model for optimising automated material handling systems with reliability considerations. *International Journal of Production Research, 52*(19), 5597–5610.

Tubaileh, A. S. (2014). Layout of flexible manufacturing systems based on kinematic constraints of the autonomous material handling system. *The International Journal of Advanced Manufacturing Technology, 74*(9-12), 1521–1537.

Udhayakumar, P., & Kumanan, S. (2010). Task scheduling of AGV in FMS using non–traditional optimization techniques. *International Journal of Simulation Modelling, 9*(1), 28–39.

Umar, U. A., Ariffin, M., Ismail, N., & Tang, S. (2015). Hybrid multiobjective genetic algorithms for integrated dynamic scheduling and routing of jobs and automated-guided vehicle (AGV) in flexible manufacturing systems (FMS) environment. *The International Journal of Advanced Manufacturing Technology, 81*(9-12), 2123–2141.

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*, 850–861.

Ventura, J. A., & Rieksts, B. Q. (2009). Optimal location of dwell points in a single loop AGV system with time restrictions on vehicle availability. *European Journal of Operational Research, 192*(1), 93–104.

Vis, I. F. (2006). Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research, 170*(3), 677–709.

Vivaldini, K., Rocha, L. F., Martarelli, N. J., Becker, M., & Moreira, A. P. (2016). Integrated tasks assignment and routing for the estimation of the optimal number of AGVS. *The International Journal of Advanced Manufacturing Technology, 82*(1-4), 719–736.

Wan, J., Tang, S., Hua, Q., Li, D., Liu, C., & Lloret, J. (2017). Context-aware cloud robotics for material handling in cognitive industrial Internet of Things. *IEEE Internet of Things Journal, 5*(4), 2272–2281.

Wang, W., Wu, Y., Zheng, J., & Chi, C. (2020). A Comprehensive framework for the design of modular robotic mobile fulfillment systems. *IEEE Access, 8*, 13259–13269.

Wu, N., & Zhou, M. (2007). Shortest routing of bidirectional automated guided vehicles avoiding deadlock and blocking. *IEEE/ASME transactions on mechatronics, 12*(1), 63–72.

Yalcin, A., Koberstein, A., & Schocke, K.-O. (2019). An optimal and a heuristic algorithm for the single-item retrieval problem in puzzle-based storage systems with multiple escorts. *International Journal of Production Research, 57*(1), 143–165.

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 & System Safety, 178*, 130–139.

Yan, R., Jackson, L. M., & Dunnett, S. J. (2017). Automated guided vehicle mission reliability modelling using a combined fault tree and Petri net approach. *The International Journal of Advanced Manufacturing Technology, 92*(5-8), 1825–1837.

Yang, Y., Zhong, M., Dessouky, Y., & Postolache, O. (2018). An integrated scheduling method for AGV routing in automated container terminals. *Computers & Industrial Engineering, 126*, 482–493.

Yuan, Z., & Gong, Y. Y. (2017). Bot-in-time delivery for robotic mobile fulfillment systems. *IEEE Transactions on Engineering Management, 64*(1), 83–93.

Zamiri, S., & Choobineh, F. (2014). Entropy-based dispatching for automatic guided vehicles. *International Journal of Production Research, 52*(11), 3303–3316.

Zeng, C., Tang, J., & Fan, Z.-P. (2018). Auction-based cooperation mechanism for cell part scheduling with transportation capacity constraint. *International Journal of Production Research*, 1–16.

Zhang, H.-Y., Xi, S.-H., Chen, Q.-X., Smith, J. M., Mao, N., & Li, X. (2020). Performance analysis of a flexible flow shop with random and state-dependent batch transport. *International Journal of Production Research*, 1–21.
Zhang, Y., Zhu, Z., & Lv, J. (2017). CPS-based smart control model for shopfloor material handling. *IEEE Transactions on Industrial Informatics, 14*(4), 1764–1775.
Zhang, Z., Guo, Q., Chen, J., & Yuan, P. (2018). Collision-free route planning for multiple AGVs in an automated warehouse based on collision classification. *IEEE Access, 6*, 26022–26035.
Zheng, Y., Xiao, Y., & Seo, Y. (2014). A tabu search algorithm for simultaneous machine/AGV scheduling problem. *International Journal of Production Research, 52*(19), 5748–5763.
Zou, B., de Koster, M., & Xu, X. (2016). Evaluating dedicated and shared storage policies in robot-based compact storage and retrieval systems. *ERIM Report Series, 52*(4), 788–811. This paper has appeared in Transportation Science https://pubsonline.informs.org/doi/abs/10.1287/trsc.2017.0786 .
Zou, B., Gong, Y., Xu, X., & Yuan, Z. (2017). Assignment rules in robotic mobile fulfilment systems for online retailers. *International Journal of Production Research, 55*(20), 6175–6192.
Zou, B., Xu, X., & De Koster, R. (2018). Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system. *European Journal of Operational Research, 267*(2), 733–753.

# Paper 6

Fragapane, G., Roy, D., Sgarbossa, F., & Strandhagen (under review).
Planning autonomous material transportation in hospitals.
In *IFIP International Conference on Advances in Production Management Systems.*
Springer, Cham

This paper is awaiting publication and is not included in NTNU Open

ISBN 978-82-326-6821-2 (printed ver.)
ISBN 978-82-326-6122-0 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

NTNU

Norwegian University of
Science and Technology