Petter Andreas Kvalsvik

Internal Logistics in Hospitals

Automated Guided Vehicles' Affect on Hospital Layout

Masteroppgave i Produktutvikling og produksjon - masterstudium (2-årig)
Veileder: Jan Ola Strandhagen
Januar 2019

Masteroppgave

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Kunnskap for en bedre verden

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Preface

This is a project master thesis written at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU) as the final thesis in the mechanical engineering programme with specialization in production management.

Acknowledgements

I want to thank my supervisors for guidance and counseling, and the case hospitals, Akershus University Hospital and St. Olavs Hospital for giving us access and information about their processes, especially the people at the logistics center at St. Olavs. Lastly I want to thank my family for their support through these years of education.

Summary

Because of an increasingly centralized and aging population, developed high-cost countries are experiencing pressure on health care services. Hospitals in these countries are therefore looking for ways to cut costs and streamline their logistics, to decrease time spent on other things than patient care, e.g. restocking supplies. A possibility is to automate internal material logistics, by using automated guided vehicles (AGVs).

AGV technology has been around for decades, but it has mostly been used in manufacturing industries and at large distribution centers. Technology advancements in the recent years has made AGV technology relevant also for other sectors, even the health care sector and more precisely the modern hospital. The layout, and other environment factors, differ largely between the straight shelves at a distribution center and the hallways of a modern hospital, so in this project thesis we are investigating how hospitals are accomodating to AGV transportation, with a focus on layout and challanges related to different layouts.

Research questions:

1. How are Automated Guided Vehicle (AGV) Systems implemented in the hospital supply chain?
2. How are hospital layouts adapted for AGV systems?
3. What are the biggest challanges related to hospital layout for AGV systems?

To answer the research questions there has been performed both a literature study and a case study, and it's mainly qualitative research.

In this thesis we have presented an overview of relevant literature on the topic automated guided vehicles and hospital layout, and through a case study of two modern hospitals in a high-cost country we have described how AGVs are implemented in a hospital supply chain. We have looked at how hospital layouts can be adapted for AGV systems, and we have discovered several challanges related to hospital layout and AGVs, e.g. challanges regarding shared elevators or lack of alternative guide paths.

We hope this research can be helpful for designers of new hospitals or the management of existing hospitals that considers implementing an AGV system.

Sammendrag

En stadig mer sentralisert og aldrende befolkning fører til at høykostland som Norge opplever et stadig økende press på helsetjenester. Moderne sykehus er derfor nødt til å se etter muligheter for å senke kostnader og øke effektiviteten i deres materiell-logistikk for å kunne fokusere deres dyrebare tid til bruk på pasienter i stedet for f.eks. lageroppfylling. En mulig løsning på dette er å automatisere intern distribusjon ved å benytte automatiske styrte kjøretøy (AGV).

AGV-teknologi har allerede eksistert i flere tiår, og har vært brukt hovedsakelig i tilvirkningsindustrien og på store distribusjonssentre. Teknologiutviklingen de siste årene har gjort AGV-teknologi relevant også for andre sektorer, selv helsesektoren og mer presist, på sykehusene. Layout (planløsning og innredning) er ganske forskjellig fra et distribusjonssenter og til et sykehus, så i dette prosjektet undersøker vi hvordan sykehus er tilpasset AGV transport med hovedfokus på layout.

Forskningsspørsmålene er følgende:

1. How are Automated Guided Vehicle (AGV) Systems implemented in the hospital supply chain?
2. How are hospital layouts adapted for AGV systems?
3. What are the biggest challanges related to hospital layout for AGV systems?

For å besvare disse spørsmålene har vi gjennomført både en litteraturstudie og en case-studie. Prosjektet bruker hovedsakelig kvalitative metoder.

Gjennom dette prosjektet har vi presentert en oversikt over relevant litteratur om AGV og sykehus-layout, og gjennom case-studiet har vi sett på to sykehus i et høykostland (Norge) og beskrevet hvordan disse har implementert AGV systemer. Vi oppdaget flere utfordringer relatert til AGV og layout, blant annet utfordringer rundt heiser som brukes både av AGV-er og mennesker, og problemer med lite alternative ruter.

Vi håper dette prosjektet kan hjelpe designere og arkiterker av både nye og eksisterende sykehus som vurderer å ta i bruk automatiske styrte kjøretøy.

Education is what remains
after one has forgotten
everything he learned in school.

ALBERT EINSTEIN

Abbreviations

AGV	Automated Guided Vehicle
E&C	Emergency and Cardiothoracic
ER	Emergency Room
IA	Instantaneous assignment
ICT	Information and communications technology
MT	Multi task
OEM	Original equipment manufacturer
OR	Operating room
U1	Basement
OU	Organizational unit
P&D	Pick-up and delivery
QAP	Quadratic assignment problem
RF	Radio frequency
ST	Single task
TA	Time-extended assignment
TCMS2	TransCar Management System
UPS	Uninterruptible power source
W&C	Woman and children
WLAN	Wireless local area network

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1 Introduction

1.1 Background

With increased pressure on health care because of an increasingly centralized and ageing population, hospitals are looking for ways to streamline its logistics to cut costs and decrease time spent on other things than patient care, e.g. restocking supplies. Health care expenditures grew with an average of 4% yearly from 2000 to 2009, and hospitals account for 29% of the total expenditures (Volland et al. 2017).

To be able to treat thousands of patients every year, a hospital need a lot of supplies, and for these supplies to be useful they need to be transported out to the hospital departments and wards. This logistic tasks has previously been carried out by hospital orderlies, or medical staff. But in high-cost countries, the high wages and other personell costs drive the hospitals to think differently, not very different from other industries, and automation is also starting to be implemented in the health care sector. One way of automate the material logistics from the central logistics center at the hospital and out to the medical departments is by the means of automated guided vehicles (AGVs).

Automated Guided Vehicles (AGVs) are portable robots used to move pallets or wagons around manufacturing facilities, ports, or airports (Vis 2006). The AGVs are usually guided around by wires, magnets, or other markers in the floor and walls, but modern AGVs are also using internal guiding systems (LIDAR) and require less modification of the environment. AGVs has been used in the industry for several decades (Egbelu and Tanchoco 1984), but the recent year's advances in communication and battery technology has led to new areas of usage, e.g. warehouses, container terminals, airports, or hospitals.

Every hospital is unique, the size, floor-layout, inventory management, level of automation in material handling, and so on differs from hospital to hospital. In this project we are looking at how different hospital's environment affects the use of AGVs.

1.2 Problem Statement

Automated guided vehicles has been used in the various industry sectors for many decades already (Egbelu and Tanchoco 1984; Vis 2006), but it has mostly been used in places like manufacturing facilities, large distribution centers, or in transshipment at large docks. The layout and environment of these places are very different from the hallways of a hospital, but there has not been much research on how the hospital environment are affected by this new technology.

In this project thesis we have performed a literature study on hospital layouts and automated guided vehicles, and we have studied two hospital-cases to analyze how automation by automated guided vehicles has affected the layouts of hospitals, and to identify challanges that hospitals that are using AGVs face.

1.3 Research Questions

The three research questions for this project is:

1. How are Automated Guided Vehicle (AGV) Systems implemented in the hospital supply chain?
2. How are hospital layouts adapted for AGV systems?
3. What are the biggest challanges related to hospital layout for AGV Systems?

1.4 Research Scope

The scope of the research is to perform a literature study on hospital layouts and automated guided vehicles, and to look at two cases where automated guided vehicles has been put to use in hospitals.

1.5 Thesis Structure

Table 1: Thesis structure

Chapter 1 **Introduction**	First, the background and motivation for the project is presented, as well as the research questions and scope.
Chapter 2 **Theoretical Background**	In the second chapter, we present relevant theory and the findings from the literature study.
Chapter 3 **Research Methodology**	The third chapter explains the approach and methods used to answer the research questions, and we discuss the strenghts and weaknesses of these methods.
Chapter 4 **Case Study**	In this chapter, the case study is presented, with all the findings relevant to the research questions.
Chapter 5 **Discussion**	Here we discuss our findings, and we try to draw lines between the case study and the literature study.
Chapter 6 **Conclusion and Further Research**	In the last chapter we conclude our thesis, and discuss the limitations in our research and make suggestions for further research.

2 Theoretical Background

In this chapter the main part of the theory regarding the thesis is summarized.

2.1 Hospital Supply Chain

A supply chain in general is defined as ”a sequence of organizations - their facilities, functions, and activities - that are involved in producing and delivering a product or service” (Stevenson 2011). For hospitals, Polater et al. (2014) describe a supply chain as ”a complex system that requires the flow of products and services, in order to satisfy the needs of those who serve patients”, and the purpose is to ”deliver products at the right time, for the purpose of fulfilling the requirements of those providing healthcare” (ibid.).

One major characteristic of health care supply chains is complexity. This is because of the multitude of different suppliers used by the institutions and the high number of distribution channels they flow through. When focusing on a hospitals supply chain, we can divide the supply chain into one external part of the supply chain and one internal. The external supply chain consists of suppliers, distributors, and other actors that are not operating within the hospital walls, while the internal supply chain is the internal distribution of supplies, i.e. between storerooms and patient care units. (Rivard-Royer et al. 2002).

2.1.1 Hospital Goods And Logistics

Logistics is the component of a supply chain that deals with the flow of goods, services, cash, and information (Stevenson 2011). Logistics activities in hospitals account for 30% of total costs, making it the seconds largest cost after personnel costs (Volland et al. 2017). Historically, material management and logistics have not been a very high priority for hospital managers. The high complexity of hospital supply chains, and that they are merely a supporting role of the main goal of hospitals; patient care and treatment, may be some of the reasons for the lack of attention on material management. (ibid.).

> The potential of hospital logistics optimiziation within the healthcare sector is considered significant both by academia and practitioners.
> - Volland et al. (ibid.)

Poulin (2003) claims that half of the logistics costs in hospitals can be removed with more efficient management (ibid.), and according to Jarrett (1998) and Volland et al. (2017) cost reductions through optimization of material logistics will not directly affect the quality of patient care. This is because logistic activities often are carried out by medical staff and takes away precious time from patient care. Optimizing material logistics can therefore *improve* the quality of patient care, by reducing the time spent on non-patient care. (Paltriccia and Tiacci 2016; Volland et al. 2017).

According to Paltriccia and Tiacci (2016) the most used replenishment policy in hospitals is *periodic replenishment* (PR), where ”medical and nursing staff check each stock at regular intervals and examine each product inventory level and then they replenish stocks up to order-up-to levels” (ibid.).

Distances can be quite long between different departments and wards in a hospital, resulting in a lot of transportation jobs just for moving patients. Patient transport can involve simply guiding patients that are able to walk on their own, or it can involve pushing patients in a weelchair or a bed (Helber et al. 2016). Transporting patients will often require two staff members because of the weight of lifting a patient from one bed to another, and with the increasingly obese population those cases will most likely continue to increase (ibid.).

According to Özkil et al. (2009) the main focus when it comes to logistics in hospitals is material flow (ibid.). Kriegel et al. (2013) on the other hand, looks at material flow as one of two main focuses in hospital logistics; material flow (goods) and people. These two groups can be divided further into subgroups, e.g. medical goods, which again can be divided into specific item groups, e.g. sterile goods or pharmaceuticals. See figure 1 adapted from (ibid.).

Paltriccia and Tiacci (2016) write about outsourcing of materials management in the healthcare sector. They present a new outsourcing model with implementation of RFID-technology and collaborative networks among the suppliers. One of the challenges presented is replenishment, most SKUs must be available in the hospital at all times. 75% of stock keeping units (SKUs) in hospitals are coming from external warehouses (Abdulsalam et al. 2015).

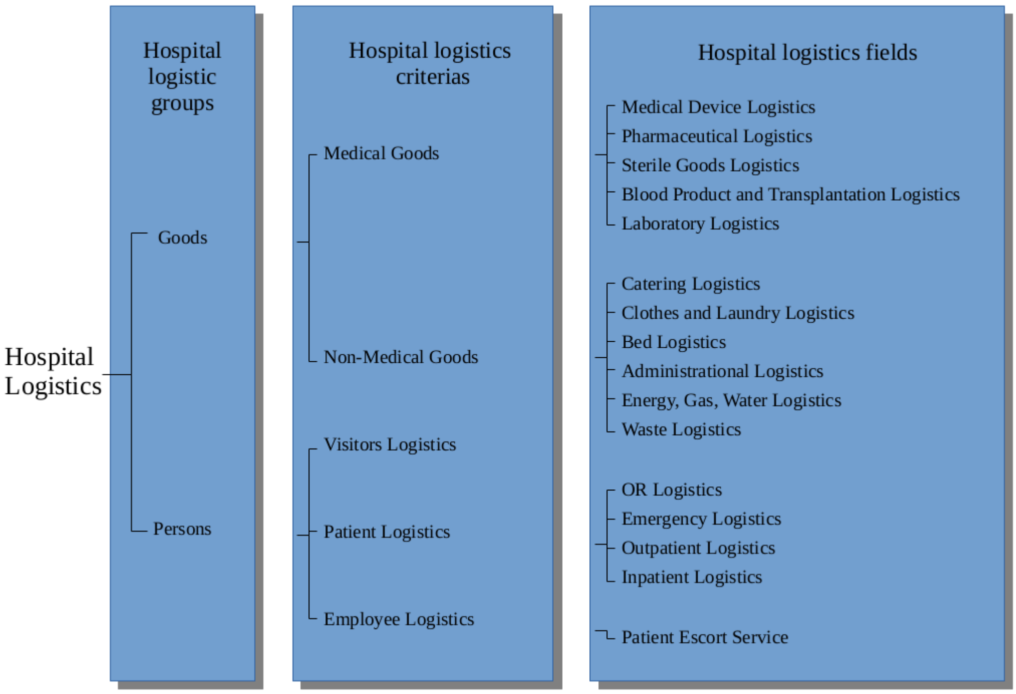

Figure 1: Characteristics of hospital logistics. Adapted from Kriegel et al. (2013).

2.2 Material Transportation Systems Used In Hospitals

Material transportation in hospitals are in many ways similar to material transportation in other industries, automation is therefore starting to become quite common in hospitals like for example the car industry (Özkil et al. 2009). Pneumatic tube systems have been used for many years, and it is one of the most common delivery systems in hospitals (ibid.). Pneumatic tube systems are limited to small items, such as papers or pharmaceuticals, and work by placing the cargo into small cylinders which then is placed into the tube system at a tube station, then the cargo cylinder is moved by pneumatic forces from fans and pumps to its destination. Track and conveyor systems are also used to transport larger items between hospital units or floors (ibid.). In this thesis we are focusing on a more modern alternative that require less modification to the buildings, this solution is automated guided vehicles (AGVs).

2.2.1 Automated Guided Vehicles

An automated guided vehicle (AGV) is an autonomous vehicle mainly used for horizontal movement of materials and can be used in both inside and outside environments. AGVs are most suitable in environments with repeating transportation patterns (Vis 2006) e.g. manufacturing facilities, distribution centers and transshipment. The AGV is often guided around by wires, magnets, or other markers in the floor, but modern AGVs are using internal guiding systems and require less modification of the environment. AGVs come in many different shapes and sizes depending on what transportation tasks they are designed for, from transshipment of shipping containers, to maneuvering through hospital corridors and elevators.

AGVs has been used in the industry for more than 50 years (ibid.). It has also been an area of research for decades, e.g in the 1980s Egbelu and Tanchoco (1984) was researching AGV dispatching rules. The recent year's advances in information and communications technology (ICT) and battery technology has led to new areas of usage, e.g. warehouses, container terminals, airports, or hospitals.

AGVs can replace human labor in different ways; they remove the need for a person to either carry supplies or equipment or push it on carriages around a facility, or they replace forklifts or other human-driven vehicles. In the car industry some original equipment manufacturers (OEMs) are replacing forklifts by tow-trains driven by fully automated AGVs to do the delivery to line-part of internal logistics (Boysen et al. 2015).

Figure 2: An AGV at St. Olavs Hospital

2.2.2 AGV Systems

AGVs are operating under many different conditions, from inside a clean and dry hospital environment to the outside environment of a container yard. In all these environments a number of AGVs are carrying out transportation jobs from one location to another in a *Automated Guided Vehicle System* (AGV system) (Vis 2006). The AGV system is often a part of a larger system. Vis (ibid.) describe the parts that can be distinguished in an AGV system: The *vehicles*, the *transportation network*, the *pick-up and delivery points*, and the *control system*. The pick-up and delivery points operates as interfaces between the transportation system and the production or storage system. Between the pick-up and delivery points the AGVs travel on guide-paths which forms the transportation network. Historically the AGVs have been guided along these paths by wires or rails in the floor, but modern AGVs operates without physical guide-paths. Vis (ibid.) refer to these as free-ranging AGVs. Le-Anh and De Koster (2006) describe the main characteristics of guide-path systems to be *flow topology*, *number of parallel lanes*, and *flow direction*, with the different options presented in table 2.

Table 2: Guide-Path Characteristics

Flow topology	Number of parallel lanes	Flow direction
Conventional	Single lane	Unidirectional flow
Single loop	Multiple lanes	Bidirectional flow
Tandem		

Research topics on AGV systems are on both the tactical and operational level. Because of the many variables in an AGV system, impacts on performance of different decisions are difficult to predict. In addition to the guide-path layout the following decisions need to be addressed when designing an AGV system (Vis 2006):

- traffic management: prediction and avoidance of collisions and deadlocks,
- number and location of pick-up and delivery points,
- vehicle requirements,
- vehicle dispatching,
- vehicle routing,
- vehicle scheduling,
- positioning of idle vehicles,
- battery management,
- failure management.

Traffic management is important to avoid deadlocks where two or more vehicles are blocked, and to avoid collisions. This is done in practice by e.g. tandem queue configuration (problem eliminated), collision sensors and vehicle backtracking and/or rerouting, or more extensive zone control and preplanning. (Reveliotis 2000). Zone control and programming/planning AGVs to avoid deadlocks is a complicated problem, Reveliotis (ibid.) proposed a modeling and analysis framework to avoid deadlocks.

The number of pick-up and delivery points should also be considered in relation to the guide-path planning. Vehicle requirements must be considered during the procurement, this can be battery type, range, or if the AGV should carry one or two loads at a time, *one-load-carrying* or *multiple-load-carrying* (Vis 2006). Asef-Vaziri and Laporte (2005) did a survey article to examine issues related with facility design, material handling design, and fleet sizing and operating of AGVs. Asef-Vaziri and Laporte (2005) found that a single-loop produces a shorter travel time and idle time, but tandem loop systems results in a higher task completion rate. This extra time in a tandem-loop system comes from the transshipment between the loops.

To find the optimal guide-path we want to minimize the total vehicle trip distance which De Guzman et al. (1997) proves are an NP-complete problem. There are therefore many research papers to improve the models used to calculate optimal loops. Some of what these models must take into account is fleet sizing, home location of idle vehicles, collision avoidance and deadlocks, single- or multi-load AGVs, and more. Asef-Vaziri and Laporte (2005) highlights the main contributions in the field of loop configuration systems.

According to Egbelu and Tanchoco (1984) there are two categories of vehicle dispatching decisions. One category is the selection of a vehicle from a set of idle vehicles to assign to a pick-up task. This class of decisions involves a single pick-up and delivery point, and two or more vehicles. The decision is to determine which vehicle to assign to the pick-up task. The secondary category is when there are two or more pick-up and delivery points requesting pick-ups simultaneously. This decision is to determine which pick-up task to execute first. These decisions are made according to the vehicle dispatching rules that are pre-programmed into the AGV system.

Jeon and Lee (2017) describe the AGV system to be either a *disconnected network* where the AGV cannot access the network while moving, and can only be assigned a task when at the base station, or a *connected network* where the AGV can access the network and be assigned new tasks while on the move. There are also a difference in how many tasks each AGV can perform at a time; *single-task robots* (ST) or *multi-task robots* (MT). There are also *instantaneous assignment* (IA) where one can only assign one task at a time, or *time-extended assignment* (TA) where you can assign a series of tasks at a time. With a TA system several tasks that are a close distance from each other on the task queue in a certain time window the system can assign them to a single robot to shorten the travel distance. The challenge in a TA system is to define the size and threshold of this time window (ibid.). Conventional AGV systems use the STIA method (Single Task Instantaneous Assignment), Jeon and Lee (ibid.) proposes a MTIA method and a combinatorial search method to select the best AGV. This method can add a new task in between the remaining tasks for an AGV to ultimately reduce cost.

2.3 Hospital Layout

> Layout refers to the configuration of departments, work centers, and equipment, with particular emphasis on movement of work (customer and materials) through the system.
> - Stevenson (2011)

Layout decisions are important for three basic reasons according to Stevenson (ibid.): (1) They require large investments. (2) They require long-term commitments, wrong decisions must be avoided. (3) Their impact on cost and efficiency of operations is large.

Hospitals are typically made up by several specialized medical departments, often with corresponding wards, such as

- Emergency (ER)
- Anesthesia
- General Surgery
- Radiology
- Oncology
- ...

Plus non-medical service units, e.g. kitchen, sanitization, warehouse, maintenance department, and IT department. Large and highly specialized hospitals will often serve as teaching hospitals as well, usually connected to a university, and provide research and teaching facilities as well (Helber et al. 2016).

2.3.1 The Hospital Facility Layout Problem

The allocation of different departments, or *organizational units* (OUs) as we will refer to them as from here on out, affects the logistics activities in the hospital in a great deal, which means it also affects costs (Helber et al. 2016; Volland et al. 2017). The placement of OUs should therefore be determined according to the type of goods and the amount of goods needed by each OU, to minimize the total cost of logistics. Alas, there are multiple other factors that must be taken into consideration as well, making this a very complex problem (Helber et al. 2016). For example when building a new hospital, or build additions to existing hospitals, there will be limitations to how much area that is available or within budget, and some OUs require more space than others. Another example from Helber et al. (ibid.) is that the ER must be easily available for ambulances, and must therefore be located on ground level with vehicle accessibility. Another factor can be that some OUs shouldn't be too close to each other, i.e. patients on a surgical ward need to be protected from infectious areas. For other OUs the opposite may be the case, and two units are preferred to be neighbors because the medical staff will be routinely moving between them (ibid.).

It is not only the transportation of goods and patients that are affected by the layout of a hospital, according to Helber et al. (2016) physicians and nurses spend an economically relevant part of their time just travelling between different OUs.

2.3.2 Layout Planning In Hospitals

To plan the layout of a large hospital many OUs must be allocated to the right place to optimize efficiency and reduce logistics resource consumption. There are also a number of different needs and constraints that must be taken into consideration. It is also challenging from a mathematical perspective, and can be seen as a quadratic assignment problem (QAP), which is one of the most challenging problems in the NP-hard class (ibid.). There has not been published much literature specifically with respect to *layout planning in hospitals*, Helber et al. (ibid.) provides a overview of the most relevant literature:

Elshafei (1977) is one of the first to formulate the problem of allocating hospital OUs as a QAP to minimize transportation of patients. A paper by P. M. Hahn and Krarup (2001) describes a case from a German hospital, Klinikum Regensburg, where the allocation of OUs was described as a QAP and solved already in 1972. This case was also included in the QAP Problem Library of 1991 (Burkard 1991). Butler et al. (1992) worked out a two-stage solution for the hospital facility layout and bed allocation problems, involving a optimization model for the facility layout, and then a simulation-optimization procedure for the bed allocation. Vos et al. (2007) performed a discrete-event simulation to evaluate different hospital scenarios from an operation management perspective, to evaluate if hospital buildings designs support the efficient and effective operating of care processes. For layout planning in hospitals, the multi-story space assignment problem described in P. Hahn et al. (2010) is highly relevant.

2.3.3 Layout Planning For Autonomous Robots

Tan et al. (2016) proposes a framework for creating robot-inclusive environments, and has worked out five guidelines and criteria for design of environments with autonomous robotic systems:

1. **Observability** - AGVs utilizes sensors that in many cases imitates our human senses, e.g. vision and hearing. The environment should minimize noise that interfere with the AGVs sensors. Appropriate selection of colors, textures, and materials for the floor and walls that positively interplays with the sensors is also important. (ibid.).

2. **Accessibility** - Similar to how buildings and environments must be accessible to all people regardless of disability, age, and other factors, it should also

be accessible for autonomous robots. Doors must be located and designed in a way that makes it easy for robots to operate, e.g. door handle/knob-placement and/or automatic doors. There should also be designated recessed areas for robots to cease work when required, and non-slippery, non-reflective, levelled floor without sills. (Tan et al. 2016).

3. **Manipulability** - Manipulability refers to the term manipulation from robotics. A robot manipulates its environment by e.g. grasping, pulling, carrying, or pushing objects. This can be a complex task according as the complexity of the object, and usually require a simulated and controlled environment, like a robotic cell in a factory. To create environments that are useable for both humans and robots the environment and objects in it can instead be designed for robots. Fixtures and objects that may be manipulated by robots should have a shape, material, and weight that the robots easily can grasp/operate/control/move. Things that require robot manipulation should not require wrist or fine dexterity to operate, and they should be installed at consistent heights and ranges so the robots easily reaches them. (ibid.).

4. **Activity** - It is important to consider how much and what kind of activities that are taking place in the environment, i.e. how much human and robot traffic are there, and where can queues and blockages arise? The environment should provide the robots with aids to recognize different areas of the environment and aid in finding the best routes. Pathways must have sufficient hight and width to accommodate expected flow of humans and robots, and ensure appropriate integration or segregation of accessible routes for robots. (ibid.).

5. **Safety** - Should always be a priority. Tan et al. (ibid.) extends the safety perspective from government policies and international standards to look at safety as ”a principle that ensures the protection of robots against environmental hazards that can cause, for example, falling, loss of power autonomy, or other irreversible failure situations” (ibid.). Some of the safety principles are mentioned in the accessibility and activity paragraphs, other principles is to provide self-charging spaces to prevent disruptions from loss of power, design level platforms where robots perform tasks, e.g. before doors or shelves, to prevent the robot from rolling backwards, and to design physical blockages in front of edges to avoid any falls in case a robot drives out of course. There should also be signs or indicators when the surface type or level changes in accordance with the observability principle.

Barber (2014b) from Swisslog, a supplier of AGV systems for the health care sector, presents twelve important considerations for planning a hospital where an AGV System is going to be used:

1. *Corridor space* - The corridor size and form must be in accordance width local laws and standards for fire safety and to minimize potential hazards related to the automated system, i.e. in Norway *NS-EN 1525:1997 Safety of industrial trucks - Driver less trucks and their systems.* There must also be taken into account if it should be wide enough for two AGVs to meet everywhere or just in some places, and where AGVs should be able to turn around, and where pick-up and delivery (P&D) stations should be placed.

2. *Floors and floor coverings* - The floors must be able to support the weight of the AGVs, and be tough enough to withstand continuous and repeated travel of heavy AGVs. The floor should also have anti-static properties. Any inclining/declining ramps must be evaluated by the system supplier and may impact the carrying capacity of the AGVs.

3. *Carts* - The cart's footprint must be known, as well as their capacity/volume to derive the number of cart movements.

4. *Elevators* - Regular elevators or simpler cart-lifts can be used for vertical movement. It's normal to dedicate some elevators near P&D stations for AGV transport to reduce crash between cart traffic and staff and patient traffic. Size and weight capacity requirements for the elevators must be considered.

5. *Send and receive stations* - The placement and amount of Pick-up and delivery stations (P&D), also called send and receive stations, must be considered. Normally there are at least P&D stations on patient floors and on each of the main support-areas. P&D stations is cart positions where the AGVs can pick-up and deliver carts/containers. The send stations require guides in the floor to correctly position the carts for the AGVs to pick up, while the both send and receive stations also require a sensor in the ceiling to detect the presence of a cart underneath.

6. *Automatic doors and fire doors* - Doorways in the AGV System must be held open by electromagnets or motorized. The AGV control system must be able to communicate with the automatic door system. The automatic door-system must be controlled in a way so that it holds a door open when an AGV starts passing through the doorway, and holds the door open until the AGV is completely through and clear of the swing radius of the door. Fire doors must also be programmed to delay closing if an AGV is in the doorway at the time of an alarm.

7. *Power Circuits* - Three-phase power and fused disconnects are required at the AGV charging stations, and single-phase power to the other units in the AGV System, e.g. the I/O controller, dispatch terminal, and the management computers. The AGV System should be backed up with emer-

gency power and all computers backed up with uninterruptible power sources (UPS).

8. *Clean and soiled P&D rooms* - Cart queuing near the patient areas is best provided in clean and soiled P&D rooms. These rooms function as lobbies for the AGV elevators, adjacent to the general circulation of the ward/nursing unit. The clean room should be locked with controlled access to protect the materials being delivered, while the soiled room may be open for housekeeping personnel to deposit materials and soiled carts. Architects and designers should consult with the AGV System manufacturers on the proper layout of these elevator lobbies.

9. *System Control Center* - At least one client with user interface to access the AGV System server should be located in a AGV System maintenance room somewhere along the travel path for the AGVs.

10. *Robot Vehicle Maintenance Room* - A lockable maintenance room should be provided, to service the vehicles and keep important manuals, tools, and spare parts.

11. *LAN/WLAN Drops and Configuration* - The AGV System uses the hospital's wireless local area network system (WLAN) for communication with the vehicles, so WiFi access is required along the whole AGV network.

12. *Environment* - The operating environment for Swisslog's AGV System should be dry, indoors, with controlled temperatures between +5 and +35 degrees Celsius, with humidity between 30% and 80%.

3 Methodology

In this chapter we present the approach and methods used to answer the research questions, and why these methods were used.

3.1 Approach

To answer the research questions there has been performed both a literature study and a case study. Creswell et al. (2007) describe this approach as *mixed methods*, because it usually involves both quantitative and qualitative methods. In this project we have focused on qualitative research, because we are looking at challenges in the use of AGVs related to layout, e.g. placement of departments, hallways, etc, through case studies in addition to a literature study, and the results from these studies are not necessarily quantifiable.

3.2 Literature Study

A literature study has been performed to get an understanding of the topic, and to acquire an overview over relevant literature. The approach to the literature search has been perhaps less structured than a *literature review* would have been, but we are still quite confident that most relevant literature has been covered.

The literature search was split into two parts, part one was literature search regarding hospital layout, and part two was regarding AGVs and material flow. This was done mainly because the author recently did a literature review on automated guided vehicles and material flow, but also because there are a very limited number of publications combining the topics automated guided vehicles, material flow, and hospital layout.

The literature search process has been a three-step approach. Firstly the scientific search engine *Google Scholar* was used with several combinations of the search words *hospital layout and automated guided vehicles* to get a quick overview of what literature that can be found in the area and to fine-tune the search words and phrases. Secondly the scientific databases *SCOPUS* and *Science Direct* was used with the search phrase (including field specifications and boolean operators):

1. *TITLE-ABS-KEY(((building OR floor) AND layout) AND (hospital OR ”health care”))*
2. TITLE-ABS-KEY((”automated guided vehicles” OR ”mobile robots”) AND (”supply chain” OR ”value chain” OR ”material flow”)).

Table 3: Search structure part 1

Level 1		Level 2
”building” *OR* ”floor” *AND* ”layout”	*AND*	”hospital” *OR* ”health care”

Table 4: Search structure part 2

Level 1		Level 2
”automated guided vehicles” *OR* ”mobile robots”	*AND*	”supply chain” *OR* ”value chain” *OR* ”material flow”

The results from this search was sorted in a descending order from the most cited article to the least cited. Using this method yields a high reliability and validity, although there’s a risk of missing out on the absolute newest research, so we did a quick review of the top most recent articles as well. This method of literature search resulted in several well cited articles and literature reviews regarding hospital layout. Thirdly, a backwards and forwards search using the articles found in step two concluded the literature search. When going through the list of results from the literature databases, the workflow shown in figure 3 was used.

3.3 Case Study

According to Yin (1994), *case study* is a research method that can be used to study general phenomenons in a real-life context. Case study should be used when one want to answer ”how..” or ”why..” research questions, and when the investigator has little or no possibility to control the events (ibid.). Case study is a powerful method for research in operations management (OM), it is a good way to explore ”real world” conditions and is often used in the development of new theories (McCutcheon and Meredith 1993; Voss et al. 2002).

In this thesis we want to investigate *how* automated guided vehicles are used in hospitals, and *how* the layout of the hospitals has been customized for these robots,

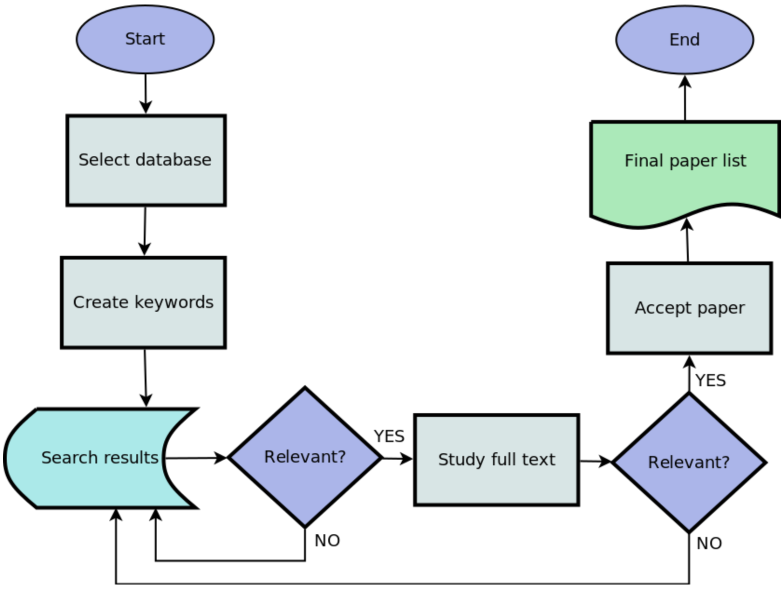

Figure 3: Literature search flowchart

and *what* could be done better in the future. Since the first two research questions are "how" questions, and because there are limited information about this in the scientific literature, we decided to conduct a case study in addition to a literature study to answer the research questions in this thesis.

This project thesis involves two case companies, or case *hospitals*, but one of the cases are more thorough and considered the "main" case. St. Olavs Hospital is the main case company for this project because of its convenient location in Trondheim close to the university (NTNU), as well as an already established relationship with the department of mechanical and industrial engineering. The second case company is Akershus University Hospital (AHUS). There is also a co-operation between the department and AHUS, but the information from this case company is second-hand through the project co-supervisor who is doing research at both hospitals. For the second case hospital we present less general information, and focus on the differences in layout and challenges related to the AGV system.

3.3.1 Information Gathering

To gather information about the case hospitals there has been used three methods; Firstly direct observation through two visits to St. Olavs Hospital, and open-ended interviews with logistics managers and operators. To supplement the case study, public documents and online information about the hospitals, plus an earlier case study by Vaule (2018) has been consulted. Lastly the co-supervisor on this project has been consulted regarding the AHUS-case, because he has knowledge about the hospital from another case study he is working on as part of a PhD.

4 Case Study

In this chapter everything related to the case hospitals are presented.

4.1 Material Flow

Figure 4 shows a simple model visualizing material flow within the supply chain for both case hospitals (Note, patient flow is not included). The supply chain can be divided into internal and external parts, and in this project thesis we are focusing on the internal part.

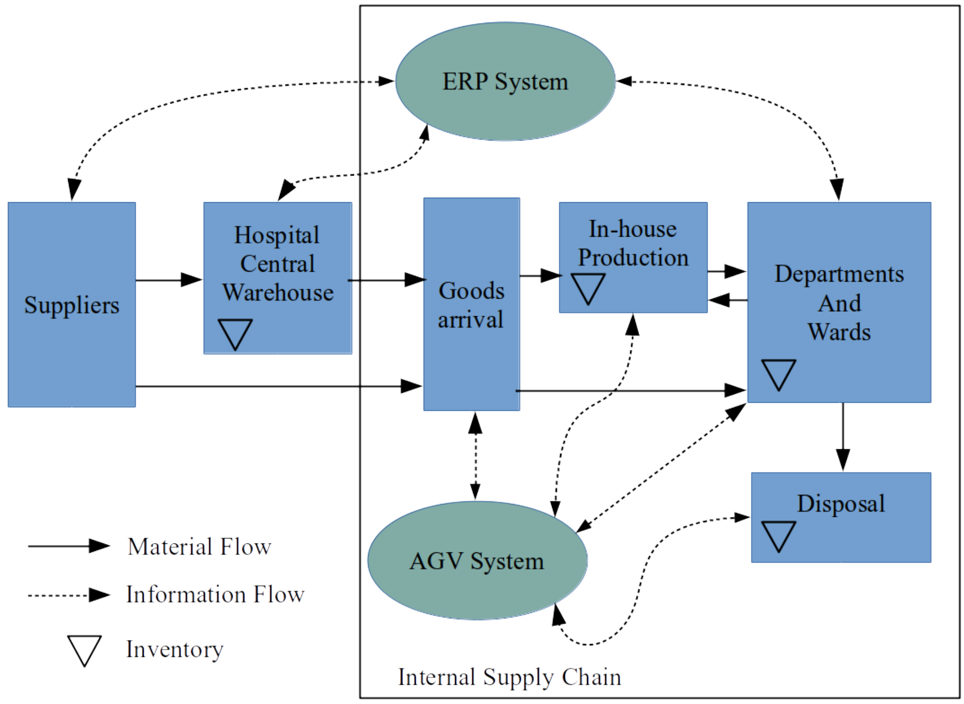

Figure 4: The Hospital Supply Chain

The case hospitals are using automated guided vehicles (AGVs) in the internal transportation. The AGVs transport medical and non-medical goods (figure 1), e.g. food, consumables, equipment, laundry, and waste.

4.2 St Olavs Hospital

St. Olavs Hospital is regional public hospital located in the city of Trondheim, Norway. St. Olavs Hospital has 1000 beds and 800 employees, and treats 60.000 inpatients and 370.000 outpatients every year (Bakken 2012; Nedland 2016).

The hospital has been through two major renewal periods since 2005. More than 80% of the old buildings where replaced in construction phase one from 2005 to 2010, and several new buildings, including a new emergency room and a supply center, has been completed in construction phase two (Nedland 2016; St. Olavs hospital 2017). The AGV System was added during construction phase one.

St. Olavs Hospital is made up of six clinical centers; the Emergency and Cardiothoracic (E&C) Center, the Gastro Center, the Mobility Center, the Neuro Center, the Woman and Children's (W&C) Center, and the Knowledge Center. Non-clinical departments are the Laboratory Center, the Supply Center, the Administration Center, and the Norwegian BrainCenter. These are all supplied by an AGV System, as visualized in figure 5. There are also a patient hotel, a PET center and a psychiatry center, but there is no AGV transportation to these locations.

4.2.1 General Layout

St. Olavs consists of several buildings with one or more clinical centers in each building, and most of the buildings are connected through the basement floor (U1), which functions as a channel between the buildings. Figure 5 displays a simplified representation of the building-layout and AGV network between the buildings on level U1. The layout of the AGV network is kind of formed like a figure of eight with departments and wards at every corner and line-center.

The hospital are distributed over seven floors distributed as pictured in figure 6. The top three floors consists of inpatient wards, the third floor houses technical and university functions, second floor got radiology and operation rooms with corresponding wards, while the first floor consists of outpatient departments, auditoriums and cafés. The basement, U1, functions as described earlier as a channel between the centers in addition to some other technical functions, and it contains several storage areas.

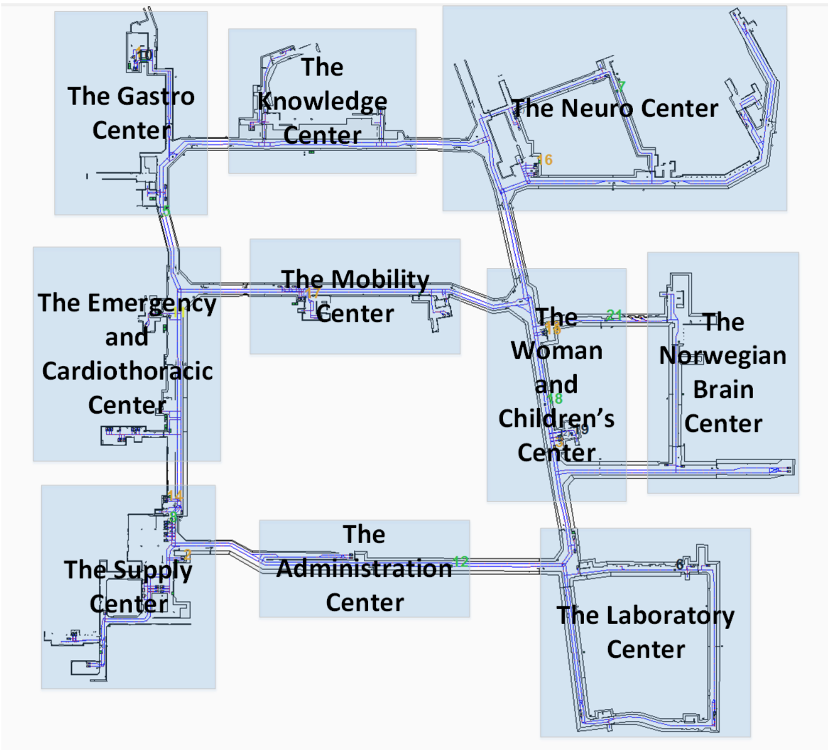

Figure 5: AGV Layout at St Olavs Hospital (Vaule 2018)

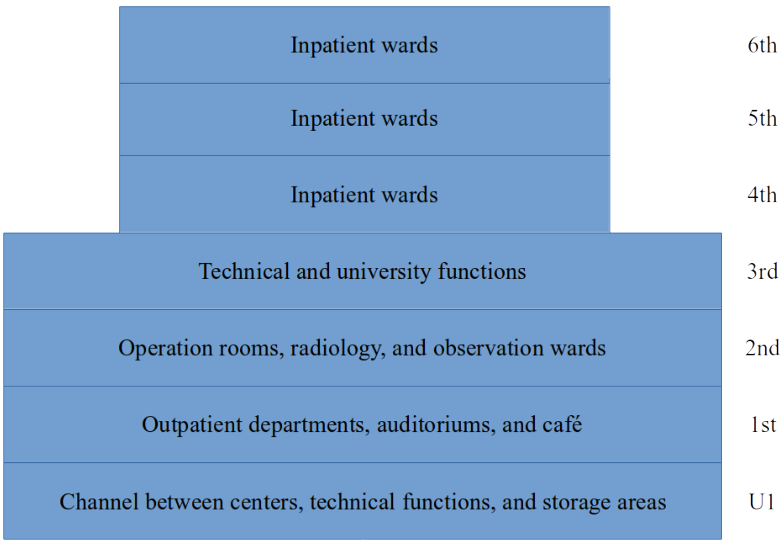

Figure 6: Floor Layout at St Olavs Hospital

4.2.2 The AGV System At St Olavs Hospital

We can describe an AGV System using its four main parts as described in Vis (2006): The *vehicles*, the *transportation network*, the *pick-up and delivery points*, and the *control system*.

4.2.2.1 The Vehicles

The AGVs at St. Olavs are delivered by Swisslog, a company specialized in automation systems for the health care industry. Figure 2 shows an AGVs in operation at St. Olavs. Each vehicle weighs about 250kg and has a lifting-capacity of 500kg. The vehicles has a maximum speed of 3.5km/h and cost around 1.2MNOK each.

The vehicles are used to transport large wheeled hampers or other carriages that has enough ground clearance between the wheels to fit an AGV. See figure 7. The AGV drives itself underneath the container and lifts it with its top-platform a few centimeters up from the ground so the AGV can transport the container and its load to the destination.

The AGV ”speak” to notify personnel, patients and visitors of its presence. A speaker on the AGV calls out in the local language *“robot trolley on the move” (“robottralle på vei”)* at certain intervals, and *“can you move?” (“kan du flytte deg litt?”)*, if something is blocking the vehicle’s path. When an AGV is using an elevator, there is a voice notifying other elevator users and asks them to use another elevator.

At the time of the original purchase of the AGV system at St. Olavs the AGVs was equipped with lead batteries. In the last few years the technology development in the battery industry has made Lithium-Ion (Li-Ion) batteries more affordable, so now that they are starting to replace the AGVs (two vehicles are now replaced every year due to wear, until all AGVs are replaced), the new ones are equipped with Li-Ion batteries. Li-Ion batteries increases the range each vehicle can travel before it require a recharge.

4.2.2.2 The Transportation Network

The basement (U1) functions as the ”main artery” of the AGV transportation network at St. Olavs. This is shown in figure 5. The length of the total driving paths in the AGV system is 4.5km (Nedland 2016).

Each AGV is equipped with a digital map of the hospital layout. This map, in addition to nodes that are located in the floor along the transportation path, enables the AGVs to navigate the hallways. The system will find the shortest path to transport a container from pickup to delivery station. The vehicles also use

Figure 7: An AGV about to pick up a hamper

laser beams which scan the environment around the vehicle and let the AGV "see" its surroundings to make sure it stays clear of any obstacles along the path.

In some parts of the transportation network, the AGVs are programmed to use the elevators to turn. The AGV waits for an elevator to arrive, enters the elevator, and exits the elevator to continue back the way it came. There are two places in U1 where this can occur.

4.2.2.3 Pick-up And Delivery Points

St. Olavs has 114 combined pickup and delivery stations for the AGVs, as well as 49 single pickup stations and 46 single delivery stations. To function as a pickup station the station needs a transponder-reader to read the transponders that are attached to the containers. To send a container by AGV from a pickup station, the personnel places the container on alignment-tracks on the floor, and presses a button on the transponder-reader which informs the AGV system that a container at this station is ready for pickup.

To function as a delivery station, it requires a scanner in the roof of the station. This scanner detects when a container is delivered. When the vehicle arrives with a container, it places it next to the tracks (not on the tracks like the container ready for pickup). The scanner then detects the container and sends a notification to a nearby operator's phone, and informs that a container is ready for pick-up.

4.2.2.4 Control System

St. Olav's Hospital uses a central model for their AGV control system. The system, TransCar Management System (TCMS2), is delivered by Swisslog Healthcare Solutions (HCS). Swisslog defines the AGV system as "One or more TransCar Automated Guided Vehicles (robots) that are coordinated by a central PC" (Barber 2014a).

To communicate between the control system and the AGVs, as well as between the AGVs and the elevator system and the automatic-door system, radio frequency (RF) technology is used (Nedland 2016).

The system is utilizing a transportation schedule to control when each container group is permitted to be transported. A container group is for example laundry supply or disposal, all the groups are shown in figure 8 in a transportation schedule example. The system does not plan transportation jobs in advance, but when a container has been prepared and a button on the pick-up or delivery station has been pressed, the transportation job is placed in a queue according to predefined priority rules and the system allocates an available AGV to the job. The system distinguishes between *supply* and *disposal* containers. Supply containers are transportations *to* the customer, e.g. from the warehouse to a operating room, and disposal containers are transportations *from* the customer, e.g. waste.

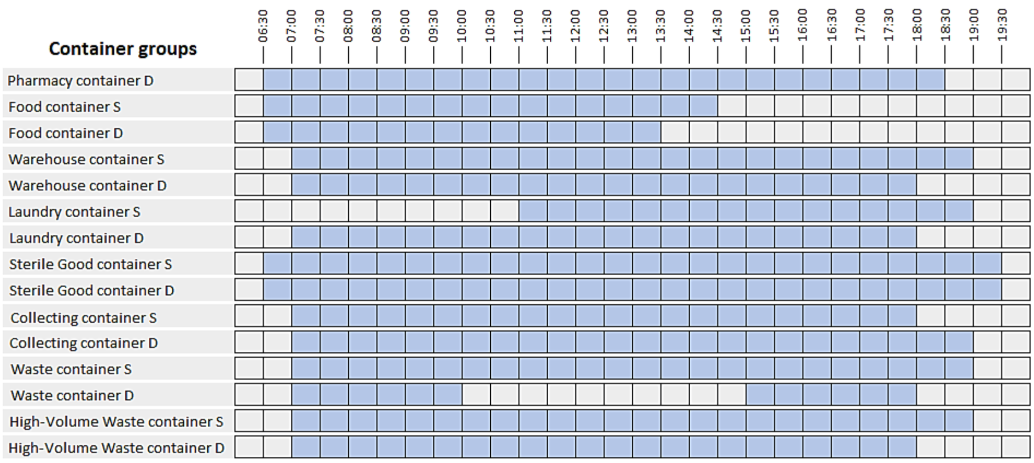

Figure 8: Example transportation schedule. S = Supply, D = Disposal (Vaule 2018)

The priority rules that decide which containers should be picked up first is basically first-come-first-serve (FCFS). That means the transportation jobs with the highest waiting time gets picked up first. If a job need to be prioritized further than that, e.g. the recipient complains that their shipment is late, or there are occurrence of queues before a delivery station, transportation jobs can be given an artificial high waiting time by the operators to make sure it is carried out quickly. This is usually done if there is an urgent job, and for the empty containers at the waste disposal stations.

As a safety measure, the AGVs are programmed to keep a distance between each other, and certain areas like around pick-up and delivery stations, can only be occupied by one AGV at a given time. If an AGV is on its way past a pick-up station while another AGV is picking up a container, the first AGV will not enter the area and drive past the station before the second AGV is finished, even if it would be enough space to pass.

The AGV system is operative between 06:30 to 19:30 Monday through Friday, as displayed in the example transportation schedule in figure 8. This schedule can be altered on the fly by the operators at the supply center. It was initially considered by the developer, Sykehusbygg, if the AGV system should be operating 24 hours or 18 hours a day, but due to man power and noise issues it was reduced to 13 hours.

4.2.3 Findings

4.2.3.1 The Kitchen and Sanitization Area

The main kitchen and the sanitization department are located right next to each other. These are both departments that receive and send a lot of AGV shipments. Especially the kitchen sends a lot of AGV containers out to the other departments and wards in the morning, mid-day, and evening, when the main meals for the day are sent out. As we see in figure 9 these two departments share a narrow hallway (red circle), and they use the same elevators which results in a lot of waiting and queues for AGVs.

The elevators up to the emergency room (ER) are the next elevators down the hallway, where there also are a lot of transportation needs, and AGVs going there often gets hold up because of the traffic. Other bottlenecks are the elevators, especially the elevators to the ER gets a lot of human traffic in addition to AGVs, which results in a lot of waiting time for AGVs.

4.2.3.2 No alternative routes

One of the biggest challenges for the logistics operators (hospital orderlies) at St Olavs is that the AGVs always will follow the same path. This means that if one of the vehicles has a break-down or for some reason stops dead in the road, other vehicles are not able to pass the stopped vehicle to continue their work without human interference. They are not able to turn around and follow another path to their destination either.

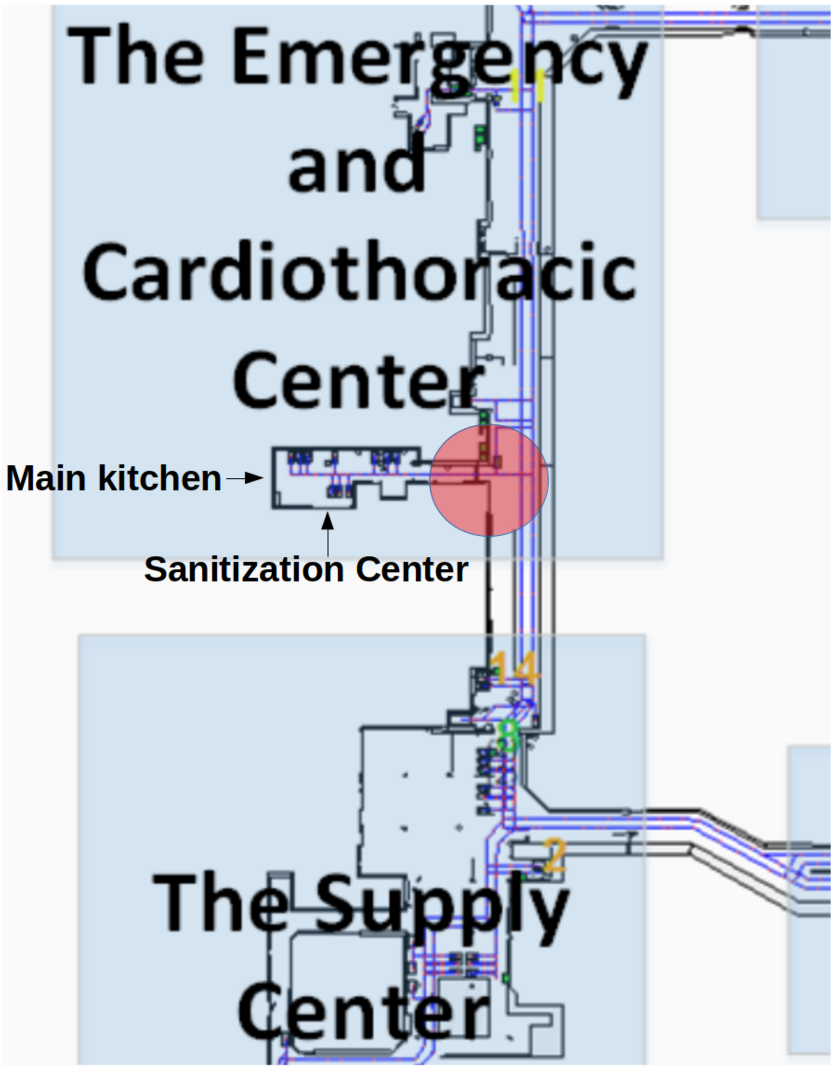

Figure 9: Problem area: Kitchen and Sanitization

4.2.3.3 Observability

As presented in chapter 2, Tan et al. (2016) tells us that an important design criteria for environments where autonomous robots are used is to make sure the observability is good. For the AGV system at St Olavs Hospital, a challenge related to this occurs when the environment changes. This can be something placed temporarily in the hallway, blocking the AGVs path, or just a pallet placed upright against a wall. Even if the path isn't blocked, the AGV will adjust its path according to what the AGV *observe* to be the wall, and if this wall really is a pallet the AGV will lose track of its path and an operator is then required to re-adjust the vehicle.

4.2.3.4 Weight restrictions

Even though the AGVs can lift up to half a tonne, the containers are never filled anywhere close to that, partly because of capacities elsewhere in the supply chain and to reduce waiting time for the end customers, but also because heavy weight containers and hampers gets too hard to move manually for the hospital personnel because of the friction between the wheels and the floor. It is not clear for us through this case study if this could be fixed through better floor-materials, or if the size and material of the wheels are the main cause.

4.2.3.5 Communication Between Control Systems

At the hospital there are three separate automation systems; the system controlling the automatic doors, the elevator control system, and the AGV control system. According to the AGV operators at St Olavs, communication problems between the three control systems are the root cause of many unplanned stops for AGVs.

4.3 Akershus University Hospital (AHUS)

Akershus University Hospital, also called AHUS, is a local and regional hospital located in Lørenskog municipality in Akershus county in Norway. Ahus is one of the country's largest acute hospitals, with almost 300.000 outpatients (somatic patients, i.e. physical deceases and injuries), and 60.000 somatic inpatients in the year 2017 (Kvinnsland et al. 2018). AHUS was expanded and modernized between 2004 and 2008, and the main building is 120.000 square meter, with 6200 rooms, 705 beds, and 23 operating rooms (ORs) (Akershus Universitetssykehus 2018).

4.3.1 AGV System and Layout

Similar to St Olavs Hospital, AHUS is using an AGV system in addition to pneumatic tubes and forklifts or tow-trains to transport materials and supplies from the main inventory to other parts of the hospital facilities. At AHUS the goods arrival, the main kitchen, and the waste facilities are located on one side of the hospital area, while the medical departments and wards are placed on the other side with a connecting "channel" between (see figure 10).

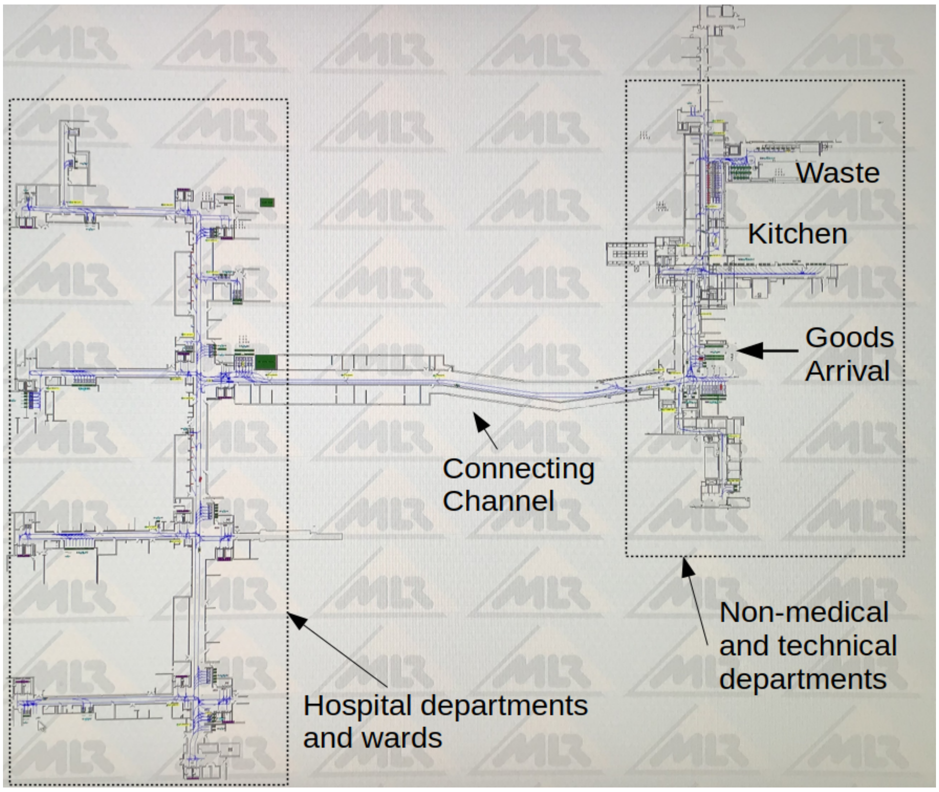

Figure 10: General Layout at AHUS

At AHUS, the AGV System utilise several *buffer stations*. This is a kind of pick-up and delivery station that only is operated by the AGVs, where the AGVs can place their containers if the goal-station of that trip is fully occupied by containers or hampers, and then later pick it up again and finish the job. The placement of these buffers are pointed out on figure 11.

AHUS also have a different system than St. Olavs Hospital next to the sending stations at the goods arrival center. This system lets the operators place several carts/containers on one station.

4.3.2 Findings

4.3.2.1 Layout Problem

Because of the layout, all AGV traffic must go through the connecting channel between the non-medical and technical departments and the hospital departments and wards, as pictured on figure 10. This leads to a bottleneck in the system at the area pointed out on figure 11.

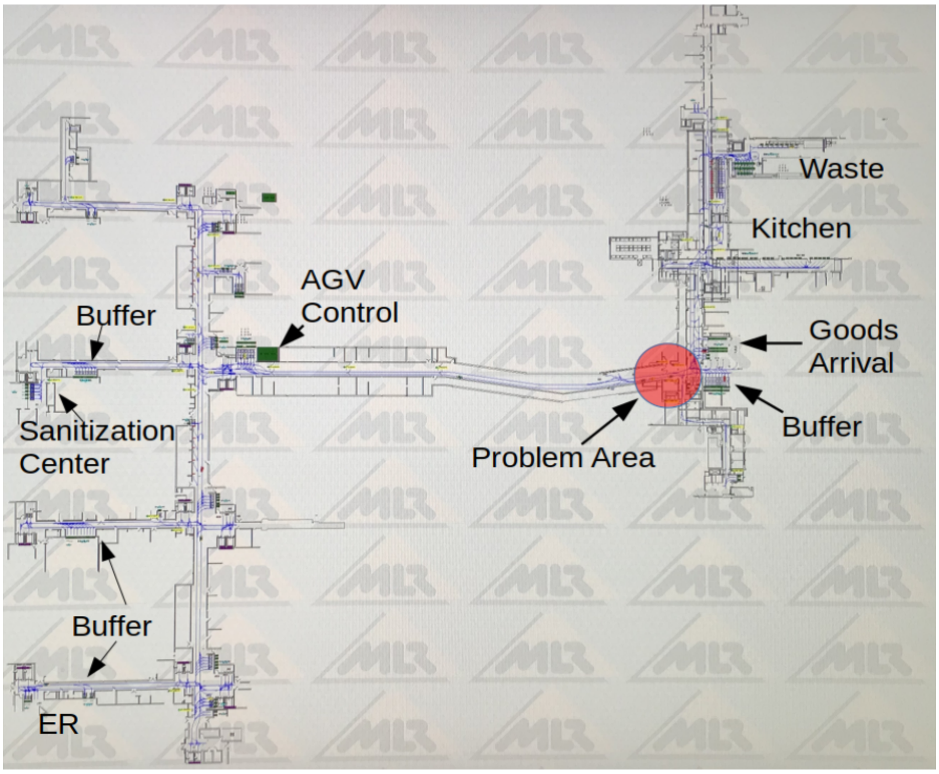

Figure 11: AGV Layout at AHUS

4.3.2.2 The Emergency Room

The emergency room (ER), is located furthest away from the goods arrival center, giving it the longest route for AGVs to travel. At the same time some supplies, especially the disposable covers used on the stretchers, need a 100% availability at the ER, so they are using manually guided pallet trucks for these deliveries once a day.

5 Discussion

In this chapter our findings are discussed, and we try to draw lines between the case study and the literature study. We begin by discussing the topic in general, before we move on to the case study.

5.1 Hospital Layout

With manufacturing logistic-terms, hospitals are generally built with a *functional* layout. This is a layout where departments where similar activities are performed are grouped up, creating a complex flow of materials. (Stevenson 2011) The biggest advantage of a functional layout is its ability to handle large variations in processing needs, i.e. high flexibility (ibid.).

As we learned from the literature study (chapter 2.3.2), to plan a large hospital is an immense task; in addition to the material logistics, one must consider the needs of the patients, the staff, and of course the budget. Thus, it may not be that strange if the hospital layout is not optimized in regards of material logistics.

5.1.1 Material Transportation In Hospitals

As described in chapter 2.2.2, automated guided vehicles (AGVs) are best suited for horizontal transport in indoor environments (outdoor AGVs do exist, but it is usually either-or to avoid damage to the indoor floors). Therefore hospital facilities with large footprints, i.e. wide and/or a composition of several connected buildings rather than high rise buildings, are best suited for AGV transportation. This is visualized in figure 12.

For high rise buildings and skyscrapers, AGVs are not the best solution for material transport. For these buildings customized elevator systems may be a better choice.

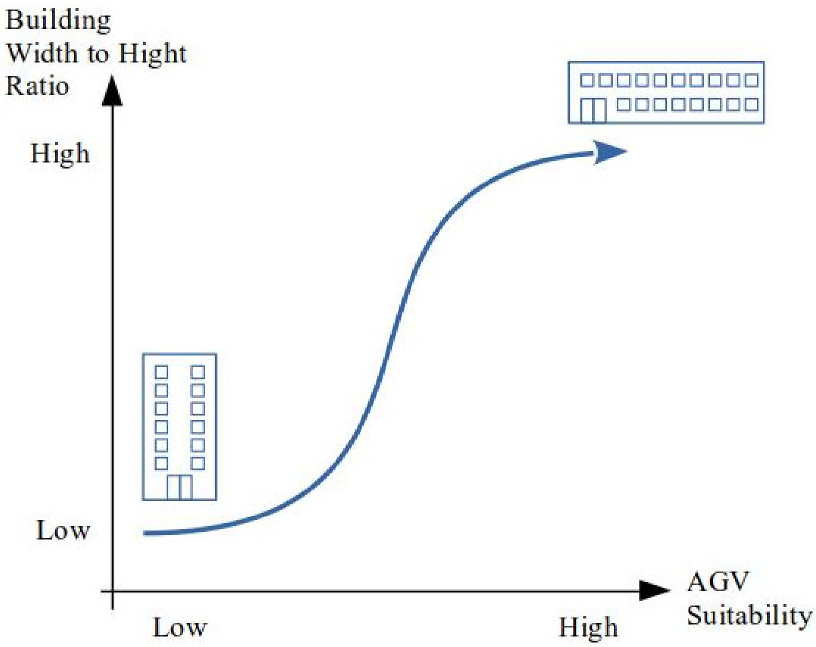

Figure 12: AGV suitability diagram

5.2 St. Olavs Hospital

5.2.1 Layout

At St Olavs Hospital, we have pointed out two areas that stands out as challenges to the material transportation by AGVs, this is outside the kitchen and sanitization department where the hallway and intersection is too narrow for more than one AGV to pass at the same time, and the elevators, especially the elevator up to the emergency room.

5.2.1.1 Elevators

There are many elevators along the AGV System's route, not all the elevators at the hospital are included, but those that are prioritizes AGV transport. AGV-queues are still forming around the elevator areas, because of AGVs that are waiting for free elevators to ascend to a department also hinders AGVs behind them that cannot drive pass the elevator-queue.

Even though the elevators in question will priority AGV transport over people, they are just as available to humans as the other elevators, and that is necessary in case there's an emergency and the other elevator for any reason is out of service. One way to reduce people transportation in these elevators, could be signs urging people to use the stairs or one of the other elevators.

5.2.2 AGV System

In many places where the AGVs are experiencing stops and queueing, for example when an AGV is waiting for another AGV to pick up or deliver a cart, or when other AGVs can't pass a waiting vehicle outside an elevator, there *are* actually enough physical space for an AGV to pass. The limitation is often programmed in the AGV System, and how much of it that is for safety concerns and how much of it that is caused by hardware and software limitations is not known due to proprietary software.

5.3 Akershus University Hospital (AHUS)

Some of the issues that are discussed previously in the St. Olavs Hospital case, are also applicable to AHUS. The safety distance between vehicles during pick-up and delivery, and the bottleneck effect at elevators are also a topic at AHUS.

5.3.1 Layout Planning

We can argue that the placement of departments and wards are better at AHUS, regarding material logistics, than it is at St. Olavs. The only issue is that there tends to be a build-up of queues before the "connecting channel" between the technical/non-medical department area and the medial departments.

5.4 Comparison

To compare our two hospital cases, we can use the framework proposed by Tan et al. (2016), and analyse how well the hospitals do in each of the five design guidelines for environments with autonomous robotic systems.

1. **Observability:** Both case hospitals are excellent at this. Hospitals tend to have a very practical design, and so the materials and colors on the floors and walls are very uniform and smooth to make them easy to maintain and keep clean. They are also used to sensitive equipment at the medical departments, so noise and interference are not an issue.

2. **Accessibility:** Hospitals are made to be accessible for wheelchairs and stretchers, and beds need to be able to move around. So the floors are made non-slippery, levelled and without sills. Most doors are automatically operated or can be pushed open without turning a knob or handle. So both our case hospitals have good accessibility for autonomous robots.

3. **Manipulability:** The AGVs at our case hospitals are only transporting a few different carts, which are customized to fit over the vehicle. Everything else in their environment is not really designed for robots to operate, except the doors and elevators which is automatically operated.

4. **Activity:** The environments the AGV Systems at our case hospitals are operating in can be quite hectic. The AGVs are navigating through the same hallways as the medical staff, patients, and visitors. Both case hospitals' AGVs share elevators with people, and both are experiencing some AGV-queues in relation to elevators, and at AHUS they have put up signs asking people to use the stairs if possible. This could be an idea for St. Olavs as well.

5. **Safety:** In addition to the high accessibility design and public regulations, a safety principle for the AGVs are that they automatically go to a charging station to charge up their batteries at about 20% charge. This prevent the AGVs from running out of power and blocking the hallways.

5.5 Research Questions

5.5.1 RQ1: How are Automated Guided Vehicle (AGV) Systems implemented in the hospital supply chain?

Through our literature and case studies, we have shown that AGVs are implemented as internal transportation systems for both medical and non-medical goods. The AGV System the larger and more regular shipments between the logistics center (goods arrival) and the hospital wards, as well as meal delivery from the kitchens and waste removal from all the departments and wards to the waste management department.

The case study was conducted at two of the largest regional hospitals in Norway, a developed, high-cost country. Hospitals in general, will always seek to cut any costs that doesn't directly affect the level of care, to be able to treat as many patients as possible. In high-cost countries, employee wages are one of the largest cost items, so naturally they will look for ways to automate processes. Thus, the results from this project thesis may only be valid for similar hospitals, i.e. regional hospitals in high-cost countries.

5.5.2 RQ2: How are hospital layouts adapted for AGV systems?

This topic is not widely covered in the scientific literature. Through our case studies we have shown that even two quite recently modernized hospitals are experiencing major challenges regarding their layouts and the use of AGVs.

The hospital layouts are customized by adding pick-up and delivery (P&D) stations at the logistics center and outside (almost) each department and floor. There is also made changes to the hallways, by adding RF transmitter-nodes at evenly spaced intervals to help guide the AGVs, an automatic door system has been implemented and connected to the AGV System, as is an automatic elevator system.

The hospital layout does generally not seem to be optimized with regards to material logistics or material flow. As we discussed earlier, this is most likely because the hospital's primary focus is to maximize patient care within a budget, and everything else is a secondary concern.

5.5.3 RQ3: What are the biggest challenges related to hospital layout for AGV Systems?

From our case studies, we have uncovered that one of the biggest challenges for automatic guided vehicles in hospitals is the complexity of the layout. Long, sometimes narrow, hallways spread out over a large area and several floors with elevators as transportation between them, makes the hospital a tough nut to crack for the system planners.

Another major challenge regarding AGVs in hospitals, is the demand for flexibility and adaption to a changing environment, e.g. people walking in the hallway or placing something along the walls.

6 Conclusion and Further Research

In this chapter we will conclude our thesis, and discuss the limitations in our research and make suggestions for further research.

6.1 Research Questions

Through the first research question we wanted to investigate how automated guided vehicle systems are implemented in hospital supply chains. Through a multiple case study, we have visualized how an AGV system has been implemented in an existing hospital, St. Olavs Hospital, plus an example of how it is done when the hospital was designed with an AGV system in mind, at Akershus University Hospital (AHUS). Where the hospital was designed with an AGV system in mind, the layout does seems to be more suitable for AGV transportation, with regards to the department placements (high-traffic departments are spread out, compared to the kitchen, sanitization, and ER placement at St. Olavs). Alas, as we have learned from operations management, removing one bottleneck only uncovers the next, and AHUS experience a different bottleneck at the entrance to the connecting channel between the technical departments and the medical departments.

The second research question are about how hospital layouts are adapted for AGV systems. As we learned by answering research question one, some newer hospitals are planned with an AGV system in mind, like AHUS, while other hospitals are more or less using retro-fitted AGV systems. Both of these cases have the same additions to the standard hospital layout, but the first case seems to have a better material flow because of better division between technical and medical departments where the departments with most AGV traffic are spread out, although, if this was purposefully done is not known. The additions to the standard hospital layout are for example: RF-transmitting nodes in the hallways, pick-up and delivery stations, and an automatic door and elevator systems that communicates with the AGV's control system. Through both the literature study and the case study, we learn that hospital layouts does not generally seem to be optimized towards a perfect material flow. We believe that this is because the hospitals want to focus on patient care and because of limiting budgets they can't focus on both patient flow and material flow.

In the last research question we want to find out what challenges related to hospital layout and AGV systems exists. Our case study shows us that one of the biggest challenges for AGVs in hospitals is the complexity of the hospital layouts. In addition to the complexity of the layout, the AGVs can have a challenge adapting to a changing environment, e.g. people walking in their paths or objects placed temporarily in the hallway.

6.2 Contribution

This thesis aims to heighten the knowledge about automatic guided vehicle systems in hospitals, first and foremost to aid hospital designers in the planning phase of new hospitals, but also for existing hospitals that want to implement an AGV system. We have highlighted a few challenging areas that can be improved through better layout design and/or more intelligent AGV systems.

6.3 Research Limitations and Further Research

Lack of background information about why different decisions regarding the AGV System and the hospital layout was made, has been a limitation of this project. There are also limited scientific literature on the topic, a lot of the information about AGV System design has to be sourced from suppliers of AGV Systems, and that can have both positive and negative sides to it. It can be positive because they certainly has a lot of knowledge and experience about their systems, but they might also be bias towards not disclosing negative sides to their products.

Another limitation is that the AGV Systems are running proprietary software, and that makes it difficult to know why different behaviors of the AGVs are as they are, e.g. not being able to pass other vehicles even though there is enough physical space. Thus, we can not conclude if the safety measures in the system is too considerate, or if this is a technical limitation. Further research into the control systems of AGVs could be of interest.

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