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Measures for Timely Delivery of Materials Transported by Automated Guided Vehicles (AGVs) in Hospitals

Ida Borgen Vaule

Global Manufacturing Management
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Supervisor: Marco Semini, MTP
Co-supervisor: Giuseppe Fragapane, MTP

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

Preface

This thesis is the final part of my master degree in Global Manufacturing Management at NTNU. This thesis investigates the AGV system at St. Olav's Hospital, with an objective of finding measures for achieving timely delivery for materials transported by AGV.

I would like to thank my supervisor Marco Semini for taking the time to give constructive feedback and for always being available for meetings. This is much appreciated. I also want to thank co-supervisor Giuseppe Fragapane, for great help and guidance though the whole semester, and for giving constructive and useful feedback. This has been a great help.

I also want to thank St. Olav's Hospital, and especially Bjørn Steinar Aune and the people at the Supply Center, for always being very helpful and for giving me much useful information. I hope this thesis can be helpful for them in some way.

Finally, I want to thank my friends and family for always being there for me, and for giving me words of encouragement when I needed it. And a special thanks to Nathalie, for always making sure we ate dinner.

Trondheim, 18.06.2018.

Ida Borgen Vaule

Summary

In recent years there has been an increase in material demand in Norwegian hospitals, and studies show that there are high expenditures for hospital logistics. This signifies the importance of developing favorable logistics solutions for the hospital supply chain. The hospital supply chain is characterized as highly complex with multiple suppliers and many operations that must be coordinated for the internal transportation of materials.

St. Olav's Hospital have implemented an Automated Guided Vehicle (AGV) system for internal transportation of materials. The hospital is noticing problems related to timely delivery for the AGV system, however there is uncertainty regarding which measures that should be done to improve the degree of timely delivery. Little, if any, literature exists on timely delivery of materials in hospitals by using AGVs. Therefore, the project objective is to improve the transportation of materials performed by AGVs in order to achieve timely delivery.

Research questions:

1. What is the current characteristics and dependencies of the internal transportation of materials performed by Automated Guided Vehicles at St. Olav's Hospital?
2. What measures should be done for the internal transportation of materials performed by Automated Guided Vehicles at St. Olav's Hospital to facilitate timely delivery?

The methodology consists of a literature study and a case study. The literature study is focused around finding information on the hospital supply chain, internal transportation in hospitals, and AGV systems in particular. For the case study, the methods used are observations and semi structured interviews. Raw data on the AGV transportation was also retrieved and analyzed from the case company, to investigate the performance of the AGV system in regards to waiting times, transportation times, transportation volume, and transportation capacity.

In the literature study, it was found that the hospital supply chain is characterized as highly complex with multiple suppliers and many operations that must be coordinated with the internal transportation. Such as supply and procurement, inventory management, distribution and scheduling, and having a holistic view of the supply chain where beneficial solutions are

developed and responsibilities are appropriately allocated. The activities related to the supply chain must be coordinated with the AGV system.

The AGV system is responsible for the transportation of consumer goods, laundry, food, sterile goods, pharmaceuticals, and waste. These materials must be internally transported from either in-house suppliers or the goods arrival at the hospital, to ten different hospital centers that each consists of various hospital departments.

In the analysis, it was evident that the waiting times for materials waiting to be transported, can often be very high, and will be influenced by the transportation volume and the transportation capacity.

A framework for measures for facilitating timely delivery by AGV is presented in the discussion. The framework is categorized into three main measures for achieving timely delivery. These are levelling the transportation volume, reducing the transportation volume and increasing the transportation capacity.

So conclusively, this thesis adds to the research on AGV systems in a hospital environment, and gives a framework for possible measures for ensuring timely delivery of materials in hospitals.

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Abbreviations

Admin	Administration
AGV	Automated Guided Vehicle
CODP	Customer Order Decoupling Point
CU	Care Unit
E&C	Emergency and Cardiothoracic
FCFS	First come first served
GDP	Gross domestic Product
ID	Identification
Lab	Laboratory
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
P/D	Pickup and/or delivery
RF	Radio Frequency
RFID	Radio Frequency Identification
SKU	Stock-Keeping Unit
SoS	System of Systems
TCMS2	TransCar Management System 2 (The AGV system of Swisslog)
U1	Basement
VMI	Vendor-Managed Inventory
W&C	Women and Children

1. Introduction

In this section, the background and problem areas that serves as the reasoning behind the study are explained. Further, the research objective and research questions are presented, and finally the specific research scope and thesis structure.

1.1 Background

There is an increasing number of patients in Norwegian hospitals, and this is also a trend in most OECD countries (Bačík et al., 2017; OECD, 2018; SSB, 2017). This, as well as the introduction of new hospital goods and equipment in a wider variety, and a higher share of disposable goods in hospitals, results in a higher demand for material supply and increased requirements for efficiency for the internal transportation (Bačík et al., 2017; Jørgensen, Jacobsen, & Itoh, 2012; Ozkil et al., 2009). Studies have found that at least 30% of hospital expenditure are for logistics activities, making logistics the second largest cost group after personnel costs (Poulin, 2003; Volland, Fügeren, Schoenfelder, & Brunner, 2017). In the past, little priority have been given to logistics in hospitals, both for practitioners and in academia. However, in the last one or two decades, logistics have been identified as a vital contributor for managing costs (Rimpiläinen & Koivo, 2008; Volland et al., 2017). Thus, the high expenditures for logistics and the increasing demand of material supply, signifies the importance of developing favorable logistics activities for the hospital supply chain (Volland et al., 2017).

Developing favorable logistics activities can be challenging considering that the hospital supply chain usually is characterized as highly complex (Rivard-Royer, Landry, & Beaulieu, 2002; Volland et al., 2017). To explain a hospital supply chain it can be viewed as an external and an internal supply chain where the physical limits of the hospital is the boundary between them (Rivard-Royer et al., 2002). In the perspective of the external supply chain, there are multiple different suppliers and numerous distribution channels, which generates a complex chain. There is also complexity in the internal supply chain, because the hospital facility in itself is not the end customer. I.e. the various materials must be internally transported to the appropriate hospital departments at each hospital center, either from an in-house supplier or from a goods arrival area at the hospital. This means that the hospital must establish its own internal logistics network that correlates with the external supply (Rivard-Royer et al., 2002).

The complexity of the hospital supply chain, as well as the increase in material demand gives challenges to the internal transportation at the hospital. This is also the case at St. Olav's Hospital, which is the case company for this thesis. The present St. Olav's Hospital was opened in 2010. For the development of the new university hospital, an Automated Guided Vehicle (AGV) system was implemented as the main tool for the internal transportation of hospital materials. AGVs have been utilized for decades in the manufacturing industry, and have since the new millennium become increasingly popular also in the healthcare industry (Ozkil et al., 2009). An AGV System can be defined as "a driverless transport system used for horizontal movement of materials" (Vis, 2006), and it can also transport materials vertically between floors, by elevator.

The vehicles at St. Olav's Hospital are coordinated by a central computer (Barber, 2014). There are 21 of these vehicles and the central computer is located at the Supply Center at the hospital. The computer system contains an AGV transportation schedule controlling when various materials are permitted to be transported. The AGVs transport materials automatically based on the transportation schedule, and specified routes, pickup and delivery stations.

The materials are transported to the customer in containers. The transportation is initialized when an operator places the container onto a pickup station and presses a button to notify the AGV system that a container is ready for delivery at that station. Thereafter, the container is automatically picked up, transported, and delivered to a delivery station by the AGV. At the delivery station, an operator must manually move the container from the delivery station after it is delivered by AGV. The pickup and delivery stations are situated in various areas in each floor of the hospital to allow close proximity to the customer, i.e. hospital departments. The materials that are internally transported at St. Olav's Hospital can be categorized into consumer goods, laundry, food, sterile goods, pharmaceuticals, and waste.

In the construction of the new hospital, the hospital constructors, Sykehusbygg, developed and simulated various AGV transportation schedules, where the operating time for the AGV transportation was planned to be either 24 or 18 hours per day. However, St. Olav's Hospital had an aim of performing most transportation tasks during daytime. This was to account for personnel costs, and to enable most personnel that the AGV transportation is dependent on to work at daytime and only on the weekdays, i.e. Monday to Friday. Taking this into consideration, the AGV transportation schedule that was implemented is a 13-hour schedule, operating from 06:30 to 19:30 on the weekdays. So, the transportation schedule that is currently used is not systematically developed, i.e. it is not implemented based investigations on the performance of the hospital with this schedule.

For the internal transportations at the hospital, two pneumatic tube systems were also developed. These are a waste-disposal tube-system and a general tube-system for smaller materials. However, the main portion of the overall internal transportation volume is conducted by the AGV system. Based on statements from the case company and data acquired on the AGV transportation, the share of internal transportations on weekdays performed by AGV is estimated to be between 70 % and 75 %. The remainder of the internal transportations are either performed by the two tube-systems or by manual transportation. For transportations that would ordinarily be performed by AGV, but that are performed outside of the AGV operating time i.e. from 19:30 to 06:30 or on the weekends, manual transportation is required. The only materials this applies to are sterile goods and waste, so the transportation volume at these times is considerably lower than the volume transported in the AGV operating time.

1.2 Problem description

The AGV transportation schedule at St. Olav's Hospital was established in 2008, and other than minor changes, the same transportation schedule is still followed today. However, as previously mentioned, the demand for material supply has increased in this same period.

The personnel at the Supply Center at the hospital will, several times every hour, receive complaints from various customers or in-house suppliers, on orders not arriving at the planned delivery times. Late deliveries can be especially critical for the supply of food and sterile goods because these goods are required for specific hospital activities at a specific time. When there are late deliveries, the laundry will often be least prioritized for AGV transportation. The personnel responsible for handling the materials upon delivery will then often transport these materials manually in order to have time to complete their tasks during their shift. About 25 % of the laundry use manual transportation as a result of this, which means that the personnel must use their capacity on manual transportation rather than performing their original tasks. So problems with timely delivery will not only affect the customers, but also the capacity of the personnel.

As mentioned, the AGV system is responsible for a large share of the overall internal transportation, and the system will therefore have a great impact on the performance of the hospital supply chain. In regards to research on AGV systems, the main part of the existing literature focuses on AGV transportation in general (Le-Anh & De Koster, 2006; Ullrich, 2015; Vis, 2006), or in the context of more matured environments, such as flexible manufacturing systems (Mehrabian, Tavakkoli-Moghaddam, & Khalili-Damaghani, 2017), container terminals (López-Plata, Expósito-Izquierdo, Melián-Batista, & Moreno-Vega, 2018), or various industrial environments (Bechtsis, Tsolakis, Vouzas, & Vlachos, 2017). However, considering that the implementation of AGVs in hospitals is a relatively new field and that, in the past, little priority has been given to logistics in the healthcare industry (Nivas, Krishnan, & Fredrhic, 2016; Rimpiläinen & Koivo, 2008; Volland et al., 2017), there is a relatively scars amount of literature specifically aimed at AGV systems in hospitals.

The research that do exist on AGV systems in hospitals mainly tackle issues such as benefits of implementation (Pedan, Gregor, & Plinta, 2017), task management (Ozkil et al., 2009), and vehicle design (Bačík et al., 2017; González, Romero, Espinosa, & Domínguez, 2017). However, to the best of my knowledge, there is little, if any, research specifically dealing with timely delivery of materials in hospitals by using AGVs. At St. Olav's Hospital, it is apparent to the personnel that there are problems related to timely delivery for the AGV system. However, there are challenges related to developing an understanding of the characteristics and dependencies for the AGV system, as well as an understanding of the overall performance of the supply chain. As a result of this, it is difficult for the hospital to determine which possible measures to implement to achieve timely delivery of the various materials.

1.3 Project objective

The AGV system accounts for a large share of the overall internal transportation of materials at the case company and it is clear that there are problems related to timely delivery for the AGV system. Also, there is evidently a gap in the literature on this field. For these reasons the project objective is to improve the transportation of materials performed by AGVs in order to achieve timely delivery.

Research question 1:

What is the current characteristics and dependencies of the internal transportation of materials performed by Automated Guided Vehicles at St. Olav's Hospital?

The first research question focuses on developing an understanding of the supply chain of St. Olav's Hospital, in order to investigate the performance of the supply chain and the characteristics and dependencies related to the AGV transportation. The characteristics and dependencies that are to be discovered are specifically those related to the control of the AGV transportation. I.e. investigating the activities in the hospital supply chain that are connected to the AGV transportation, as well as the various factors that influence how the transportation is performed.

Research question 2:

What measures should be done for the internal transportation of materials performed by Automated Guided Vehicles at St. Olav's Hospital to facilitate timely delivery?

The second research question concerns finding measures for achieving timely delivery of materials transported by AGV. The measures will be presented in a framework where they are categorized into measures performed at three hierarchical levels; these are the AGV system, the hospital environment and supply chain management. The measures are aimed at St. Olav's Hospital, but they can also be found relevant in other hospital supply chains where AGVs are used for internal transportation, because the structure of various hospital supply chains can often be similar (Rivard-Royer et al., 2002).

1.4 Research scope

The focus area is on the internal supply chain and the activities and actors related to AGV system in particular. I will focus in the control of the AGV system, as opposed to the vehicle design and technical issues.

For the hospital supply chain, the first-tier suppliers are included, but the processes further upstream are excluded. This is because including the actors further upstream would not be beneficial for this thesis given that the focus is the AGV system, since it is the deliveries from the first-tier suppliers that must be coordinated with the AGV system.

Other transportation tools are also used for internal transportation of some materials, and in these instances, the other transportation tools are also presented and described. This is done to get a holistic view of the internal transportation, and to understand the AGV system in the context of the entire internal transportation. However, patient transportation, hospital bed transportation, and the transportation of tests and blood via a tube-system connecting the hospital bed departments and the LAB center are excluded because these transportations have no relation or dependencies with the AGV system.

1.5 Thesis structure

Chapter 1 Introduction	This chapter presents the background and motivation for the project, as well as the objective, research questions and research scope.
Chapter 2 Research methodology	This chapter explains the approach and methodology used for each of the research questions, as well as assessments regarding the quality and relevance of the approach. There is also an explanation of the process of extracting data from the findings, and a presentation of validity threats.
Chapter 3 Literature study	In this chapter, the research that was retrieved for the research questions, is presented. First, the hospital supply chain is studied, followed by research on material distribution in hospitals and AGV transportation in hospitals.
Chapter 4 Case study	The findings from the case study is presented here with the control model methodology used as a tool to present the findings.
Chapter 5 Analysis	The analysis presents a control model of the supply chain of St. Olav's Hospital, as well as a statistical analysis of transportation data retrieved from the hospital.
Chapter 6 Discussion	In the discussion, the main findings discussed for both research questions. A framework for possible measures for achieving timely delivery of materials transported by AGV is presented and discussed.
Chapter 7 Conclusion	The conclusion deliberates on how the research questions were answered and what the outcome was, as well as suggestions for further research.

2. Research methodology

In this chapter, the research methodology is explained. First the approach for this thesis is presented, followed by an explanation of the various methods that are utilized. Thereafter, an the methods used for the analysis is given, and lastly, the research quality is discussed.

2.1 Approach

Croswell (2003) explains that the "execution of a project can be performed by applying one of three approaches: a quantitative, qualitative, or mixed methods approach (Creswell, 2013)." For this project, mixed methods will be used, which is a combination of qualitative and quantitative methods. This approach was used to strengthen the research and increase the credibility of the results (Hesse-Biber, 2010). More precisely, the methodology used is *Triangulation*, which is one of the most common mixed methods designs. It is described as "the use and combination of different methods to study the same phenomenon" (Chris, Nikos, & Mark, 2002), and is an approach where the goal is to "validate quantitative statistical findings with qualitative data results" (Hesse-Biber, 2010). Triangulation has an underlying positivistic view where there is an assumption that there exists one objective reality that is independent of any subjective experience (Hesse-Biber, 2010).

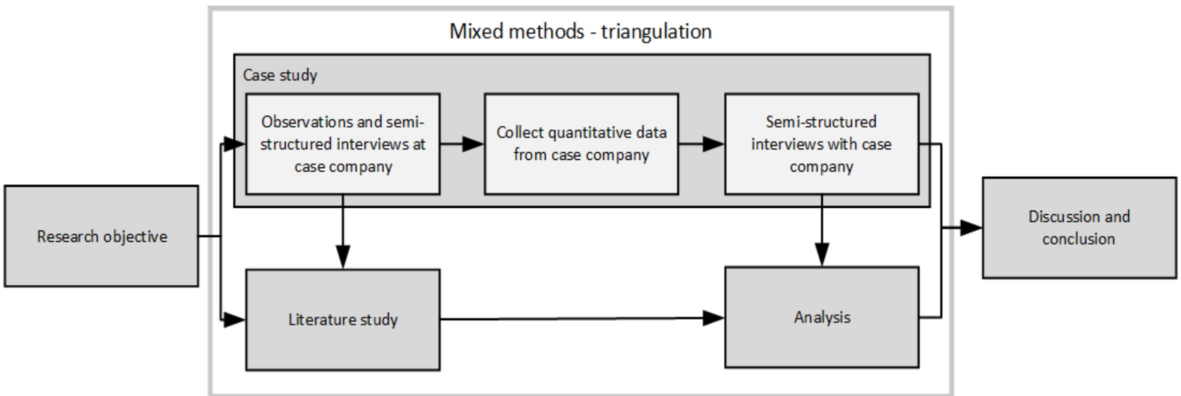

Figure 1: Research design

Figure 1 presents the research design, which consists of a case study and a literature study. A literature study was conducted to find research on the hospital supply chain, internal transportation in hospitals, and more particularly AGV transportation in hospitals. Also, observations and semi-structured interviews were performed to give an understanding of the case company and the AGV system. After this a statistical analysis, based on quantitative raw data received from St. Olav's Hospital, gave a greater understanding of the AGV performance and the daily AGV transportation of the various materials over a half year period. Based on the case study a control model is developed, and after this, new interviews were completed to validate the results from the statistical analysis and the case study. A framework on timely delivery by AGV is developed and presented in the discussion, and the conclusion presents the contribution of this thesis to the literature.

2.2 Literature study

An explorative approach was used for this literature study. According to Saunders et al. (2012), explorative research is meant to explore the research question to get a better understanding, not necessarily intended to provide conclusive solutions (M. N. K. Saunders, P. Lewis, & A. Thornhill, 2012). The purpose of the literature study was to gain knowledge regarding the topic of the project. It was conducted to find research related to the hospital supply chain and to get an understanding of material transportation in hospitals as well as AGV transportation in particular.

The following databases were utilized in the literature search: Web of Science, Google Scholar, Scopus, and NTNU University Library (Oria). The main keywords used in the literature study is presented in Table 1. Keywords 1 were first used in the literature search to get a general understanding of the subject matter, and after this, Keywords 2 were used to understand the context of the subject. The third step was to combine keywords from both columns to find literature that is more particular to the topic.

Table 1: Keywords from literature search

Keywords 1	Keywords 2
- Materials management - Material handling - Internal logistics - Distribution - Transportation - Material transportation - Internal transportation - Automated transportation - Automated guided vehicles - Autonomous robots	- Hospital supply chain - Supply chain - Health care - Hospital

The title and abstract of each article were first read, and if it was deemed relevant, the introduction, results, methodology, and discussion was viewed to determine if it was appropriate for this project. If this was the case, the full article was read more in depth.

2.3 Case study

A single case study at St. Olav's Hospital is performed for this thesis. Creswell et al. (2007) define case study research as "a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in-depth data collection involving multiple sources of information (e.g., observations, interviews, audiovisual material, and documents and reports) and reports a case description and case-based themes" (Creswell, Hanson, Clark Plano, & Morales, 2007). More precisely for this research, a *single* case study can be described as "the intensive study of a single case for the purpose of understanding a larger class of similar units (a population of cases)" (Gerring, 2007). A single case study was chosen as an approach because it allows for a more in-depth study on that particular case, relative to performing multiple case studies (Gerring, 2007).

The purpose of this case study is to gain an understanding of the supply chain at St Olav's Hospital and the logistics activities of the hospital, particularly related to AGV transportation. In the case study, the approaches utilized where observations, semi-structured interviews and gathering of statistical data concerning AGV transportation. Thus, a mix of qualitative and quantitative approaches were used, the observations and interviews being qualitative and the statistical analysis being quantitative.

The control model methodology was used in the interviews and observations as a guideline for which topics to cover and what information to determine as relevant. This approach is elaborated on in 2.4.1 Control model methodology.

2.3.1 Observations

Observation as a data collection method can be defined as “the systematic observation, recording, description, analysis and interpretation” of a case (M. Saunders, P. Lewis, & A. Thornhill, 2012).

The purpose of this approach was to get an initial understanding of the AGV system and to observe the material- and information flows at the hospital. The observations could also help to get an overview of possible problem areas. This method was chosen because it gave a basic understanding of the system in the initiation of the case study.

The observation was synchronically constructed, which is described as “observing within-case variation at a single point in time” (Gerring, 2007). This differs from diachronically constructed observation where the case or some branch of within-case units are observed over time.

The observations at St. Olav’s University Hospital was conducted over a two-week time period. The observations were documented by taking pictures or film, and by making notes.

2.3.2 Semi-structured interviews

Multiple semi-structured interviews were conducted for this case study. Semi-structured interviews is a non-standardized interview form, i.e. there were not a set of fixed questions to use when performing the interviews. It is often described as qualitative research interviews, and the method is used to collect data that will later be analyzed qualitatively (M. Saunders et al., 2012).

The purpose behind the interviews was to better understand the characteristics related to the AGV system. The reason for choosing this method was because, relative to the more quantitative methods, the semi-structured interview allows for a more in-depth study, where the interviewee can explain thoroughly and one can build on the answers to ensure an unambiguous explanation (M. Saunders et al., 2012). Also, in this case study there were many questions to be answered and a great deal of these questions were quite complex, so this made semi-structured interviews a suitable approach.

The interview schedules would contain key questions and main topics, but would not present a standardized set of questions. The interviews were first performed parallel to the observations, which took place over the course of two weeks. In the start of the case study, the questions were fairly general and superficial, and as my understanding of the system increased, the questions became more in-depth. Another interview round was conducted towards the end of the case study in order to validate the findings and the results thus far. Data from the interviews was gathered by taking notes, and it was transcribed more completely afterwards.

2.4 Analysis

The information and data gathered from the case study was analyzed in order to understand the problem areas and possible solutions. For the analyzation, a control model of the case company was developed using the control model methodology. The analyzation of the statistical data retrieved from the case company was also a part of this segment.

2.4.1 Control model methodology

A control model can be described as the set of principles, rules, and procedures that manages ordering, planning, implementation and monitoring of the manufacturing and procurement in a company (Andersen, Strandhagen, & Haavardtun, 2010).

The control model methodology was used as a framework to investigate the processes related to the material- and information flows for the hospital and to understand the investigate the characteristics and dependencies of the AGV system. It can give answers to how the resources are organized in relation to each other, and help define the control areas and the capacities in the system, and also enable the identification of bottlenecks (Andersen et al., 2010). The control model methodology was used as a base for the case study, both as an approach for executing the observations and interviews, and for the actual development of the control model.

To simplify the control model and to keep the focus on the activities influencing the AGV transportation, the control model only displays the first tier suppliers. E.g. food supply from the Supply Kitchen to customers outside of the hospital, i.e. transportations to Nidaros DPS at Lade and Orkanger Hospital, are excluded. Also, as previously mentioned, the material and information flows related to hospital bed transportation, and the transportation of tests via a tube system connecting the hospital bed departments and the LAB center are excluded. The patient hotel, the psychiatry center, and the PET center is also excluded in the control model because there are no AGV transportations to these centers.

2.4.2 Statistical analysis

A statistical analysis was performed to investigate and present quantitative data on the AGV transportation system. This allowed for a better understanding of the actual performance on the system.

Raw data concerning AGV transportation was gathered for a nine month period from the AGV central computer. I.e. for each transportation job, data is saved on the container group that was transported, the initiation time for when the job was assigned to a vehicle, the time the vehicle picked up the ordered goods, and the time it arrived at a delivery station. Also, raw data on the AGV recharging activities were gathered for a one month period. That is, data on initiation time for when a vehicle starts recharging and when it stops recharging.

This data was analyzed to produce statistical data and to view the transportation trends, as well as to discover and visualize the problem areas.

The analyzation presents statistical analyses on the waiting times, transportation times, transportation volume and transportation capacity. There is also a comparison of the different analyses in order to discover any correlations.

2.5 Research quality

Different methods and approaches, both quantitative and qualitative, where used for this project to strengthen the research. There are however some aspects related to quality concerning each individual approach.

When performing interviews, there are quality issues related to reliability and validity, where there may be biased information given or received from interviewer or interviewee, and some knowledge may be lost in translation. Generalizability, i.e. applicability of research to other settings, may be reduced because the process is qualitative where only a small sample is investigated (M. Saunders et al., 2012). These issues where recognized going into the interviews, to try to ensure research quality. For the observations, it may not show an average state since the observations only is conducted over a two-week time-period. However, the use of mixed methods helped prevent these issues related to qualitative research.

2 Literature study

In this chapter, the hospital supply chain is studied and the role of logistics in healthcare is investigated. This is done to get an understanding of the possible dependencies of the AGV system. Further, research on material transportation in hospitals conducted by AGVs is presented.

3.1 Hospital supply chain

Logistics can be described as “the movement of goods, services, cash, and information in a supply chain” (Stevenson, 2014). And a supply chain is defined as “a sequence of organizations – their facilities, functions, and activities – that are involved in producing and delivering a product or service” (Stevenson, 2014). More particularly, Polater et al. (2014) describe a hospital 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”, with the aim to “deliver products at the right time, for the purpose of fulfilling the requirements of those providing healthcare” (Polater, Bektas, & Demirdogen, 2014). The hospital supply chain can be divided into an external and internal supply chain. The external supply chain consists of the hospitals suppliers and the operations that are not restrained to the physical limits of the hospital, while the internal supply chain consists of operations and actors within the physical limits of the hospital (Rivard-Royer et al., 2002).

The healthcare sector is characterized by its complexity, where, in the perspective of the external supply chain, there are multiple different suppliers and numerous distribution channels. There is also complexity in the internal supply chain, because the healthcare facility is not the end customer, and the hospital must establish its own internal logistics network that correlates with the external supply (Rivard-Royer et al., 2002).

A study by Poulin et al. (2003) state that half of logistics costs in hospitals can be eliminated with efficient logistics management (Poulin, 2003), and according to Volland et al. (2017), increasing logistics efficiency will not directly influence patient care in a negative way, and it may even give medical staff more time for patients related activities (Volland et al., 2017).

Granlund & Wiktorsson (2014) also state the importance of recognizing the effect of the logistics activities on the overall performance of the hospital (Granlund & Wiktorsson, 2014).

Volland et al. (2017) assert that the external supply chain has been given the most attention, and that the internal supply chain and the internal logistics is the weak spot in entire chain (Volland et al., 2017). Granlund & Wiktorsson (2014) argue that the performance of the internal supply chain highly affects the organization's overall performance, and remark the importance of continuous improvement in this segment in order to achieve competitiveness. They explain that the focus of internal logistics is often to provide supplies to the company's core activities, which for hospitals is patient care. Logistics and material handling is described as an extensive and important part of the healthcare industry, but that it is far from the industry's core competences (Granlund & Wiktorsson, 2014).

Ozkil et al. (2009) describes the main focus of logistics in hospitals as the management of material flow (Ozkil et al., 2009). While Kriegel et al. (2012) present materials as one of the two objects of the hospital logistics, the other one being persons (Kriegel, 2012). This is displayed in Figure 2.

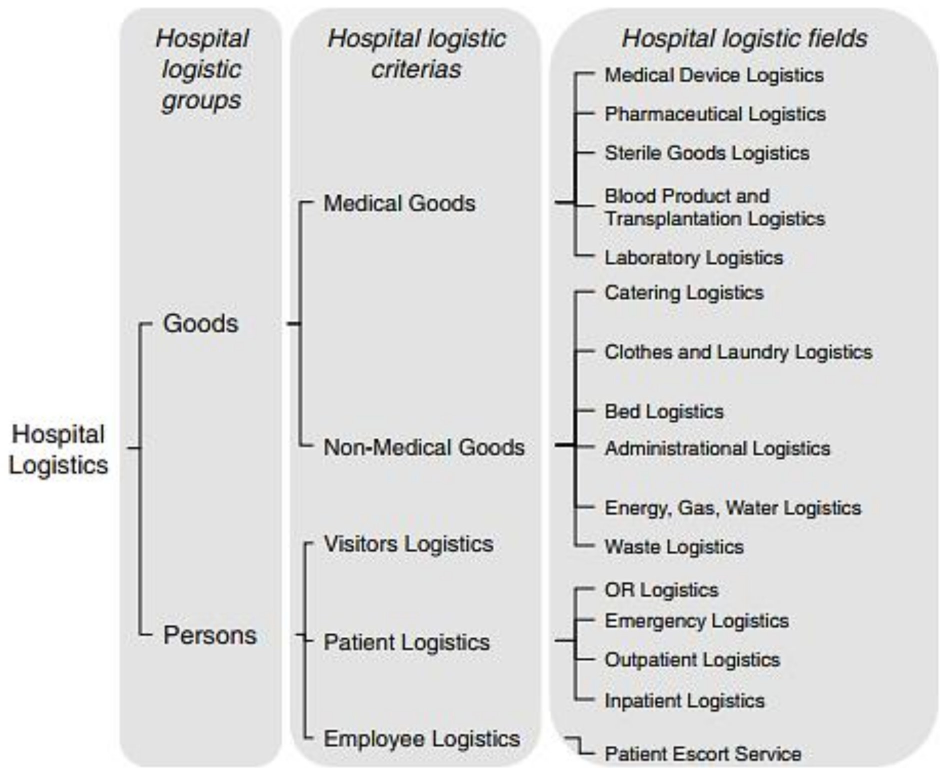

Figure 2: Characteristics of hospital logistics. Adapted from Kriegel (2012).

They explain the characteristics of hospital logistics and divide the objects (i.e. materials and persons) into different criteria and further into various logistics fields. The criteria for materials are divided into medical goods or non-medical goods. Medical goods are categorized into logistics regarding medical devices, pharmaceuticals, sterile goods, blood products and transplantation, and laboratory. Whereas the non-medical goods are categorized into logistics regarding catering, clothing and laundry, beds, administration, gas, energy, water, and waste (Kriegel, 2012; Kriegel, Jehle, Dieck, & Mallory, 2013).

Thus, a high variety of materials are often required in a hospital, which usually gives complex logistics activities where different departments are responsible for various procurement activities, e.g. food services that are responsible for the food supply, a pharmacy service that manage the procurement of pharmaceuticals, etc. (Ozkil et al., 2009; Poulin, 2003). Lapierre & Ruiz (2007) presents key decisions for a hospital supply chain, shown in Figure 3, and explain four main activities related to the supply chain (Lapierre & Ruiz, 2007). The first involves replenishment and stock control at the care units, and the second is order picking and delivery from central storage to the care unit. The third activity refers to purchasing from suppliers to central warehouse (or to care unit for direct delivery), and the last activity is material handling at central warehouse and goods arrival. They state that when planning these activities, it must be done in a way that ensures that resource availability is accounted for (Lapierre & Ruiz, 2007).

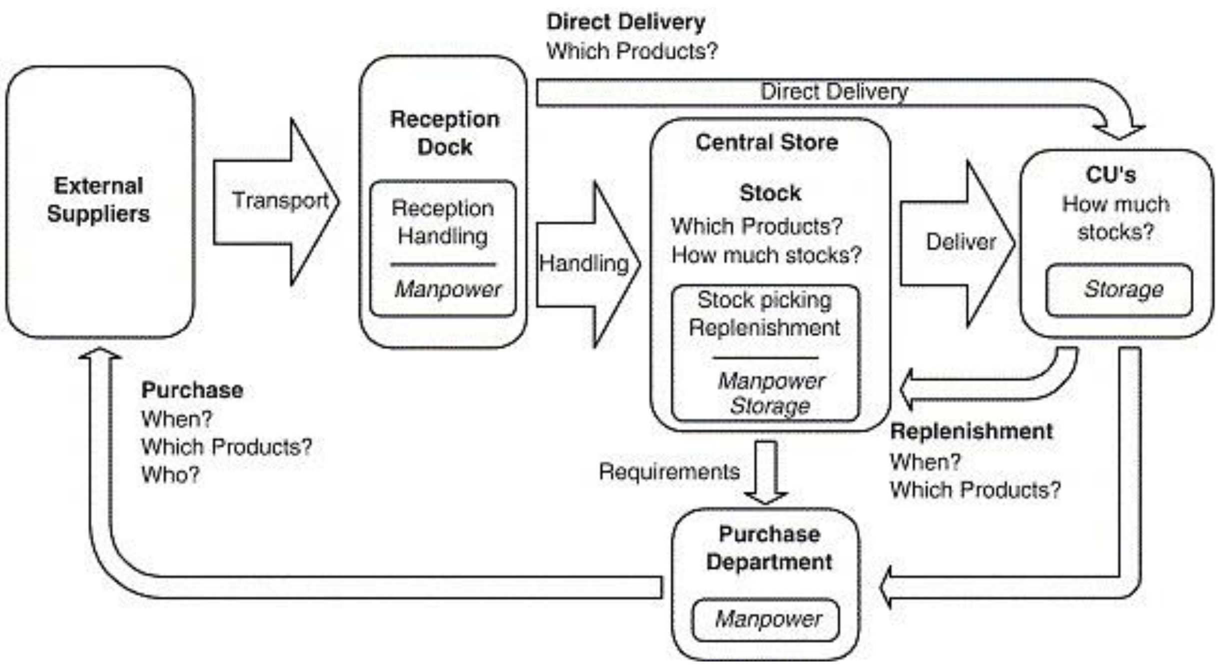

Figure 3: Key decisions for the hospital supply chain. Adapted from Lapierre and Ruiz (2007). CU = care unit.

The hospital supply chain can be viewed as a System of Systems (SoS). SoS is an essential part of systems engineering and can be defined as “a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities” (U.S. Department of Defence, 2004). In the hospital supply chain, there exists large scale behaviours performing the function of the system, but it is often difficult to extablish a central management and a consensus regarding the purpose for the system that also fits for all actors. This characteristics of an SoS can be categorised as a Virtual SoS, which is relative to Collaborative, Acknowledged, or Directed SoS where the components of the system are more tightly coupled (Kossiakoff, Sweet, Seymour, & Biemer, 2010).

3.1.1 Supply chain structure

Due to the complexity of the supply chain, there are high requirements for efficient collaboration between the different actors. Volland et al. (2017) present three alternatives for the supply chain structure. They state that the most common is delivery to a central warehouse from a supplier, and from the central warehouse to the care unit at the hospital. The othre two alternatives are called semi-direct and direct delivery, and do not utilize a central warehouse. Semi-direct delivery referred to delivery by supplier to a local storage at the hospital, and for direct delivery, the supplier react to patient demand and replenishes the goods. The last alternative is closest to the Just-in-time philosophy (Volland et al., 2017). A study by Abdulsalam et al (2015) found that 75% of SKUs in regular hospitals are stocked outside of the hospital (Abdulsalam, Gopalakrishnan, Maltz, & Schneller, 2015). A model of the use of a central warehouse as opposed to delivery from supplier is developed by Bijvank and Vis (2012) and displayed in Figure 4 (Bijvank & Vis, 2012).

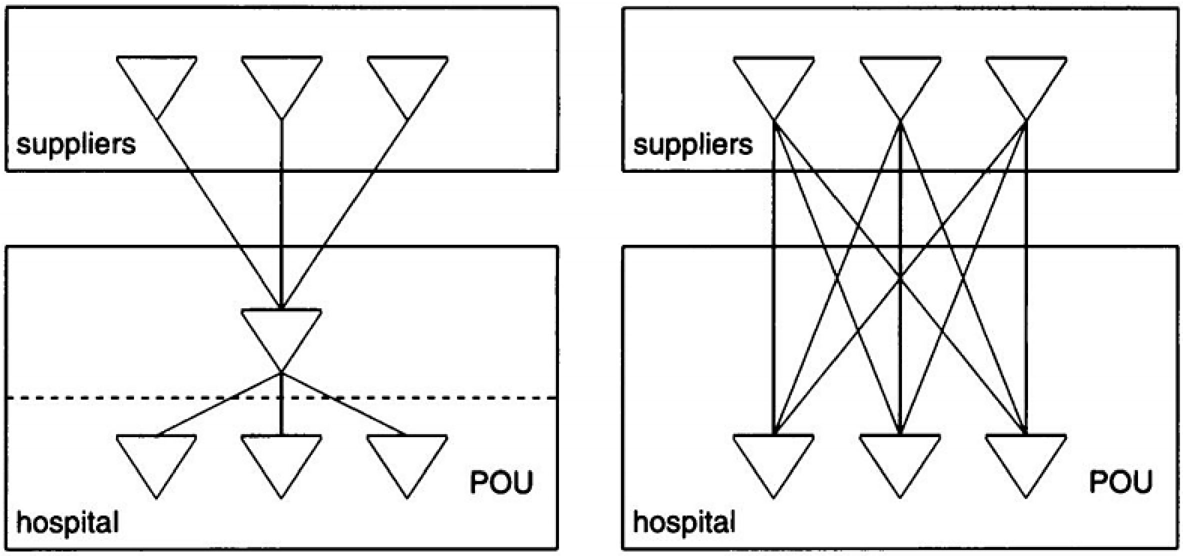

Figure 4: Supply chain structure. Adapted from Bijvank and Vis (2012).

There are advantages and disadvantages of material flow via a central warehouse as opposed to delivery from supplier. Stocking a product at the central warehouse will reduce inventory at care unit and reduce replenishment frequency, but it will also increase stock levels at central warehouse and increase the delivery time for orders. While delivery from supplier will reduce delivery time, but increase replenishment frequency. And, for semi-direct delivery, there will be increased stock levels at care unit (Lapierre & Ruiz, 2007). Thus, there are tradeoffs between in regards to inventory costs, purchasing frequency, and delivery time that must be considered. Lapierre & Ruiz (2007) state that it is important to find a good balance for each individual system and coordinate the activities (Lapierre & Ruiz, 2007).

3.1.2 Replenishment

For the replenishment of materials for hospitals, the materials criticality varies. Some materials can handle a certain lead time when there is demand, however, many of the products must be available in a sufficient quantity at all times (Chiara & Lorenzo, 2016).

Volland et al. (2016) present two replenishment policies for *when* to order. Either continuous or periodic. They also demonstrate two replenishment policies for deciding *how much* to order: either fixed order quantity, or the use of order-up-to level (Volland et al., 2017). This is displayed in Figure 5.

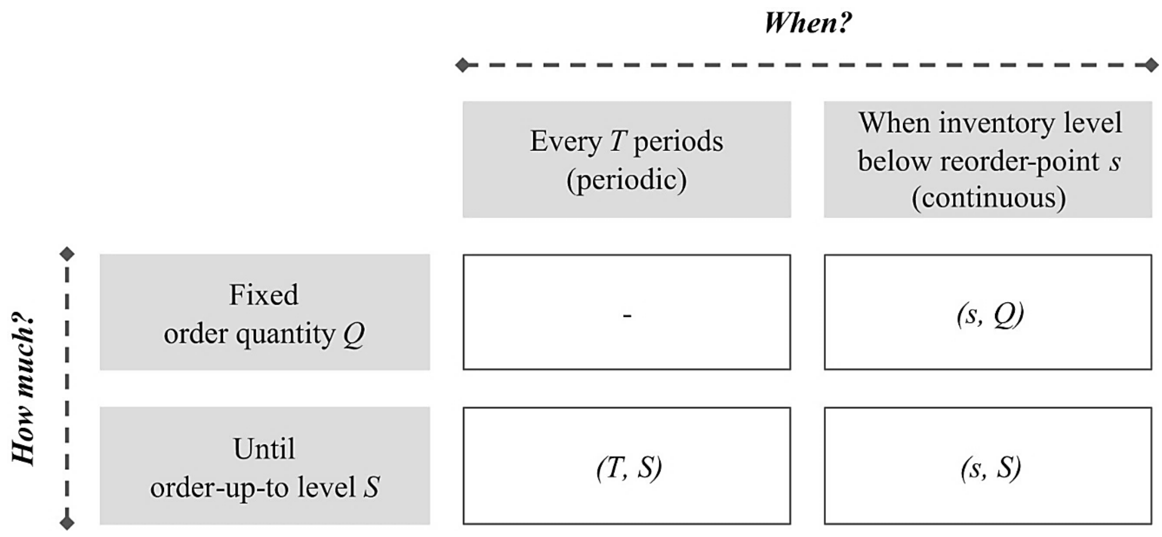

Figure 5: General inventory policies. Adapted from Volland et al. (2016).

Chiara & Lorenzo (2016) state that the order-up-to level policy combined with the periodic policy is commonly used in hospitals, where personnel will check the inventory levels for each product at regular intervals, and then order so that the stocks for each product will be replenished to a specific level (Chiara & Lorenzo, 2016) . Little & Coughlan (2008) describe this type of policy as a periodic review inventory system, where the personnel are responsible for determining the order-up-to level for each product, the order frequency for the products, and the service level that the hospital intends to provide (Little & Coughlan, 2008). Little & Coughlan (2008) note that in a hospital, the inventory space and the labor are limited, so the order frequency, the order-up-to level, and the service level must be determined based on these limitations (Little & Coughlan, 2008). For hospitals determining these factors, the authors present four stakeholders; the materials management personnel seeking cost effectiveness, the medical personnel seeking a highest possible service level, the patients also seeking a high service level individually, and the department managers seeking cost visibility. Thus, there can be tradeoffs which need to be considered in the decision making process, and there will be different scenarios depending on where the focus lies (Kriegel et al., 2013; Little & Coughlan, 2008).

There has been an increase in the use of identification technologies in recent times for the ordering of goods in the healthcare sector (Volland et al., 2017). This is elaborated on in 3.1.3 Automation.

3.1.3 Automation

Introducing automation in logistics processes in the healthcare sector is viewed as a measure for improving efficiency and productivity (Bačík et al., 2017). Granlund & Wiktorsson (2014) study the implementation of automation in internal logistics. They explain that logistics and material handling in healthcare is not conventionally associated with automation (Granlund & Wiktorsson, 2014). To examine how to successfully implement automation in internal logistics, Granlund & Wiktorsson (2014) performed a case research on internal logistics and automation in the healthcare system, and discovered that the main challenges were issues related to knowledge transfer and adoption of knowledge and technology, rather than the absence of available technology. Appropriate distribution of tasks and responsibilities was also an important issue, as well as the ability to have a comprehensive view in the planning process, and to implement strategies and technologies on the basis of long-term benefits (Granlund & Wiktorsson, 2014).

Granlund & Wiktorsson (2014) discovered a set of success factors for automation implementation. These are benchmarking, looking at other industries, involving hospital personnel, building constructors and other functions both inside and outside of the healthcare system in the decision making process, and also personnel involvement in general, as well as recognising the influence of the internal logistics function on the business performance. Other success factors were conducting comprehensive strategic studies and analysis of current state of the business, setting goals and finding clear desired structures (e.g. the extent and types of automation, and ownership decisions). The current state can be identified by measuring the performance or mapping the processes within the supply chain. It is essential to find the current state in order to find the improvement potential, which is the gap between the current state and the desired state (Granlund & Wiktorsson, 2014).

Radio frequency identification (RFID) is a common tool for materials management in the healthcare sector (Fescioglu-Unver, Choi, Sheen, & Kumara, 2015), and refers to a "technology that uses radio waves to identify objects, such as goods in supply chains" (Stevenson, 2014). I.e. the technology can use chips that are attached to objects to enable identification of these objects. RFID allows material tracking, and can increase efficiency, lead times, accuracy, and traceability, as well as reduce inventory losses (Little & Coughlan, 2008).

Research on automation for internal transportation in hospitals is discussed in 3.1.6 Material transportation in hospitals, and research on transportation by AGV specifically, is deliberated on in 3.2 Automatic guided vehicles in hospitals.

3.1.4 Outsourcing

In the healthcare system, outsourcing is seen as a measure to increase equity, quality, efficiency, and access to specific competencies, where the hospitals can take advantage of economies of scale and suppliers expertise in areas that are not defined as the hospitals own core competencies (Little & Coughlan, 2008).

There has been an increase in outsourcing in most industries in recent times, where the main goal is to obtain a competitive advantage in the market by focusing on core competencies and reducing costs (Little & Coughlan, 2008). According to Schüller et al (2008), there was an increase in outsourcing for the healthcare industry in the 1990s, followed by a reverse trend in the new millennium where more activities is performed in-house. However, this differs from the traditional approach, in that, rather than performing the activities themselves, subsidiaries were established to execute the services (Schüller & Hübner, 2008).

3.1.5 Comparisons to other industries

There are a number of similarities and differences in a hospital supply chain compared to other industries. Abdulsalam et al. (2015) highlight a major difference. That it, that there is an especially sharp trade-off between cost and quality in the healthcare sector, where the main aim is to give patient care and to save lives, often regardless of cost issues. This can in some cases give conflicting interests within the supply chain (Abdulsalam et al., 2015).

Volland et al. (2017) describe some comparisons for logistics activities in hospitals related to other industries. They note the similarities of hospital inventory management to retail inventory management, where there, in both cases are constraints in regards to storage space at point of use (Volland et al., 2017). They state that logistics activities in hospitals are similar to industrial manufacturing plants, in terms of the considerations to be made for the spare parts inventory, where there is a trade-off between cost of delivery delays and costs of safety stock (Volland et al., 2017). However, Abdulsalam et al. (2015) state the issue of product criticality, which may be particularly consequential for the healthcare supply chain compared to other industries. Some products, especially certain products for patient treatment, must always be available in case of an emergency admission, and consequences may be fatal if the patient do not instantly get the treatment. The products in general are very complex and often expensive and require specific handling. They may also change frequently with new developments, so there are few standards and performance measurements for the products (Abdulsalam et al., 2015). Also there is an especially high level of customization and individualized offerings in the healthcare sector compared to for example the manufacturing industry, even though customization is an increasing trend in most industries (Dobrzykowski, Saboori Deilami, Hong, & Kim, 2014; Rimpiläinen & Koivo, 2008). This challenges the procurement process because demand cannot easily be predicted, and the Customer Order Decoupling Point (CODP) may have to be placed further upstream which increases the delivery time (Rimpiläinen & Koivo, 2008; Stevenson, 2014).

In addition, there are a large number of actors in the hospital supply chain who may have different interests, and there also is an issue regarding degree of medical personnel involvement in the procurement process. Thus, there are complexities in the healthcare supply which may be especially challenging relative to other industries (Abdulsalam et al., 2015). Rimpiläinen & Koivo (2008) also discuss the different interests of the actors in the hospital supply chain, and state that the various levels of the supply chain traditionally operate independently. Thus, they describe the supply chain as highly fragmented, which can prevent the chain from operating as a system. They highlight the need for collaboration between the different actors within the chain (Dobrzykowski et al., 2014).

3.1.6 Material transportation in hospitals

Material handling incorporates a wide variety of systems and equipment that can be manual, semi-manual, and automatic. An important part of material handling is decisions regarding the material transportation system. There is a relatively modest amount of literature on material transportation in hospitals, and, as previously mentioned, there are few standards and common practices for this subject. A reason for this is that there is a high variety of tools and structures existing (Volland et al., 2017).

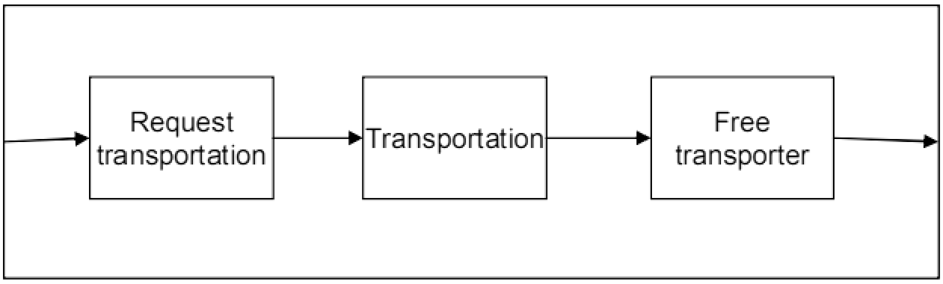

Figure 6: The transportation process. Adapted from Pimpiläinen and Koivo (2008).

Rimpiläinen and Koivo (2008) explain the transportation process in three steps, as shown in Figure 6. First there is a request for transportation, followed by the actual transportation, and finally the transporter is released to perform other assignments (Rimpiläinen & Koivo, 2008).

Various transportation tools can be utilized for internal transportation. Manual transportation is often used in hospitals, where there usually is transportation by truck or the material can be carried by hand (Ozkil et al., 2009; Rimpiläinen & Koivo, 2008). In manual transportation, the process is dependent on available human resources, in terms of material weight and volume, routes, and frequencies. Whereas the transportation can achieve increased efficiency and flexibility by acquiring automated transportation tools. This also gives hospital personnel more time to perform other tasks, such as patient related services (Ozkil et al., 2009). Thus, there are high potential benefits of introducing automation, such as increased transportation capacity, improved performance, reduced time consumption and physical strain for hospital personnel, as well as financial benefits (Granlund & Wiktorsson, 2014; Ozkil et al., 2009).

Pneumatic tube systems are one of the most common transportation systems in hospitals, where a tube connects different units of the hospital for fast transportation between two units. This system is often utilized for smaller material, e.g. pharmaceuticals, small waste, or papers (Ozkil et al., 2009). Conveyor systems are relatively common in hospitals, where conveyor belts are used for horizontal transportation between departments or vertical transportation between floors (Ozkil et al., 2009). There is also a development of autonomous robots, such as AGVs, for internal transportation in hospitals (González et al., 2017).

3.2 Automatic guided vehicles in hospitals

An Automated Guided Vehicle (AGV) system can be defined as a driverless transportation system that is used for horizontal movement of materials. The system allows for flexible material handling (Mehrabian et al., 2017; Vis, 2006). The AGVs can be used in both inside and outside environments, and the number of application areas have broadened in recent times (Bechtsis, Tsolakis, Vlachos, & Iakovou, 2017). The main application areas lie in the internal logistics, and the systems are used in container terminals, warehouses and other distribution centers, farms, healthcare units, and flexible manufacturing systems (Bechtsis, Tsolakis, Vouzas, et al., 2017; Le-Anh & De Koster, 2006; Ullrich, 2015; Vis, 2006). However, there are also special applications in areas such as facade cleaning, space travel, military equipment, and under water (Ullrich, 2015).

The main capabilities of an AGV is automated loading, transportation, and unloading (Bechtsis, Tsolakis, Vlachos, et al., 2017). An AGV is both automated and dynamic, i.e. despite being an automated vehicle it can still adapt to variations in the activities required (Bechtsis, Tsolakis, Vlachos, et al., 2017; Vis, 2006).

Some of the advantages of implementation of an AGV system as a transportation system is cost efficiency and especially savings in labor costs, reduced emissions and energy consumption, improved adaptability, and improved safety. An AGV system can achieve increased productivity and flexibility simultaneously (Bechtsis, Tsolakis, Vlachos, et al., 2017).

3.2.1 AGV transportation

Vis (2006) presents the main elements of an AGV system as the vehicles, the control system, the pickup and delivery stations, and the transportation network. The *vehicles* transport the goods, the *control system* controls 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 the production or storage and the transportation, and the *transportation network* is the routes used by the vehicles between the pickup and delivery stations (Vis, 2006).

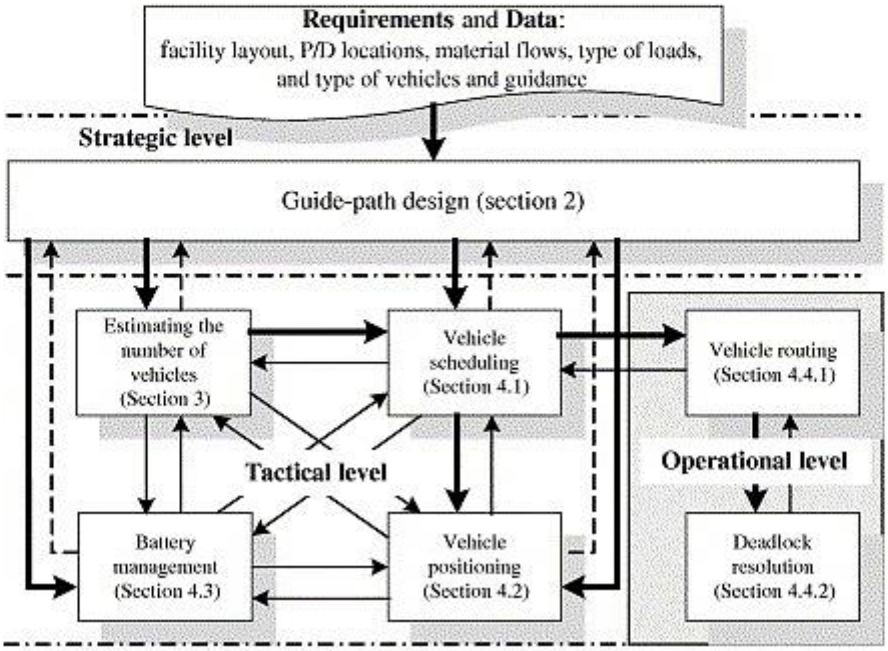

Figure 7: Framework for design and control of an AGV system. Adapted from Le-Anh and De Koster (2006).

Le-Anh and De Koster (2006) present the key issues for the design and control of an Automated Guided Vehicle (AGV) system (Le-Anh & De Koster, 2006). These are displayed in Figure 7. On a strategic level there is the guide path design, which involves establishing the different connections within the system. I.e. the pickup and delivery stations and the connecting transportation routes. On a tactical level, there are issues mostly related to the managing of the AGV systems; The vehicle scheduling must be developed, i.e. deciding when, where, and how a vehicle should perform tasks. Other issues on a tactical level are idle-vehicle positioning (to determine strategic parking areas for the vehicles when they are not performing tasks), battery management (to decide on either opportunity recharging, automatic recharging or a combination), and establishing the required number of vehicles (this can be both on a tactical and operational level). On an operational level, the issues presented are vehicle routing, and deadlock resolution and prevention. The design and control issues they present will more or less affect or be affected by each other, e.g. the guide path system will impact the number of vehicles required and the vehicle routing (Le-Anh & De Koster, 2006).

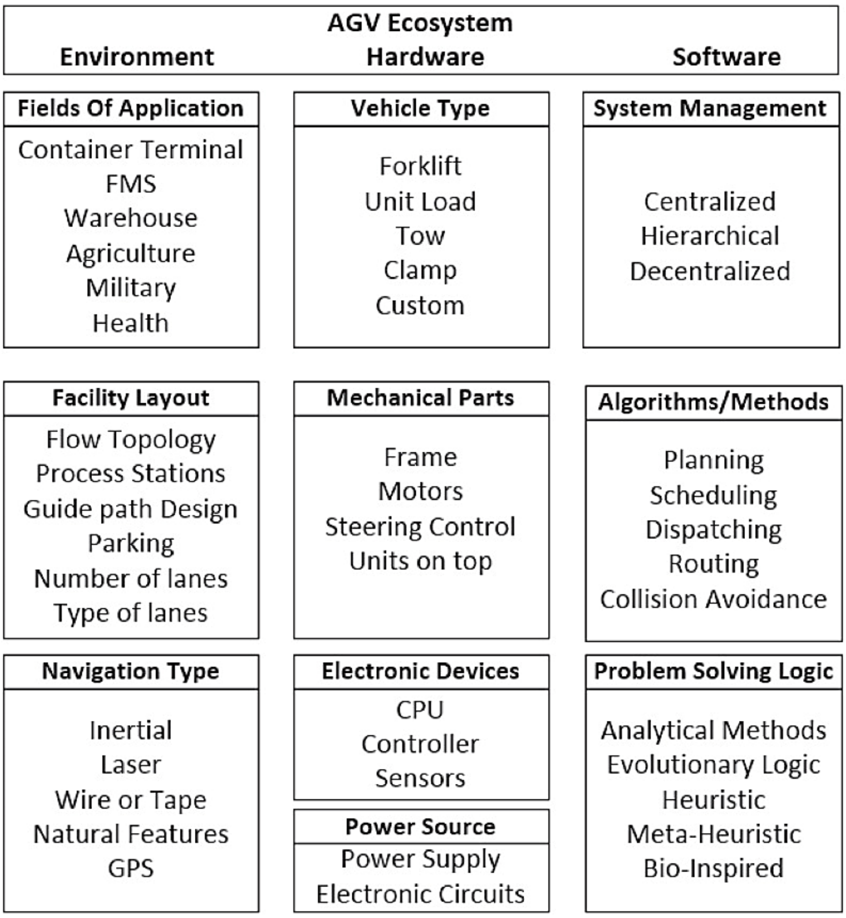

Figure 8: Framework of key focus characteristics in an AGV ecosystem. Adapted from Bechtsis et al. (2017).

Bechtsis et al. (2017) presents three hierarchical analysis levels for implementing an AGV system, which are presented in Figure 8 (Bechtsis, Tsolakis, Vouzas, et al., 2017). The first is the facility layout denoted as the environment, where decisions must be made regarding the facility and the navigation type in the context of the field of application. The second is the hardware level, where the AGV transportation should be planned by balancing requirements with hardware capacity. The third analysis level is the software level, where decisions such as scheduling and system management should be addressed (Bechtsis, Tsolakis, Vouzas, et al., 2017)

For the management of the AGV system, López-Plata et al. (2018) state the importance of synchronization between the vehicles in order to achieve appropriate resource utilization within the supply chain. They also highlight three operations that have a great influence on the overall performance of the system. These are the dispatching (where the jobs to be performed are assigned appropriate vehicles), the vehicle routing, and the vehicle scheduling (López-Plata et al., 2018).

When viewing dispatching rules and scheduling approaches, Le-Anh & De Koster (2006) found that scheduling approaches would in general outperform dispatching rules. As mentioned, they explain that vehicle scheduling “decides when, where, and how a vehicle should act to perform tasks”, and this also includes deciding what route the vehicle should take (Le-Anh & De Koster, 2006). They distinguish between offline and online scheduling, where offline scheduling is when the schedule can be determined before the operations start and is only appropriate if all tasks are known in advance. However, usually the transportation environment is fluctuating and unpredictable, and the schedule is dependent on real time information, which require online scheduling. This allows the schedule to continually be updated whenever new transportation requests arrive (Le-Anh & De Koster, 2006).

3.2.2 AGV transportation in hospitals

AGVs have been utilized for decades in the manufacturing industry, and have in since the new millennium become more popular in the healthcare industry (Ozkil et al., 2009). This is because new technologies have allowed for a transfer and adaption into the healthcare sector (Bačík et al., 2017).

Thus, in recent times, there has been a large increase in the AGV technology and the use of AGVs, also in Norwegian hospitals (Utheim, 2013). The need for distribution of a high volume of goods within the hospital, and long travel distances within the hospitals makes the AGV system a suitable transportation system (Utheim, 2013). It also frees up capacity for the personnel at the hospital in situations where manual transportation is the alternative option, which allows more time invested in other activities. A simulation conducted by Pedan et al. (2017) found that AGV transportation as opposed to manual transportation saved 24% of the medical assistants time, which instead could be used to perform patient related tasks (Pedan et al., 2017).

Ozkil et al. (2009) describe the AGV system as an alternative to the conveyor system in hospitals, in that they both can perform horizontal and vertical transportation (by the use of elevators assigned to AGVs) between different departments and floors (Ozkil et al., 2009). According to Bačík et al. (2017), the AGV system is however the most suitable solution for most contemporary hospitals compared to conveyor systems and pneumatic tube systems (Bačík et al., 2017). Compared to manual transportation, an AGV system generally carries higher fixed costs. Nevertheless, Bechtsis et al. (2017) found greater economic potential with an AGV system than conventional vehicles that must be manually operated, by maintaining lower variable costs and labor costs. An advantage with AGVs is that, apart from the time needed for recharging, they can function 24 hours of the day (Bechtsis, Tsolakis, Vlachos, et al., 2017).

Bačík et al. (2017) present four requirements for AGVs specifically in hospitals. These are, (1) there should be an option to quickly switch between automatic and manual mode, (2) the AGV should stop instantly if it is about to hit an obstacle (e.g. a person or an object), (3) there should be warning signals notifying the vehicle's surroundings of its presence, and lastly, (4) the vehicle should look esthetically pleasing (Bačík et al., 2017).

3.3 Challenges

As explained in this chapter, there are many activities related to the external and internal supply chain of a hospital. Such as supply and procurement, inventory management, distribution and scheduling, and the overall supply chain, which should be viewed in a comprehencive way in order to develop beneficial solutions and appropriately allocate responsibilities (Volland et al., 2017).

These activities related to the external and internal supply chain must be coordinated with the AGV system. For AGV systems, the complexity of the supply chain, and the high variety of different materials to be internally transported, challenges this process.

3 Case study

This chapter presents the case study conducted in this thesis. First, the case company is explained, followed by an explanation of the AGV system, and lastly an explanation of the supply chain activities.

4.1 St. Olav's University Hospital

St. Olav's University Hospital is one of five university hospitals in Norway. Most of the enterprise is situated at Øya, which is a district in Trondheim. The hospital functions as a university hospital for the inhabitants of Trøndelag, i.e. 700 000 people, and as local hospital for the inhabitants in Trondheim and the surrounding areas, i.e. 300 000 people (Nedland, 2015).

There are 60 000 patients receiving inpatient treatment per year at the hospital, and 370 000 patients receiving outpatient treatment. Out of all hospital treatments, 64% are acute, and the remaining share are planned treatments. The hospital contains 1000 hospital beds. It comprises of 8000 employees and has an annual budget of 8.2 billion NOKs (Nedland, 2015).

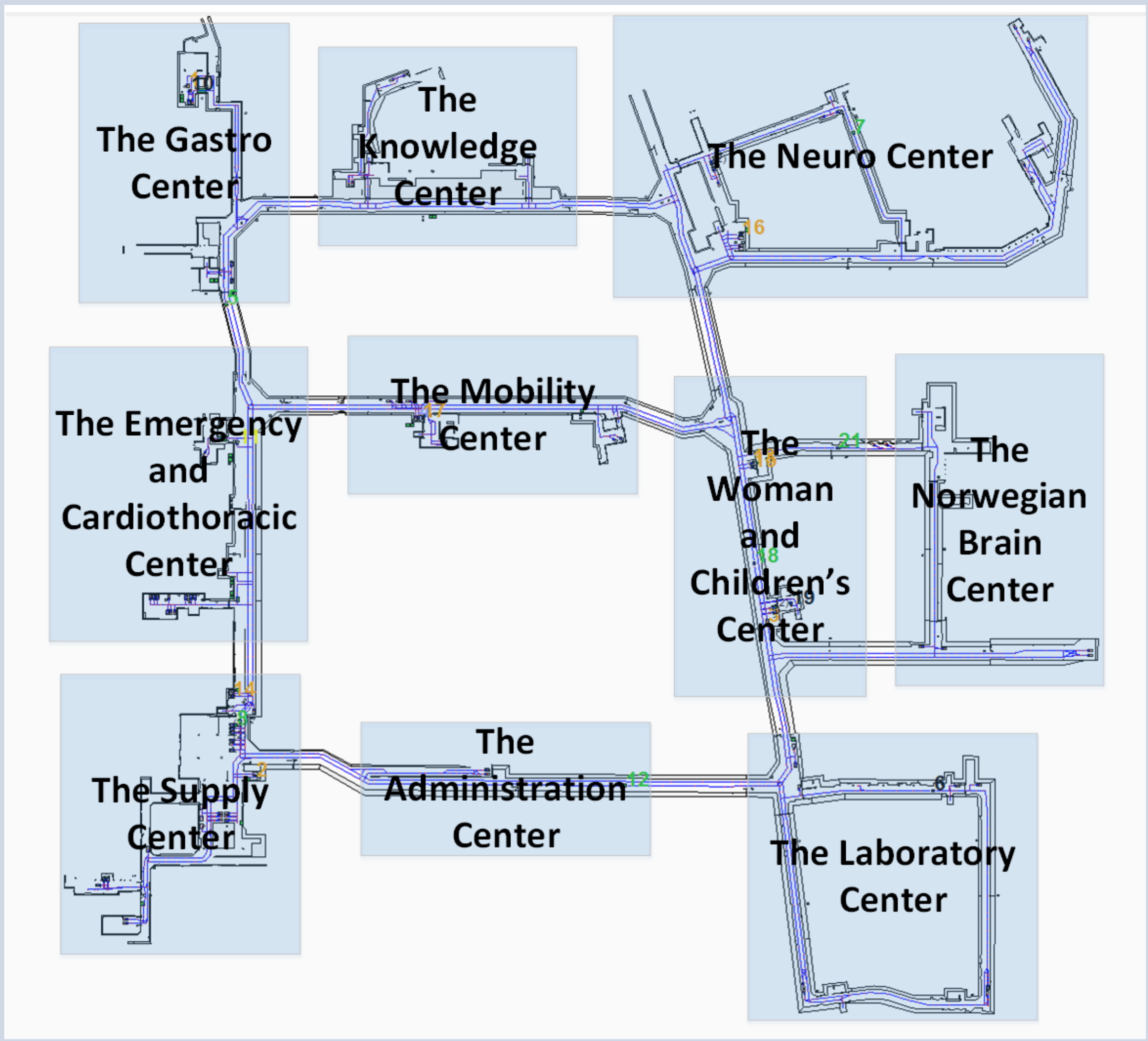

Figure 9: Layout of St. Olav's University Hospital and the AGV transportation routes.

Figure 9 displays the layout of St. Olav's Hospital located at Øya, and the routes of the AGV system. These routes are located in the basement (U1) of the hospital, which functions as a channel between the centers, where the materials delivered by AGV are transported to the destined center, and then by elevator (still by AGV) to the appropriate delivery station at the right floor. For simplification, the figure does not show the exact building layout for each center, but shows the AGV transportation route and where each center is located according to the route.

The hospital consists of six clinical centers, which are 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. There is also the Laboratory (Lab) Center, the Supply Center, the Administration (Admin) Center, and the Norwegian Brain

Center. There are AGV transportation to and from all of these centers, as shown in Figure 9. There is also a patient hotel, a PET center and a psychiatry center, but there is no AGV transportation to these locations.

The clinical centers that constitute the hospital is constructed of seven floors, and consists of several different departments, as shown in Figure 10. The first floor consists of outpatient departments, auditoriums, and cafés. The second floor consists of operation departments, radiology functions, and observation areas. The third floor is reserved for technical and university functions, and the fourth, fifth, and sixth floor contain inpatient wards. As mentioned, the basement (U1) functions as a channel between the centers for the AGV transportation, and the basement also contains technical functions, storage areas, wardrobes and cleaning functions (Nedland, 2015).

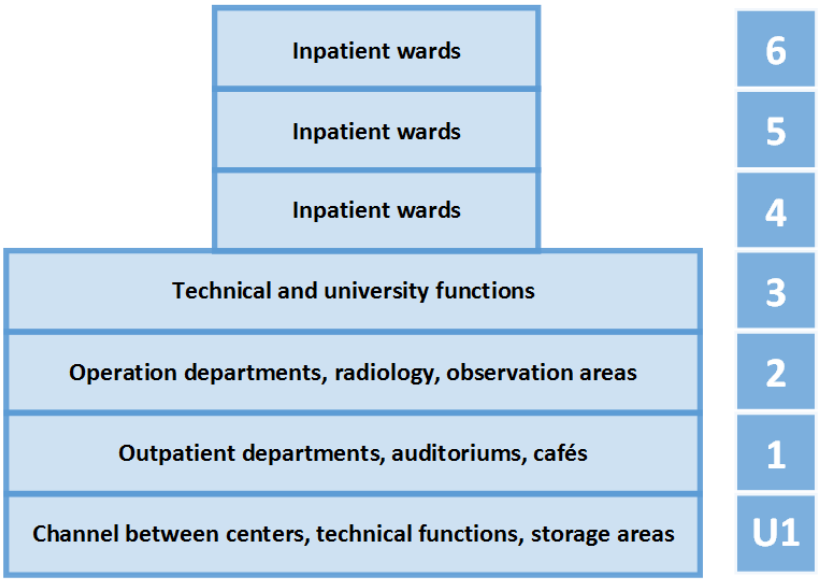

Figure 10: Hospital floors.

4.1.1 Internal supply chain

The organizational principle that was used to plan the logistics operations for the hospital said that healthcare professionals would not perform transportation and supply activities unless it was medically reasoned. Thus, the Logistics and Supply department situated at the Supply Center performs the majority of the internal logistics activities.

There are around 600 transportations conducted by AGVs per day. The six main material groups that are internally transported at the hospital are transported in different containers according to its material characteristics. This is shown in Table 2. This is because the different containers are used for different purposes and are assigned different transportation times in the AGV transportation schedule. The transportation schedule is further explained in 4.2.2.2 The AGV transportation schedule.

Table 2: Container groups and material characteristics.

Material category	Container groups	Actual container name	Material characteristics
Consumer goods	**Warehouse container**	GH_Lagervarer	Consumer goods from central WH
	Collecting container	ES_Post	Consumer goods from external suppliers
			Residual orders of consumer goods
Laundry	**Laundry container**	GR_Pasient- og personaltøy	Personnel clothing
			Fabrics
Food	**Food container**	SP_Mat	Lunch and dinner
			Groceries
			Other foods
Sterile goods	**Sterile Good container**	SP_Sterilt gods	Sterile goods
Pharmaceuticals	**Pharmacy container**	GA_Medisin	Larger medical products
Waste	**Waste container**	EM_Avfall	Larger and/or risk waste in regular volume
	High-Volume Waste container	ED_Desinfection	Large and/or risk waste in high volume

The AGV system supplies materials to most centers in the hospital, as shown in Figure 9. The vehicles also transport waste from these centers to the Waste Disposal located at the Supply Center.

Apart from the AGV transportation, four other advanced logistics systems was introduced in the development of the new St. Olav's Hospital. A waste-disposal tube system, which is a transportation system developed to transport general waste, paper, plastic and confidential papers. This was done to achieve better hygiene and a better working environment. Also, a general tube system for transportation of blood, tests, medical supply, and small sterile equipment, was implemented to achieve fast and efficient transportation of concerning items.

A system for automated supply for pharmaceuticals was implemented to achieve increased quality and patient safety regarding medical supply, as well as reduced costs by releasing capacity for nurses, and reduced inventory costs. A fabrics system with RFID was also introduced to increase the visibility in the supply of personnel clothing, and to increase the efficiency in the ordering process of these items.

Pre-projects were performed where the NPV for the AGV system, the tube systems, and the system for automated supply of pharmaceuticals was calculated. The results showed positive values for all the solutions within four to 15 years (Nedland, 2015).

4.2 The AGV system

To explain the AGV system, this section is categorized into what Vis (2006) presents as the four main components of the AGV system; the vehicle, the control system, the pickup and delivery points, and the transportation network (Vis, 2006).

4.2.1 The vehicle

The vehicles are developed by Swisslog, which is a company producing automation solutions in healthcare systems, warehouses and distribution centers. They are the suppliers of both the AGV system and the actual vehicle. St. Olav's Hospital operates with 21 AGVs.

Figure 11: An AGV at St. Olav's Hospital

4.2.1.1 Vehicle properties

An AGV weighs 250-300 kg, and can lift up to 500 kg. It has a maximum speed of 3,5 km/h. The AGVs purchased for St. Olav's Hospital cost around 1.2 mill per vehicle. Figure 11 shows an AGV at the hospital.

4.2.1.2 Movement

When a container is to be transported from a pickup station, the personnel will move the container into tracks on the floor of the pickup station, and press a button (explained further in 4.2.2.5 Transponder for containers identification) to note to the AGV system that the container is ready for pickup. When the AGV arrives at the pickup station, it parks underneath the container. Next, the flat surface on the top of the vehicle automatically rises to lift up the container. The AGV then changes direction and starts transporting the container to a specific delivery station.

At the delivery station, the AGV places the container next to the tracks on the floor of the station by driving into the station and lowering the vehicle back to its original position. The AGV then leaves the container and drives off to perform other jobs.

4.2.1.3 Sound

The AGV uses sound to inform personnel and other people of its presence. A speaker on the vehicle will say; "robot trailer on the move" ("robottrailer på vei") at certain intervals, and;

"can you move?" ("kan du flytte deg litt?"), if someone is in the vehicles path. When the AGV uses an elevator, there is a voice notifying any elevator user of taking another elevator.

4.2.2 AGV control

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

4.2.2.1 Communication

The AGV system uses radio frequency (RF) communication to control the vehicles, i.e. the vehicle communicates with RF sending and receiving devices that are attached to a suspended ceiling along the vehicle routes. The RF also allows for communication with the system controlling automatic doors, and two systems that control the elevators. This is to automatically open doors in the vehicles route, and for the vehicle to automatically utilize the allocated elevators (Nedland, 2015).

4.2.2.2 The AGV transportation schedule

The transportation schedule is a plan for controlling when each container group is permitted to be transported. I.e. it does not specify exactly what will be transported or the transportation volume, it only controls *when* each container group *can* be transported. So the AGV system does not plan for transportation jobs in advance, and it only registers a transportation job when

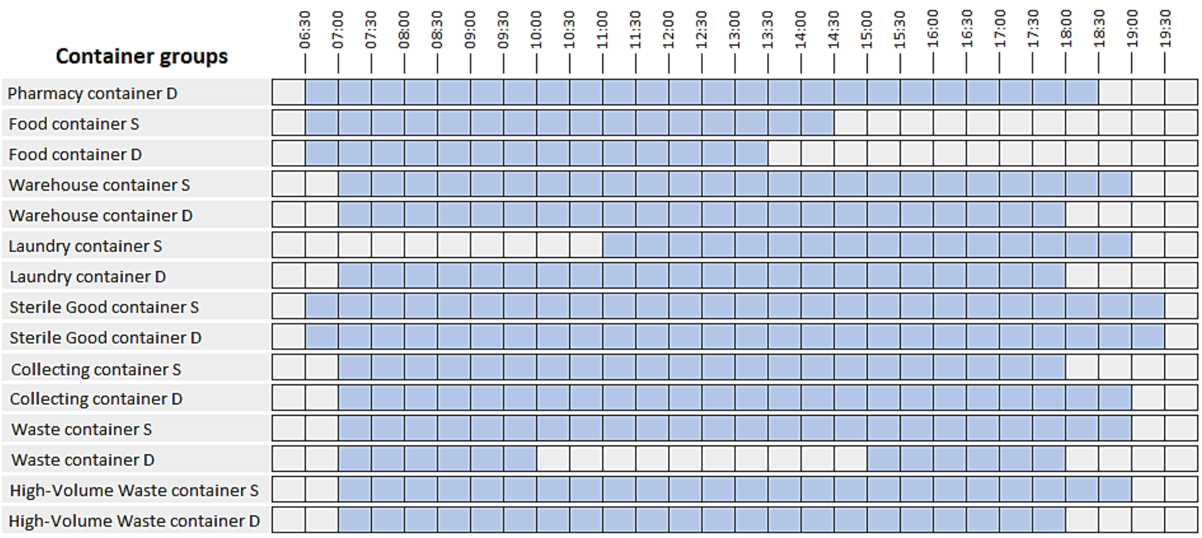

Figure 12: The AGV transportation plan, S = Supply, D = Disposal

the button on a pickup station is pressed, signalling that a container is placed there and ready to be picked up.

The schedule is operating from 06.30 to 19.30 from Monday to Friday, and it is displayed in Figure 12. Through the AGV computer system, the schedule for each of the container groups can instantly be changed by the operators at the Supply Center, however, only small changes have usually been done to the schedule.

Sykehusbygg, which are the hospital developers, simulated and developed 24-hour and 18-hour plans during the planning process. However, these plans where not directly implemented by St. Olav's Hospital.

The AGV transportation schedule distinguishes between supply and disposal. Transportation from the internal supplier to the customer is denoted as *supply*. Transportation from the customers back to the internal supplier is denoted as *disposal.* The customers are the hospital departments (or cafés for some of the Food containers) located at the various hospital centers. Table 3 displays the different AGV pickup and delivery locations for both supply and disposal according to which container is transported. Most internal transportations are supplied from the Supply Center, apart from food, sterile goods, and pharmaceuticals, which are supplied from the Supply Kitchen, the Sterile Supply, and the Hospital Pharmacy respectively. All supplies are to the various hospital centers. The disposal is always transported to the same location as the supply was transported from.

For waste, which has an opposite flow compared to the other materials, transportation *to* the hospital centers is also called supply and disposal is transportation *from* the hospital centers, same as for the other container groups.

Table 3: AGV transport destinations for supply and disposal of each container group.

Material category	Container groups	Supply		Disposal	
		From	To	From	To
Consumer goods	**Warehouse container**	Goods arrival at Supply Center	Hospital centers	Hospital centers	Goods arrival at Supply Center
	Collecting container	Goods arrival at Supply Center	Hospital centers	Hospital centers	Goods arrival at Supply Center
Laundry	**Laundry container**	Goods arrival at Supply Center	Hospital centers	Hospital centers	Goods arrival at Supply Center
Food	**Food container**	Supply Kitchen	Hospital centers	Hospital centers	Supply Kitchen
Sterile goods	**Sterile Good container**	Sterile Supply	Hospital centers	Hospital centers	Sterile Supply
Pharmaceuticals	**Pharmacy container**	Hospital Pharmacy	Hospital centers	Hospital centers	Hospital Pharmacy
Waste	**Waste container**	Waste disposal at Supply Center	Hospital centers	Hospital centers	Waste disposal at Supply Center
	High-Volume Waste container	Waste disposal at Supply Center	Hospital centers	Hospital centers	Waste disposal at Supply Center

4.2.2.3 Priority rules

The AGV system operates to a certain degree by the FCFS rule. The containers with long waiting time will have higher priority than containers with short waiting times. There is, however, a possibility of giving certain pickup stations for supply higher priority than others. In practice this enables the containers that are waiting to be transported at these stations to be picked up sooner than if there was no priority. Explained more precisely, to give certain stations higher priority than others the operators can give stations a manipulated waiting time, which is plotted into the schedule. This tells the system that a container waiting at this station will already have an apparent waiting time by the time the AGV initially starts waiting. The system will then give a higher priority to that container because it has moved higher up on the list of containers to transport since it apparently has waited for a long time.

Today this is only used for the two combined pickup- and delivery stations at the Waste Disposal. Priority is given to these stations because queues can often occur here for disposal since there are so few stations, so the emptied containers must be quickly moved from the station to enable new containers to be delivered.

In addition, there are two locations with waiting lines for AGVs. One near the Waste Disposal and one near the Supply Kitchen. At certain times when there will be many transportations from these places, the transportation schedule can program a specific number of vehicles to move to these waiting lines. The vehicles will then be ready to quickly pick up any containers placed at a pickup station at these locations.

For specific circumstances the operators in charge of the AGV system can manually plot in priority for certain containers into the computer system. This occurs only if there are calls with complaints of a late delivery or if a container is marked as in need of fast delivery.

4.2.2.4 Safety

To maintain high safety regarding the automatic transportation, Swisslog has programmed the AGVs to keep relatively long distances from each other. Especially near pickup- and delivery stations. From St. Olav's Hospital's point of view, this can be seen as too extensive in some instances because it increases the transportation time for the vehicles involved. E.g. a vehicle planning to move past a pickup station will wait if another vehicle is in the process of picking up a container from that station, before continuing the journey, even if there is space for the vehicle to pass.

4.2.2.5 Transponder for containers identification

Transponders (ID-chips) for container identification are attached to each container to trace the orders and to ensure that the right order is delivered at the right location. A picture of an attached transponder is shown in Figure 13. The transponder is either fixed to a specific container or interchangeable. The interchangeable transponders are attached to the appropriate container when the order is placed inside of the container.

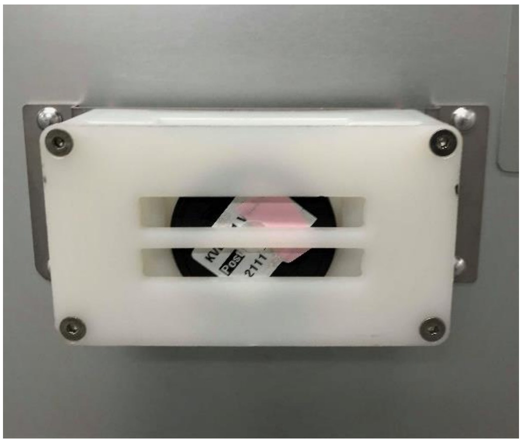

Figure 13: A transponder placed in a box on the container.

Each transponder contains information regarding the delivery location and the order type. To assign a container to an exact delivery location (delivery station) the transponder contains information regarding which center, which floor, and which part of the center (Vest, Øst, Midt, Sør, Nord) the delivery is destined for. The categorization of the order types for the transponders are identical to how the AGV transportation schedule categorizes the different types of containers, as shown in Table 2.

When a container is manually placed at a pickup station, the transponder is scanned by a transponder reader at that station. This signals to the AGV system what type of container to transport, and where the container is to be transported to.

On the return trip, the container has the same chip as for the supply trip. The container will then return to the location where it was sent from. The chips on the waste containers are permanently fixed to their container, making each container dedicated to a specific location. The ID for pharmaceuticals is not currently in use, as the supply these materials are not usually transported by AGV anymore.

Figure 14: A Warehouse container picked up by an AGV at a pickup station.

All containers have a square shape with wheels attached underneath. However, there are different variations used for different purposes. There is one type of container used for Warehouse and Collecting containers, and another for laundry. There are three different containers used for waste disposal. Also, for sterile goods there is a specific container, as well as one for food transportation. A Warehouse container is shown in Figure 14.

The utilization of each container will vary depending on the size of the order, especially for consumer goods. Thus, each order will vary in size, and *one* order is usually carried in *one* container. No quantitative data on the utilization of each container exists.

4.2.3 Pickup and delivery points

At the hospital there are AGV pickup stations, and AGV delivery stations, as well as combined pickup and delivery stations. There are also a number of calibration stations to synchronize the vehicle to its surroundings if necessary, as well as recharging stations to regularly recharge the vehicles. These different stations will be explained further.

4.2.3.1 Pickup- and delivery stations

The hospital has 114 combined pickup and delivery stations for the AGV distribution, as well as 49 single pickup stations and 46 single delivery stations.

To operate as a pickup station the station needs a transponder-reader to read the transponders that are attached to the container (explained in 4.2.2.5 Transponder for containers identification). To send a container by AGV from a pickup station, the personnel places the container on tracks on the floor of the station, 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 there is a scanner in the roof at that station. This scanner detects when a container is delivered at the delivery station. When the AGV arrives with a container it places the container beside the tracks (i.e. not on the tracks as for pickup). The scanner then detects the container and sends a notification (via phone) to an operator assigned to that station, to indicate that a container is ready to be handled.

Thus, the stations that are both for pickup and delivery consist of both a transponder-reader and a roof scanner, while single pickup stations and single delivery stations only a scanner or a transponder-reader.

4.2.3.2 Calibration points

There are calibration points at different locations in the hospital. These are used if a vehicle no longer is synchronized with its surroundings. When this occurs, the vehicle will (manually or by truck) be placed at a calibration point, which gives the vehicle its exact position and adjusts the vehicle to its environment.

4.2.3.3 Recharging stations

There are 11 recharging stations located in various places in the hospital. The vehicles have to recharge at certain intervals. The time interval before recharging can vary based on initial charging level and how much of its capacity the vehicle was using while operating (e.g. if the vehicle had breaks in between the transportation jobs the battery level may remain at a higher rate for a longer time). However, an AGV will usually need to recharge after three or four hours.

When a vehicle's battery level reaches 32%, it is programmed to start locating a recharging station. However, the vehicle first needs to finish its current job, so the time needed to arrive at a recharging station is dependent on the remaining transportation time. The AGV automatically moves to a station and starts recharging. A vehicle may be placed at a recharging station for anything from 5 minutes to several hours (at night). The recharging duration is further investigated in 5.2.2 Transportation capacity.

4.2.3.4 Parking stations

There are also parking stations in different areas of the hospital. These are utilized when a vehicle is not operating and also not recharging. The recharging stations will normally be utilized as parking stations, but when there are no available recharging stations the vehicle will park in a parking station.

4.2.4 The transportation network

As previously mentioned, the basement (U1) functions as a channel between the centers, where the material delivered by AGV are transported to the destined center in U1, and then by elevator (still by AGV) to the appropriate delivery station at the right floor. The AGV routes in U1 is shown in Figure 9.

The vehicle holds an internal map identical to the actual hospital surroundings. This map enables the vehicle to navigate. The vehicle follows routes based on nodes that are located in the floor along the transportation path. The total length of driving path within the hospital is 4,5 km (Nedland, 2015; Ullrich, 2015). The system will find the shortest path to transport a container from pickup to delivery station. The vehicles also use laser beams which scan the environment around the vehicle and let the AGV "see" its surroundings to adjust to any obstacles along the path (Nedland, 2015).

In some parts of the routes at the hospital, the AGV system has programmed the vehicles to use the elevators to turn. The vehicle will then wait for an elevator to arrive, drive into the elevator, change direction, and drive out again. There are two elevator areas in U1 where this can occur. The extent of the consequences of this issue is uncertain, but it will increase the transportation time and it obviously takes up capacity for the elevators.

4.3 Supply chain activities

As mentioned, the internally transported in at St. Olav's Hospital can be categorized into six main groups, which are consumer goods, laundry, food, sterile goods, pharmaceuticals, and waste. The categorizations are made based on literature on materials in hospital logistics (Kriegel et al., 2013). These material groups can again be divided into subgroups, which is shown in Table 4. Consumer goods are regular orders of consumer goods from the Central Warehouse, consumer goods from external suppliers, and residual and emergency orders.

Laundry are grouped into personnel clothing and fabrics. Food are lunch and dinner, groceries, and other foods, and sterile goods are reusable equipment that must be sterilized after they use. Pharmaceuticals are classified into single-dose medical products, and larger medical and pharmaceutical products. The last material type is waste, where we distinguish between small and non-risk waste, and larger and/or risk waste. The larger and/or risk waste can either be of regular or high volume.

For internal transportation, other transportation tools apart from AGV transportation are also utilized. So, in addition to AGV transportation, there is manual transportation, a general tube-system, and a waste tube-system. The other transportation tools will also be presented in the case study. This is done to get a better understanding of the supply chain and the overall internal transportation, and to understand the AGV transportation in the context of the entire supply chain.

The materials and the respective transportation tools are presented in Table 4. Thus, contrasting to Table 2, this table also includes the other transportation tools used for internal transportation, but does not distinguish between the different container groups for the AGV transportation. This is because a specific material type transported by AGV can also be transported by another transportation tool, and will then not necessarily only be carried in a container.

Table 4: Material characteristics and transportation methods.

Material category	Material characteristics	AGV	Manual	General tube system	Waste tube system
Consumer goods	Consumer goods from central WH	X	When need for faster delivery due to high AGV utilization		
	Consumer goods from external suppliers	X			
	Residual and emergency orders of consumer goods	X			
Laundry	Personnel clothing	X	For transport to sterile supply, and when high AGV utilization (ca. 50% of the transports)		
	Fabrics	X	Transport to sterile supply		
Food	Lunch and dinner	X			
	Groceries	X			
	Other foods	X	For catering		
Sterile goods	Sterile goods	X	On Saturday and Sunday	Occasionally for small goods	
Pharmaceuticals	Single-dose medical products			X	
	Larger medical products	Occasionally for disposal	X		
Waste	Small and non-risk waste				X
	Larger and/or risk waste in regular volume	X	On Saturday and Sunday		
	Large and/or risk waste in high volume	X	On Saturday and Sunday		
X = usual/intended transportation system Manual transportation is also required when defectives occur in the other transportation systems.					

Each of the materials that are internally transported and the activities related to the supply of these materials are further explained in the next sections. For the materials that are transported by AGV, flow charts are used to show the supply of these materials, to visualize the AGV transportation in the context of the entire supply process.

4.3.1 Consumer goods

Consumer goods are all the different goods required in the hospital that are not reusable and usually need to be replenished regularly.

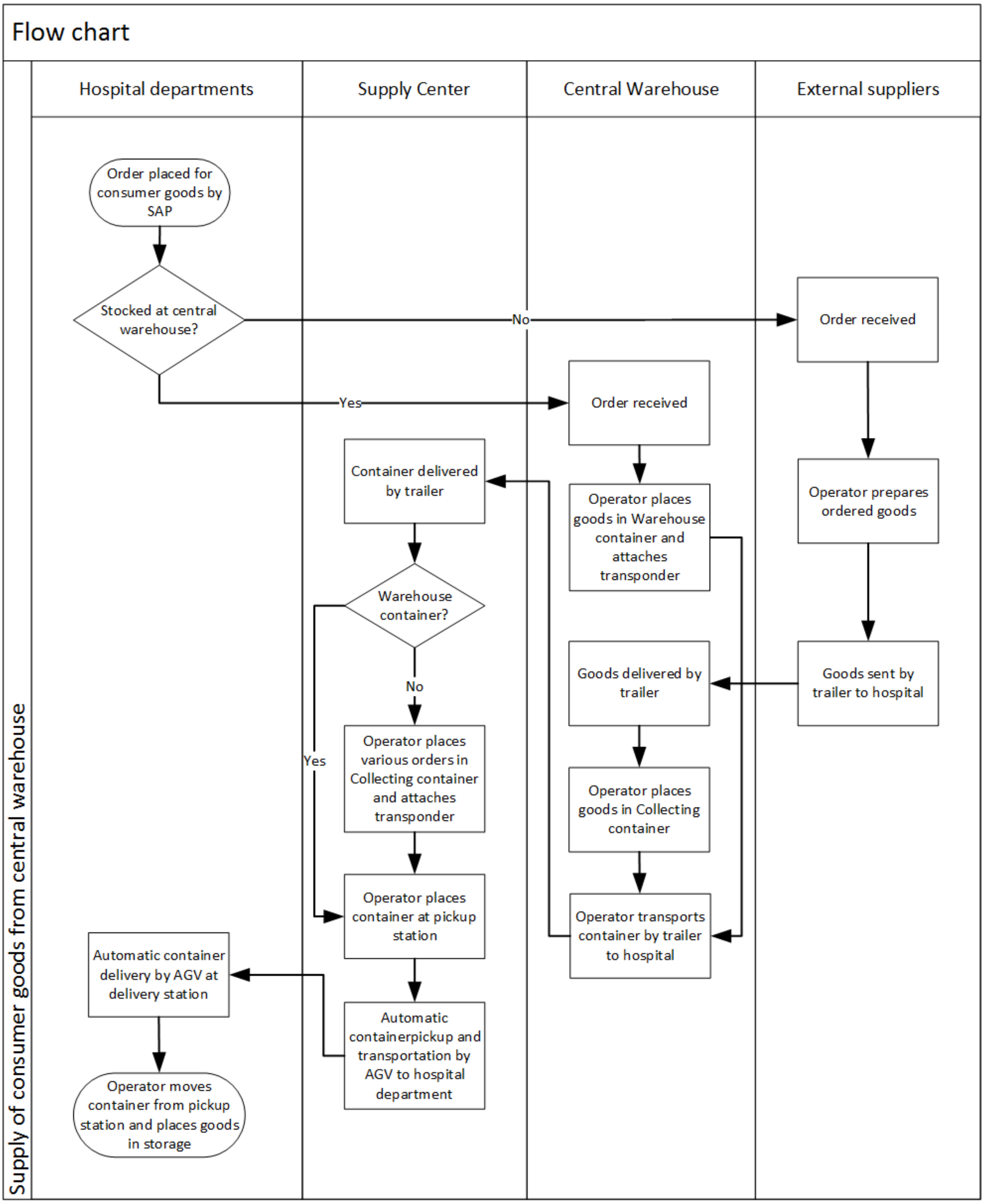

Figure 15: Flow chart of the supply of consumer goods.

Consumer goods are either ordered from the hospital's Central Warehouse at Heimdal, or from external suppliers if they are not stocked at the Central Warehouse. The supply of consumer goods is shown in Figure 15. These goods are ordered by personnel from Active Supply, who are a part of the Supply Center. Orders for consumer goods are sent Monday to Friday, and the various departments place orders from once per week to five times per week depending on necessity for replenishment and according to individual ordering plans. Thus, they use a periodic review and order-up-to level (T,S) ordering policy, also described as the periodic review inventory system.

Active Supply use SAP as an ordering system. The personnel at Active Supply check the different cabinets at the departments and order the goods that need to be replenished by scanning a barcode at the drawer or shelf of that product. The orders are then sent to the hospitals Central Warehouse in Heimdal, or to external suppliers.

4.3.1.1 Consumer goods from the Central Warehouse

The Central Warehouse stocks all the regularly used consumer goods. There are a total of 3000 SKUs at the Central Warehouse. Out of these, St. Olav's Hospital have calculated that 129 articles account for 50 % of the order volume, and 515 articles out of the 3000 articles account for 80 % of the order volume. Thus, essentially around 2400 articles account for only 20% of the orders. There are various degrees of criticality for the stock-keeping units (SKUs) at the Central Warehouse, and some articles are highly critical and must be available at the warehouse at all times in case there is an unexpected and immediate demand.

Each SKU can either be ordered in units or in packs. The number of products in one pack will vary. So the personnel has to specify how many of each product to order. In the SAP system it is often not specified whether an order quantity is in units or in packs, thus, it is uncertain whether a unit on the ordering sheet is for one single product or one pack with several products. Today this is something the personnel must learn, so that they know the case for each SKU.

When an order is received, the warehouse packs all the goods for that individual order in a Warehouse container, attaches a transponder to the container, and transports the container to the goods arrival at the Supply Center by trailer. Each trailer can transport 18-19 containers at a time. The shipping from the warehouse is based on transportation plans, which state when each order is to be delivered at the Supply Center. The delivery time is specified for each order in the replenishment plan and is usually 1-4 days.

The warehouse operates Monday to Friday, sending the first delivery at 08.00 and the last delivery around 14.00 with a 20-minute transportation time. The Supply Center operates Monday to Friday from 06.30 to 19.30. Thus, there are no deliveries of consumer goods in the evenings, at night or on the weekends. The replenishment plan states four trailer deliveries from the warehouse per day (08.20, 10.20, 12.20 and 14.20), however today there can be anything from 4 to 8 deliveries each day.

When the consumer goods arrive at the Supply Center, the containers are manually transported out of the trailers to the goods arrival. They are then manually placed onto combined pickup- and delivery stations for AGV transportation whenever there are available stations. There is a total of 12 stations at the Supply Center, however, at least one station is always kept open so that there is a place for any vehicles returning with a disposal container from the departments. The operator places the container onto a pickup- and delivery station and presses a button on that station indicating that there is a container there ready to be picked up by an AGV and transferred to the right location. The AGV system will then automatically assign a vehicle to that job whenever a vehicle is available.

When a container is transported to a customer and arrives at a delivery station, it needs to be manually transported from that station. The personnel responsible for ordering the consumer goods (Active Supply) at a specific department are also responsible for handling the order upon arrival. These personnel have a shift from 07.00 to 14.30, i.e. the materials must be handled within this time. The goods are usually stored in cabinets that are located in various rooms and in the hallways of each department. Thus, the personnel move the container from the delivery station and places the ordered goods into the appropriate cabinets.

They then move the emptied container back to the pickup station, and press a green button notifying the AGV system that the container is ready for pickup. Thus, when an vehicle is available, it will automatically pick up the container and transport it back to the goods arrival at the Supply Center.

At the Supply Center, the vehicle automatically drops off the container at a delivery station. The personnel will then manually move the container from the station to an emptied trailer. This trailer will transport the emptied containers back to the Central Warehouse, where they will be refilled with new orders.

4.3.1.2 Consumer goods from external suppliers

Regularly, there are goods to be ordered that are not stored in the Central Warehouse. In these cases, these goods are ordered simultaneously as the other consumer goods and in the same way, using the SAP system. However, the goods from external suppliers first get sent to the department manager for control before the supplier of that specific order receives it. This is done to ensure that no mistakes occur, especially because the goods ordered directly from an external supplier often are expensive, and there may be a cheaper equivalent already stored at the Central Warehouse.

For orders from external supplier, a red sticker is placed on the drawer or shelf of that item. This is to indicate that an order is placed for these items, making sure that orders are not placed multiple times even though delivery times may be longer than from one ordering day to the next. The delivery time for these orders will vary, but it will usually be between 3 and 14 days.

In each department there are also cards with replenishment needs, where different materials that are to be replenished will be noted. The healthcare personnel from that department places a card naming a specific item in a box if they want to replenish that item. The personnel ordering from Active Supply will then order that item when it is time to place a new order.

The supplier sends the ordered consumer goods to the central warehouse, which operates as a cross-dock for these orders and places them in a Collecting container. The goods are then transported by trailer (with the rest of the orders from the Central Warehouse) to the Supply Center, where all the goods that have the same delivery location are placed in the same Collecting container. A transponder is also attached to that container to inform about the contents and destination. These containers are then placed on a pickup station (use same pickup stations as the other containers from the Central Warehouse) to be transported to the right hospital center.

When the Collecting containers arrive at delivery station, personnel from Active Supply are responsible for handling the goods. The same personnel are also responsible for handling the other goods that arrive at the departments by AGV (apart from the consumer goods ordered from the warehouse which are the responsibility of the personnel from Active Supply who order the consumer goods, as previously mentioned), i.e. laundry, sterile goods, food, emptied waste containers, and the Collecting containers.

When a container is emptied, it is transported back to the supply center, just as for the other containers arriving from the Central Warehouse. A few containers will always be stored at the Supply Center to facilitate goods arriving without a container, while other containers are transported back to the Central Warehouse.

4.3.1.3 Residual orders of consumer goods

It is also possible with residual or emergency orders in between the predetermined ordering times. These materials, which are sent from the Central Warehouse, will also be delivered in Collecting containers. These containers can be challenging to handle due to the high variety in orders placed in these containers, i.e. consumer goods from external suppliers, and residual or emergency orders.

4.3.2 Laundry

Laundry is categorized into personnel clothing and fabrics. The supply of these materials are presented in Figure 16. These materials are reusable and are regularly cleaned at a Laundry, which is part of St. Olav's Hospital and situated at Heimdal. There are transportations of laundry from Heimdal to the hospital usually two times per day on weekdays, in the time interval between 11.00 to 16.00. An extra delivery can also occur on days where there are many orders. The laundry is transported to the hospital by trailer, and each trailer can carry a maximum of 45 containers for one transportation.

All transportations of laundry, apart from laundry for the Sterile Supply, are carried in Laundry containers.

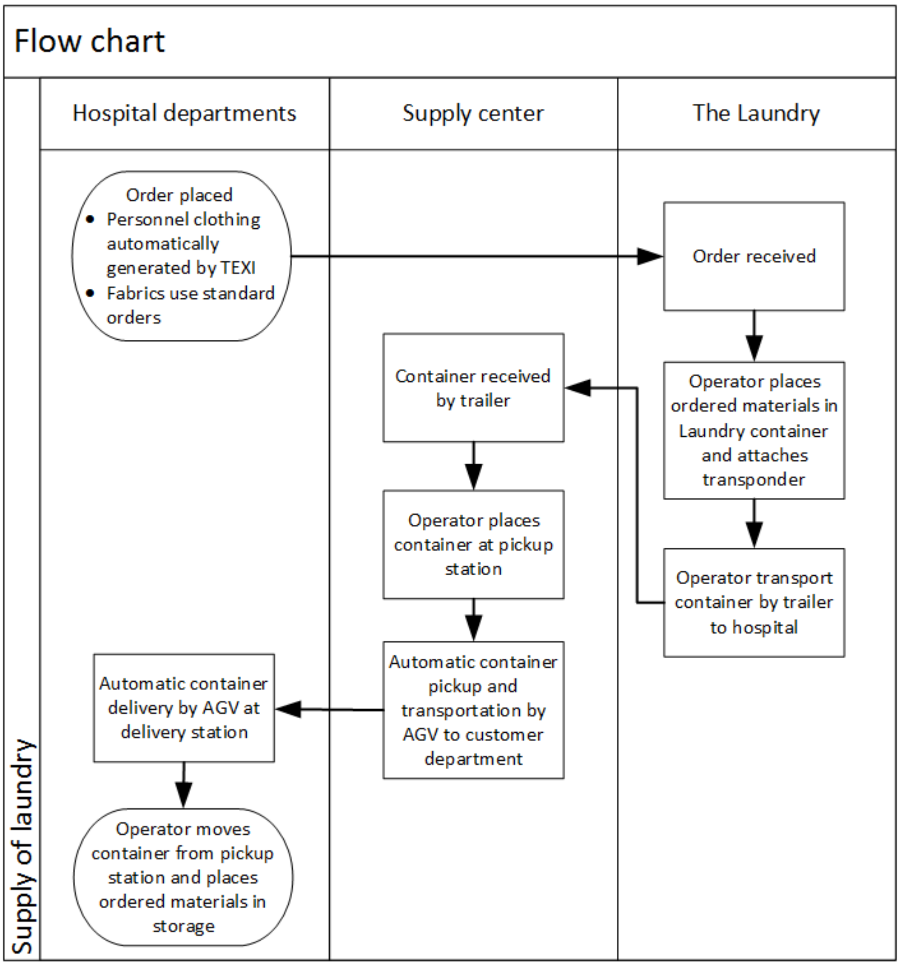

Figure 16: Flow chart of supply of laundry.

4.3.2.1 Personnel clothing

The ordering of these clothes can be controlled by the Supply Center. They use an ordering system called TEXI, which automatically places orders based on predetermined stocking levels. An RFID is attached to each clothing item, and there are antennas in the clothing cabinets at the hospital that read the RFIDs. This enables the system to always retain control of the clothing quantity stored in each cabinet. When the personnel take working clothes from a cabinet to use for their shift, they register the extraction by using their ID-cards. This allows visibility of the remaining clothing quantity, and sends the charge for the extracted clothes to the department where the personnel is situated.

The personnel at the Supply Center can decide what percent the stock levels in each of the cabinets at each department need to fall below before a new order should be placed. Thus, at 23.00 each night the system automatically checks the stock levels to identify which cabinets that have fallen under the allocated percentage and that need to be replenished, and generates an order for these. I.e. they use a continuous and fixed order quantity (s,Q) ordering policy. The next day after the orders have arrived at the Laundry, the materials for that order is placed in a Laundry container and a transponder is attached to that container indicating a specific destination.

The orders are then transported by trailer to the Supply Center, where the trailer is manually unloaded and the containers are placed on AGV pickup stations when one is available. This process is exactly the same as for the consumer goods.

The containers get transported to a delivery station at the appropriate department, and is then manually handled by personnel from Active Supply who put the clean laundry in the right cabinets.

At the end of a working day, the personnel throw the dirty laundry into a shaft that is connected to a Laundry container. When that container is filled up, personnel from Active Supply places the container at a pickup station, and the laundry is transported by AGV to the Supply Center and further by trailer to the Laundry.

4.3.2.2 Fabrics

Fabrics can be described as all fabrics from the laundry service apart from personnel clothing. For these materials, there are permanent orders that regularly get generated to the Laundry. However, these can be manually changed if there is a need for increased or decreased levels of the established order. This is done either via e-mail or by phone. Thus, the ordering policy use a periodic review, and a mix of fixed order quantity and a manual change of the order quantity.

Based on the orders, the materials are placed in Laundry containers and a transponder is attached. When the containers are sent from the Laundry to the hospital departments, they follow the same processes as for the personnel clothing.

For the return of dirty laundry, the fabrics are placed back into the Laundry containers, and transported back to the Laundry by AGV and then by trailer, just as for personnel clothing.

4.3.3 Food

The internal suppliers of foods at St. Olav's Hospital is called Food & Café ("Mat & café"), and consists of a main Supply Kitchen, five center kitchens, seven cafés, and hospital departments serving food. They supply food and meals for the entire day, to patients, visitors, hospital personnel and students at the hospital.

The Supply Kitchen situated in the basement (U1) of the E&C Center. The Supply Kitchen daily supply food to the five center kitchens in the hospital (located in five of the clinical centers; E&C, Gastro, Mobility, W&C, and Neuro Center), the seven cafés (at E&C, Gastro, Mobility, Knowledge, W&C, Neuro, and Lab Center), 90 hospital bed departments at the clinical centers, and around 900 smaller departments such as outpatient clinics and offices. The Supply Kitchen also supply food for catering. A model of the food supply is displayed in 9.3 Food in the Appendix.

The Supply Kithen follow a replenishment plan which is displayed in 9.3 Food in the Appendix. In terms of order frequency, there is daily delivery from Monday to Friday to each of the center kitchens and cafés. For the departments, between 50 and 60 of the hospital bed departments order daily, and for the 900 smaller departments there is high variety in regards to ordering frequency and ordering volume, from e few times per year to several times a week. The ordering policy is the periodic review inventory system, where the order quantity will be decided by each of the customers.

The food groups supplied by the Supply Kitchen are lunch and dinner, groceries, and a few other foods. For the ordering process, the Supply Kitchen and their customers use an inventory management system called Nutshell. The orders are then electronically transferred to the Supply Kitchen. The customers that do not have access to Nutshell contact the customer center, where the order is placed into that system. A four-week menu containing alternatives for lunch, dinner, desserts, fruits and coffee food is sent to the customers. In total, there are over 3000 recipes on the four-week menu, and the customers place their orders based on this menu.

The Supply Kitchen is operating from 07:00 to 15:00 from Monday to Friday. The five center kitchens are operating 365 days a year, to serve the patients receiving inpatient treatment. There are also two cafés in the hospital that operate every day, from 07:00 to 18:00. The remainder of the food services are not operating, i.e. closed for serving food, in the evenings and on the weekends.

The tasks performed at the Supply Center involve ordering and handling of goods from external supplier, as well as preparing prefabricated food for lunch and dinner, making desserts, baking bread, and a few other tasks. The goal of the Food & café service is to supply food as close as possible to the customers to achieve high quality and efficiency, and the tasks are distributed between the different actors with the aim to achieve this. E.g. the finalizing of warm food is done at the center kitchens because this is closer to the customer and ensures that the food stays warm, while for example caramel pudding destined for all center kitchens is made at the Supply Kitchen instead of all center kitchens having to make one each because this ensures efficiency.

All food supplied from the Supply Kitchen are carried in Food containers and transported by AGVs. There are 6 pickup stations and 4 delivery stations at the Supply Kitchen, and these stations are shared with the Sterile Supply.

The explanation of supply of lunch and dinner and the supply of groceries each have their own flow charts because the information and material flows are very different for each of the goods.

4.3.3.1 Lunch and dinner

Lunch and dinner is ordered from hospital departments. The supply of these materials is presented in Figure 17. The departments send their order to the belonging center kitchens, which further sends lunch and dinner orders to the Supply Kitchen. The orders are delivered at the same day as the order is sent.

Lunch is ordered based on the number of patients receiving inpatient care, i.e. the ordering system will generate an order based on this. The departments can make any adjustments to the orders to the center kitchen before 09.00. The center kitchen must then place their order before 09.15 to the Supply Kitchen. The orders for dinner are similar to lunch, but the orders from the departments must be sent to the center kitchen before 11.00. For dinner there are usually two alternatives to order, so the personnel at the departments need to ask each patient which alternative they want before generating the order. If no alternative is chosen the ordering system will automatically order the first alternative. The orders from the center kitchen must be sent to the supply kitchen before 11.15. As previously mentioned, the orders are sent to the Supply Kitchen via Nutshell.

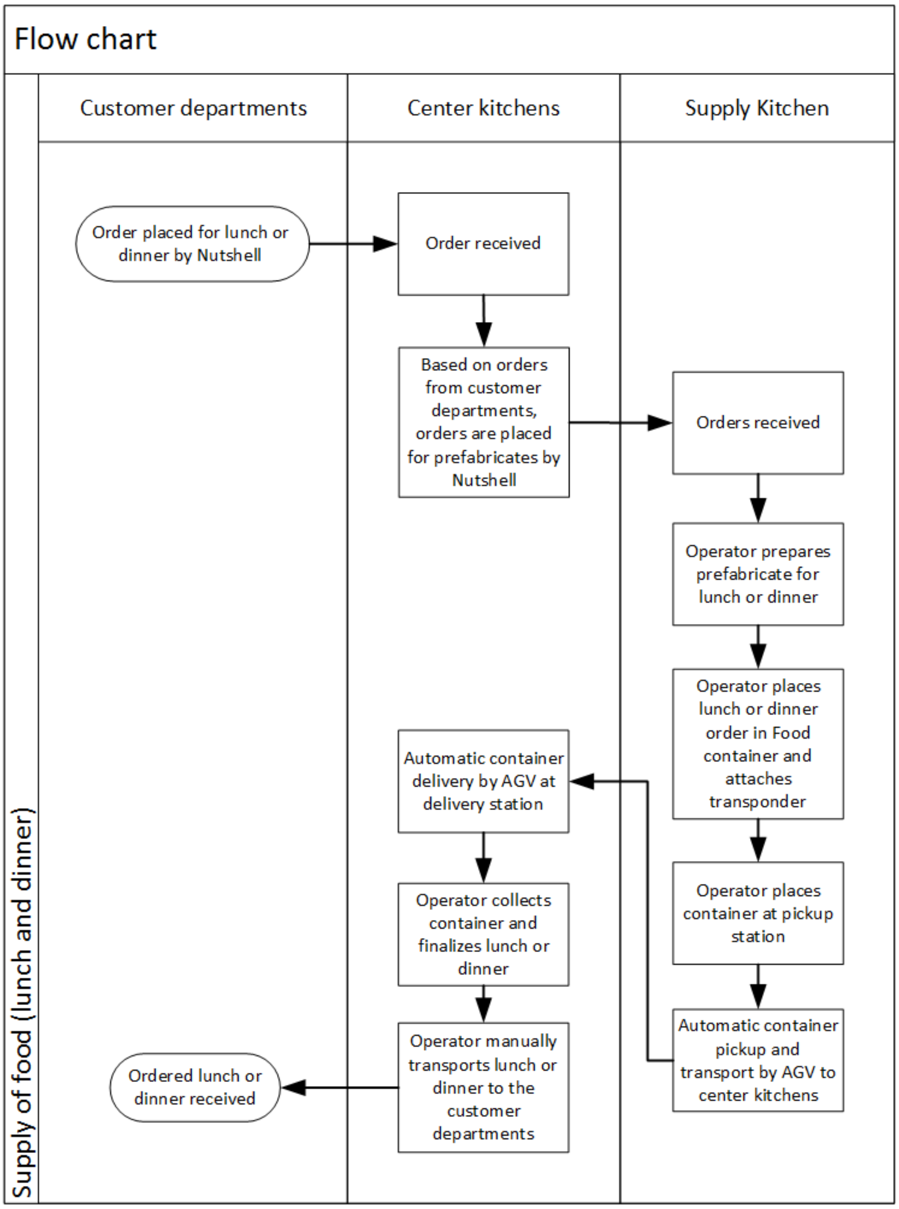

Figure 17: Flow chart for the supply of lunch and dinner.

For lunch and dinner, the personnel at the Supply Kitchen weigh and allocate food from external suppliers, and prepare prefabricated food based on the orders, which further is stocked in containers for AGV transportation. This food is then transported by AGV to the center kitchens. The lunch must be transported from the Supply Kitchen by 10.15, and the dinner must be transported by 12.45. Thus, the delivery time for lunch and dinner from the Supply Kitchen to the center kitchens are usually only a couple of hours.

Close to the Supply Kitchen there are AGV stations operating as a waiting line. At the times when order deliveries are expected, the AGV transportation schedule directs a predetermined number of AGVs to move to these stations. The AGVs placed at these stations will then pick up Food containers whenever a container is placed at a pickup station at the Supply Kitchen.

When the containers arrive at the center kitchens they will be emptied and transported back by AGV. At the center kitchens, the food is finalized and manually distributed to the departments. The actual lunch and dinner times at the hospital are at 12.00 and 16.00 respectively.

4.3.3.2 Groceries

Groceries are ordered from the departments and the cafés. The supply of these materials is presented in Figure 18. They send their orders to the storage unit at the Supply Kitchen. These orders must be placed before 11:30 on the day before delivery. Nutshell is also used for the ordering of these goods.

The groceries arrive at the goods arrival at the supply kitchen from external suppliers, and is then allocated based on the orders. The groceries are placed in containers, and transported by AGV to delivery stations near the departments or the cafés that have sent the orders. The groceries are distributed to the departments in the morning (07.15-07.45), and to the cafés in the afternoon (12.45-13.30).

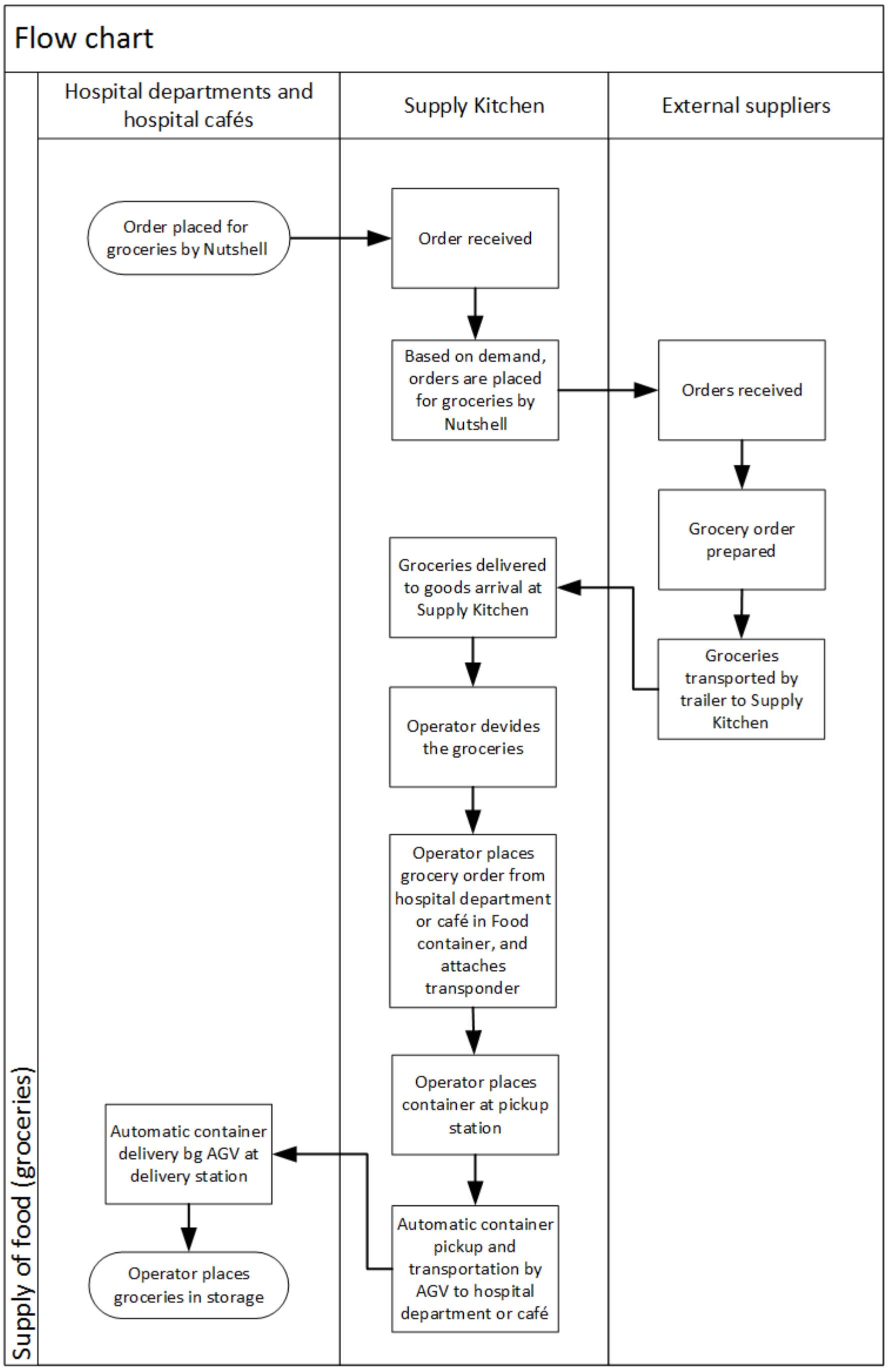

Figure 18: Flow chart of supply of groceries.

4.3.3.3 Other foods

Some other foods are also supplied from the Supply Kitchen. Such as fresh baked goods, which is distributed from the Supply Kitchen to the cafés in the mornings (07.15-07.45). These goods are also carried in a Food container and transported by AGV directly from the Supply Center to the cafés.

Catering and food for meetings are also supplied by the Supply Center. There are high variations in the demand for catering, where e.g. there are ten orders one day and zero orders the next day. These orders are sent to the catering department, and are transported manually.

4.3.3.4 Food and products from external suppliers

Personnel clothing and fabrics are supplied to the Supply Kitchen from the Laundry. The goods are transported by trailer from the laundry service to the Supply Center, and are usually manually transported from there to the kitchen.

All other materials to the Supply Kitchen are supplied externally. An employee at the procurement department is responsible for generating orders to external suppliers. Because the internal orders to the Supply Kitchen arrives the same day as the delivery, the kitchen must procure the materials from external supplier before they know what their customers will order.

All the orders from external suppliers are sent to the goods arrival at the Supply Kitchen.

4.3.4 Sterile goods

St. Olav's Hospital has an internal Sterile Supply department that are responsible for all supply of sterile goods to the departments at the hospital.

4.3.4.1 Sterile goods

Sterile goods are reusable equipment used in operations performed at the hospital. The supply of these materials is displayed in Figure 19. The sterile goods are mainly for the operation departments, as well as intensive care and the radiology departments. These departments send their orders to the Sterile Supply. The departments use a tracking system called T-DOC to track the stock levels at the local sterile inventory, which exists in these departments. Based on this they send the orders by e-mail to the Sterile Supply the evening before the delivery. Thus, the ordering policy is the periodic review inventory system.

The Sterile Supply follow a replenishment plan that shows when the goods destined for each department should be sent, just as for the other internal suppliers. Thus, the orders they receive show *what* goods should be prepared for each department, and the replenishment plan shows *when* the orders for each department should be prepared and sent. They follow the same replenishment plan every week, but each day of the week can be different.

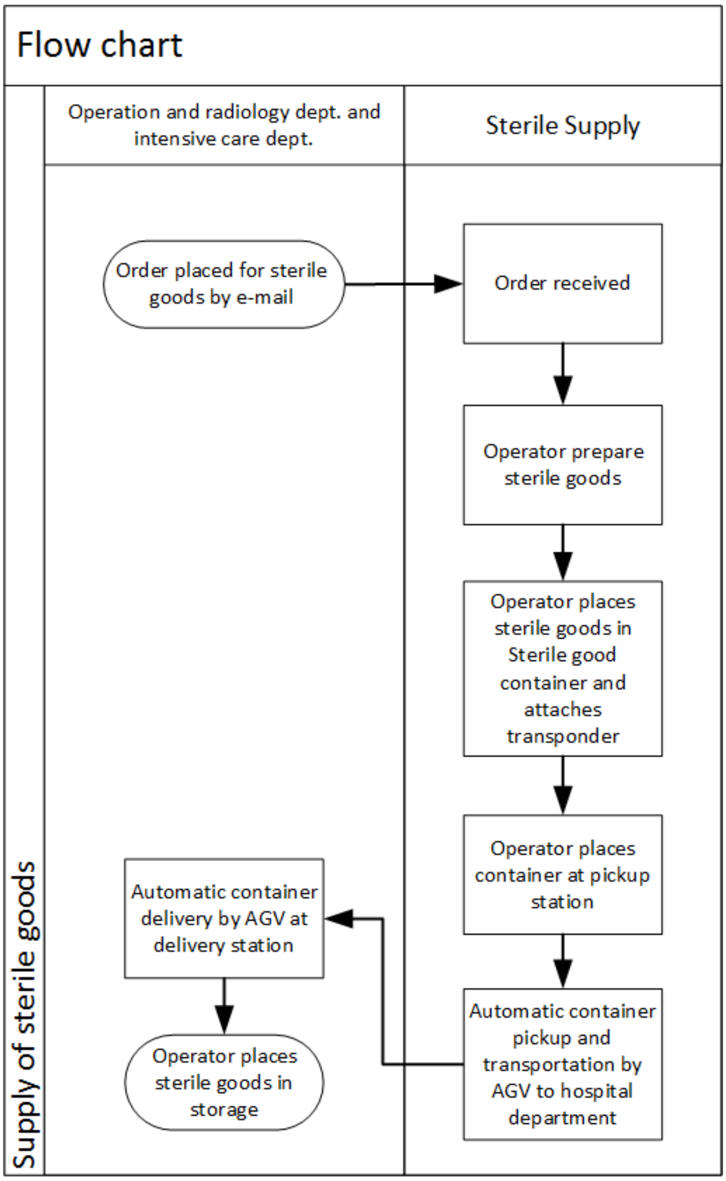

Figure 19: Flow chart of the supply of sterile goods.

The operations performed at the Sterile Supply involve cleaning, disinfection, sterilization, control, packing and distribution. The sterile goods are ordered and packed based on “brikker”, which are boxes containing categorized sterile goods. There are different types of boxes, and each type contains all the relevant sterile equipment needed for a specific medical operation. Inside the box the equipment is placed in a specific way with numbers attached to them. It is therefore very important that the handling and transportation of these goods is very smooth to prevent the equipment from changing positions, and thus making it unusable.

When the boxes for an order are ready they are placed on trolleys which are again placed in a Sterile Good container. Each container can take two trolleys. The personnel at the Sterile

Supply use a lift to place the trolleys onto the container. This is to prevent any disturbances to the boxes.

These containers are picked up and transported automatically by AGV. The orders for sterile goods get sent by AGV from 07:30 to 19:25 Monday to Friday, but in the evenings and on the weekends there are porters from the safety department at the hospital manually transporting the containers. There have been uncertainties in these cases whether the transportation by porter is done as seamlessly as by AGV.

There are less orders for the weekend, and only the operation departments at two centers (the E&C Center and the W&C Center) receives sterile goods at this time.

When an AGV (or a porter on the weekends) arrives at the appropriate department with a Sterile Good container, the personnel from Active Supply responsible for the delivery of these containers (also responsible for Food, Laundry, Waste, High-Volume Waste and Collecting containers at that center), use a lift to take the trolleys off of the container and transports the trolleys to the storage area for sterile goods.

These employees are also responsible for returning the trolleys (with the used equipment) back to the Sterile Supply. This must be done maximum three hours after use because bloody equipment has to be cleaned in this time to ensure that the equipment becomes fully sterile. During the daytime, this personnel go around every hour to their assigned departments to place the sterile goods containers (and the order containers) back on the pickup stations enabling the AGVs to transport them back to the Sterile Supply.

When the used equipment arrives back at the Sterile Supply it is cleaned through a multiple step cleaning process, then stored and ready for use again.

4.3.4.2 Materials from external suppliers

The Supply Center sporadically receive a small volume of materials (mostly just cardboard boxes used for storing and some other goods) for the Sterile Supply. These goods are usually manually transported by the personnel at the Supply Center to the Sterile Supply. The materials are replenished whenever there is demand.

4.3.5 Medicine and pharmaceutical products

Medical supply and pharmaceutical products are ordered from the Hospital Pharmacy to the hospital departments. To create an order, a requisition for replenishment is generated from each department, and is then checked by the pharmacist before the order is prepared. They use a periodic review for the ordering policy. The materials are either transported in a tube-system or by manual transportation. The only AGV transportation used for pharmaceuticals are for some of the return trips for the containers transported from the departments and back to the Hospital Pharmacy.

4.3.5.1 Single-dose medical products

Cytostatics, intravenous nutrition, and around 88% of all medicine types are packed in single-dose bags (éndose) at the pharmacy, and transported to the hospital departments by the general tube system. For multiple bags transported to one single patient, the bags are attached by a ring and included a label with information regarding the patient and the products. The average transportation time by the tube system today is 3,4 minutes, and most orders are transported in 2,5 to 4 minutes (Nedland, 2015).

4.3.5.2 Larger medical products

The medicine and pharmaceuticals that are unsuitable to transport via the tube system is transported manually in Pharmacy containers. . The reason for manual transportation for the supply is simply to protect the medicine and to prevent anyone from steeling it during the transportation. The empty containers are transported back to the pharmacy by AGV or manual transportation. The quantity of AGV transportations of these containers is very low.

4.3.5.3 Medical goods from external suppliers

To order goods from external suppliers to the Hospital Pharmacy, the pharmacy orders to a wholesaler which operates as an intermediary. The ordering process is semi-automatic where a suggested order is generated based on sales, and the personnel at the pharmacy checks the order and make any necessary corrections. The order is electronically sent via their industry system to the wholesaler two times per day.

The pharmacy receives delivery from the wholesaler once per day, and the materials are sent by trailer.

4.3.6. Waste

The main portion of the hospital waste gets transported through a waste disposal tube-system from the departments to the Waste Disposal located at the Supply Center. However, waste that is unsuitable to transport via the tube-system is transported by AGV. In addition, incidents that stops the tube-system from working can occur sporadically, and the AGVs must also transport the waste on these occasions. The AGV transports the waste to the same Waste Disposal as the tube-system does.

4.3.6.1 Small and non-risk waste

For the tube-system there are shafts located in different areas of the hospital. Next to each shaft there are buttons representing different types of waste. When waste is ready for disposal at a department, the personnel performing the task press the button representing the waste they want to dispose, and then places the waste bag in the shaft. It then gets transported by tubes at 80 km/h to the Waste Disposal.

The Waste Disposal inhabits a variety of different sorting bins, which are connected to the tube-system. The waste arriving by tube is automatically sorted into the right waste bin according to what the personnel assigned the waste to.

4.3.6.2 Larger and/or risk waste in regular volume

Waste that is either too large for transportation by tube or is denoted as risk waste and is carried in Waste containers. It is then transported by AGV, which happens two times per day for most of the waste. There is manual transportation on the weekends. The disposal by AGV of these materials is explained in Figure 20.

At the Waste Disposal there are two AGV pickup- and delivery stations and two single pickup stations. When the AGV arrives with the waste, an operator needs to manually sort the waste into the right bin. Given that there are only two delivery stations, the operator must perform his or her tasks as fast as possible after the waste has arrived to prevent queues into the Waste Disposal. This is the responsibility of the personnel situated at the goods arrival at the Supply Center, and they have a plan of always having an operator at the Waste Disposal from 07.00 to 10.30 and from 15.00 to 18.00 to perform these tasks. This is because these time frames are when the most waste will arrive given that this is when the transportation schedule allows for disposal of regular volume waste (see 4.2.2.2 The AGV transportation schedule).

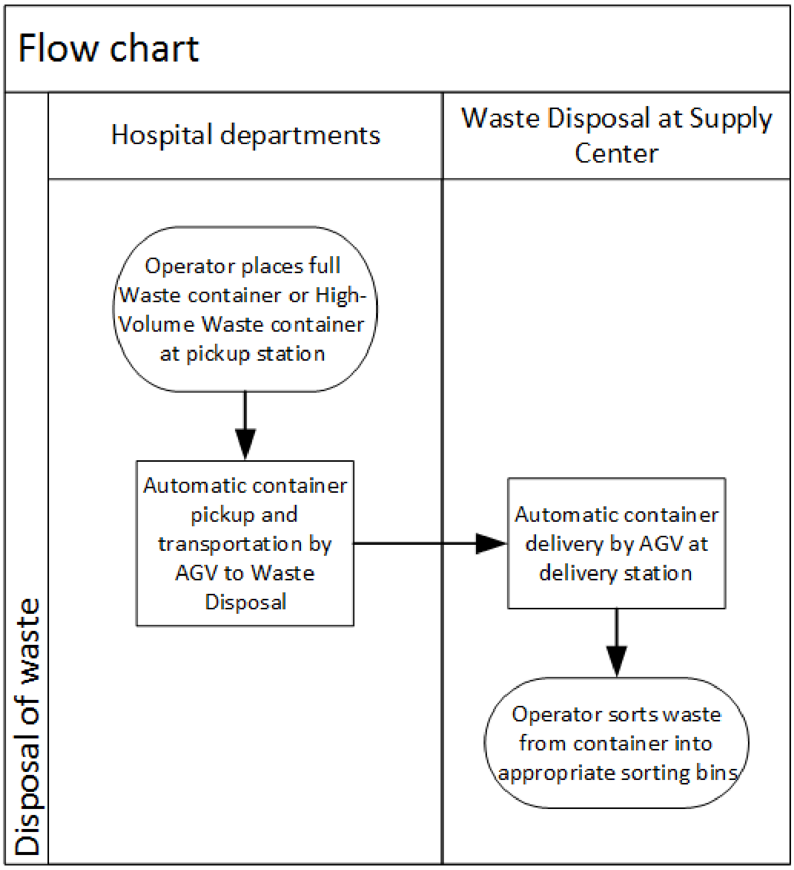

Figure 20: Flow chart of the disposal of waste.

In the AGV control system, the containers at the pickup stations at the Waste Disposal is given a waiting time (see 4.2.2.3 Priority rules). This is another measure for preventing queues. So, there is a 1-hour waiting time in the control system for these stations. I.e. an empty container that is to be transported back to a hospital department from the Waste Disposal will be given an hour waiting time when the waiting time for that container initially starts. This gives the containers here a higher priority because the system believes that these containers have waited longer than they actually have.

The AGV system also uses a station that operates as a waiting line outside of the Waste Disposal, just as for the Supply Kitchen. The personnel can control how many AGVs they want placed at this waiting line and at what time. This is also to reduce queues because containers at the Waste Disposal will then be picked up faster after they are emptied because AGVs are already waiting to pick them up.

4.3.6.3 Larger and/or risk waste in high volume

For larger and/or risk waste, there are some departments where there can be a need for more disposal. For these instances, there are eight dedicated High-Volume Waste containers. The material flow for these containers are identical to that of regular volume waste, as explained in Figure 20. These containers can transport waste as many times as needed. In the weekends the waste must be transported manually to the waste disposal.

The material handling of the high-volume waste at the Waste Disposal is identical to the handling of regular-volume waste, as explained in the previous section.

4.3.6.4 Collected waste

When a sorting bin at the Waste Disposal is full, each bin is mechanically moved onto a trailer and transported to different external waste disposals according to the type of waste.

4.4 Summary

The complexity of the internal transportation is apparent through this case study, where there is a diversity in material types, ordering processes, and transportation tools. In the next chapter the information retrieved in the case study will be analysed.

4 Analysis

In this chapter, a control model of the hospital supply chain is presented and statistical data on the AGV transportation is analyzed. The statistical data contains analyses of waiting times and transportation times for the AGV system, analyses of AGV recharging activities, as well as daily transportation volume and the transportation volume for each container group and each hospital center.

The analysations presented here is conducted to get a better understanding of the characteristics and dependencies of the AGV system, and to investigate the performance of the system.

5.1 Control model

Hospitals have a complex supply chain, which challenges the development of optimal logistics activities. Changing one area of the supply chain can affect the other parts of the chain, but due to the complexity, it is difficult to understand all characteristics and dependencies of the AGV system. The control model, presented in Figure 21, will help to view the supply chain in a comprehensive way, in order to understand the different characteristics and dependencies, and the interactions between the different actors.

The control model includes the main hospital at Øya, St. Olav's Hospital as an enterprise, and the first-tier suppliers of the hospital. The model displays the material and information flows for the hospital's supply chain and presents how the internal and external actors of the supply chain are related to the AGV system.

In the hospital the Kitchen Supply and Sterile Supply is actually located in the basement in the W&C Center, but they are separated in the control model to clarify the material- and information flows. In the model there are arrows in both directions for material flow where there are both supply and disposal of containers. The material and information flows are explained in detail in Table 5 and Table 6.

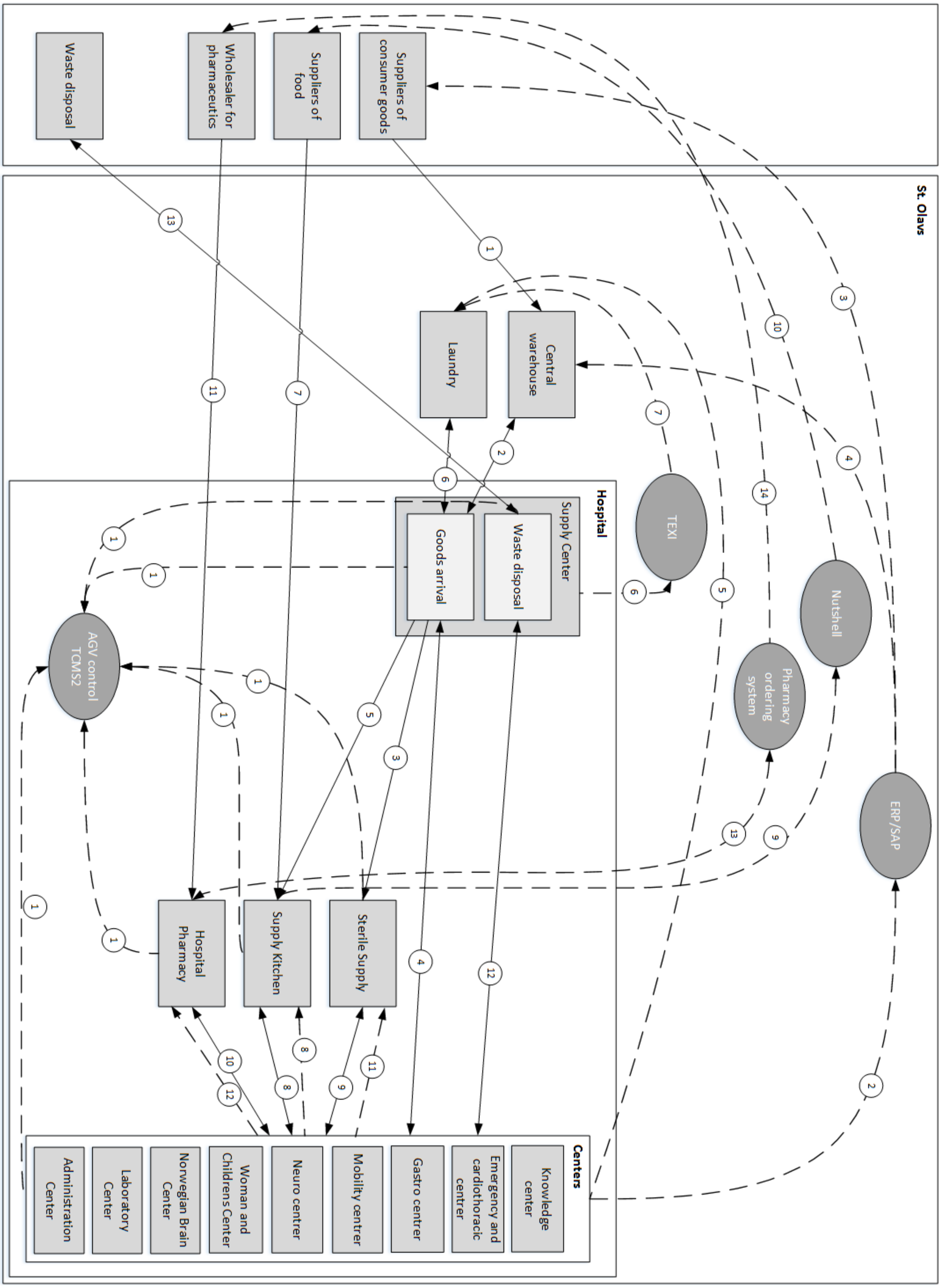

Figure 21: Control model of St. Olav's Hospital

Table 5: Explanation of the information flows in the control model

Material category	#	What	Characteristics	How	How often	System
All	**1**	Order	Containers at Pickup and Delivery stations	Semi-automatic by operators at pickup stations	Real-time	TCMS2
Consumer goods	**2**	Order	Consumer goods	Manual scan by Active Supply	1-5 times per week for each department, Monday to Friday	SAP
	3	Order	Consumer goods from external supplier	Controlled by dept. manager, then generated	As needed	SAP
	4	Order	Consumer goods from central warehouse	Automatic	Several times a day, Monday to Friday	SAP
Laundry	**5**	Order	Fabrics	Manual by hospital dept.	When different order than standard order is needed, Monday to Friday	Phone/ email
	6	Order	Personnel clothing	Automatic based on pre-determined stock levels	Once per day for each cabinet, at 23.00 Sunday to Thursday	TEXI
	7	Order	Personnel clothing	Automatic	Once per day, Sunday to Thursday	TEXI
Food	**8**	Order	Lunch and dinner, groceries, or other foods	Semi- Manual by hospital dept. or café	Varies, several times per day	Nutshell
	9	Order	Food	Manual by procurement personnel	Daily	Nutshell
	10	Order	Food	Automatic	Daily	Nutshell
Sterile goods	**11**	Order	Sterile goods	Semi-Manual by hospital dept.	Daily	Email
Pharmaceuticals	**12**	Order	Pharmaceuticals	Manual by hospital dept.	As needed	Phone/ email
	13	Order	Pharmaceuticals	Semi- Manual by Hospital Pharmacy	Two times per day	Pharmacy ordering system
	14	Order	Pharmaceuticals	Automatic	Two times per day	Pharmacy ordering system

Table 6: Explanation of material flows in the control model.

Material category	#	What	Characteristics	Transport tool	How often	Lead time
Consumer goods	1	Supply	Consumer goods	Trailer	Daily	Uncertain
	2	Supply	Multiple Warehouse containers with consumer goods (max. 19 containers)	Trailer	4-8 times per day, Monday to Friday	1-4 days
		Disposal	Multiple empty Warehouse containers (max. 19 containers)	Trailer	4-8 times per day, Monday to Friday	1 day
	3	Supply	Cardboard boxes	Manual	When needed	1-4 days
	4	Supply	Warehouse or Collecting container with consumer goods	AGV or manual if delays	Several times a day, Monday to Friday	15 min to a few hours
		Disposal	Emptied Warehouse or Collecting container	AGV	Several times a day, Monday to Friday	15 min to a few hours
Laundry		Supply	Laundry container with clean laundry	AGV and manual	Several times a day, Monday to Friday	15 min to a few hours
		Disposal	Laundry container with dirty laundry	AGV and manual	Several times a day, Monday to Friday	15 min to a few hours
	5	Supply	Personnel clothing	Manual	When needed	1 day
	6	Supply	Multiple Laundry containers with clean laundry (max. 45 containers)	Trailer	2-3 times per day, Monday to Friday	1 day
		Disposal	Multiple Laundry containers with dirty laundry (max. 45 containers)	Trailer	2-3 times per day, Monday to Friday	1 day
Food	7	Supply	Food	Trailer	Once per day, Monday to Friday	Uncertain
	8	Supply	Food container with food	AGV	Several times a day, Monday to Friday	1-2 hours
		Disposal	Emptied Food container	AGV	Several times a day, Monday to Friday	1-2 hours
Sterile goods	9	Supply	Sterile Good container with sterile goods	AGV and manual outside AGV operating time	Several times a day	1 day
		Disposal	Sterile Good container with used sterile goods	AGV and manual outside AGV operating time	Several times a day	Max. 3 hour after use
Pharmaceuticals	10	Supply	Pharmacy container with pharma-ceuticals and medical products	Manual	When needed	1 day
		Supply	Single-dose medical products	General tube-system	When needed	1 day
		Disposal	Emptied Pharmacy container	AGV or manual	When needed	10 min to a couple of hours
	11	Supply	Pharmaceuticals and medical products	Trailer	Once per day, Monday to Friday	Uncertain
Waste	12	Supply	Emptied Waste or High-Volume Waste container	AGV and manual on weekends	Several times a day	15 min to a few hours
		Disposal	Waste or High-Volume Waste container with larger and/or risk waste	AGV and manual on weekends	Several times a day	15 min to a few hours
		Disposal	Smaller and/or non-risk waste	Waste tube-system	Several times a day	2-5 min
	13	Disposal	Waste	Trailer	Daily	A few hours

5.1.1 Dependencies displayed in the control model

An overview of the all transportation tools used for internal transportation is displayed in Table 4. As previously mentioned, AGV transportation on the weekdays account for 70% to 75% of the internal transportations of materials at the hospital. As indicated in the control model, the AGV transportation is dependent on a number of logistics activities and require a comprehensive view in order to understand all dependencies.

The consumer goods and the laundry are ordered from facilities at Heimdal and transported to the Supply Center at the hospital before being distributed to the different hospital centers. For consumer goods, SAP is used as an ordering system. Laundry distinguishes between two types, personnel clothing and fabrics, where personnel clothing are automatically ordered via TEXI, whereas fabrics practice standard orders and healthcare personnel use email or phone in situations where the orders must be changed. Here the AGV transportation is dependent on when ordered goods arrive at the hospital, which again is dependent on the replenishment plan for when orders are sent and when the materials are transported to the hospital.

The food and sterile goods are ordered from the Supply Kitchen and The Sterile Supply situated at the hospital. All food is ordered via Nutshell, while sterile goods are ordered by email. From the Supply Kitchen and the Sterile Supply the goods are transported to the different hospital centers. For these goods the AGV transportation is dependent on the replenishment plans of food and sterile goods, which describe when orders are sent to the suppliers and when they should be ready for delivery by AGV.

Lastly, the waste is transported from different hospital centers to the Waste Disposal at the Supply Center. The AGV transportation is for these materials dependent on plans for disposal. Most of the transportation of pharmaceutical containers are performed manually, so the AGV transportation is not significantly influenced by the supply of these materials.

Thus, the AGV transportation is dependent on various activities related to the materials they are transporting, and this is elaborated on and discussed in 6.2.1 Level transportation volume in the Discussion.

5.2 Analysis of the AGV transportation

Statistical data from the AGV system have is analyzed to get a clearer understanding of the current transportation performance at St. Olav's Hospital. The analyses are made from raw data retrieved from the AGV computer system at the hospital. The study period for the analyses is nine months, from September 2017 to Mai 2018.

5.2.1 Supply and disposal times

An analysis is conducted to investigate the average waiting times and average transportation times for AGV transportation both for supply and disposal, i.e. supply *to* the customer and disposal *from* the customer. The average waiting time refers to the time from when a job is assigned to a vehicle until it is picked up by the vehicle. The job is assigned to a vehicle when an operator places a container on a pickup station and presses the button on that station, signalling that the container is ready to be transported. The average transportation time refers to the actual transportation time from the vehicle picks up the container until it is delivered at a delivery station.

5.2.1.1 Supply times

As previously stated, Sykehusbygg, the developer of the new St. Olav's Hospital, developed transportation schedules for the AGV system. They calculated estimated waiting times and transportation times based on simulations of four selected schedules, with operating time of either 24 or 18 hours per day. For all transportation schedules, the average waiting time for supply was estimated to be between 2.9 minutes and 5.1 minutes. The average transportation time was estimated to be between 11.4 minutes and 11.7 minutes. These times where concluded to fulfill the requirements for capacity and performance in regards to time needed to deliver a container.

The AGV operating time that the hospital currently is using is 13 hours, from 06.30 to 19.30, Monday to Friday. The average waiting time and transportation time for supply at each half hour of the AGV operating time is shown in Figure 22. The table also shows the combined waiting and transportation time.

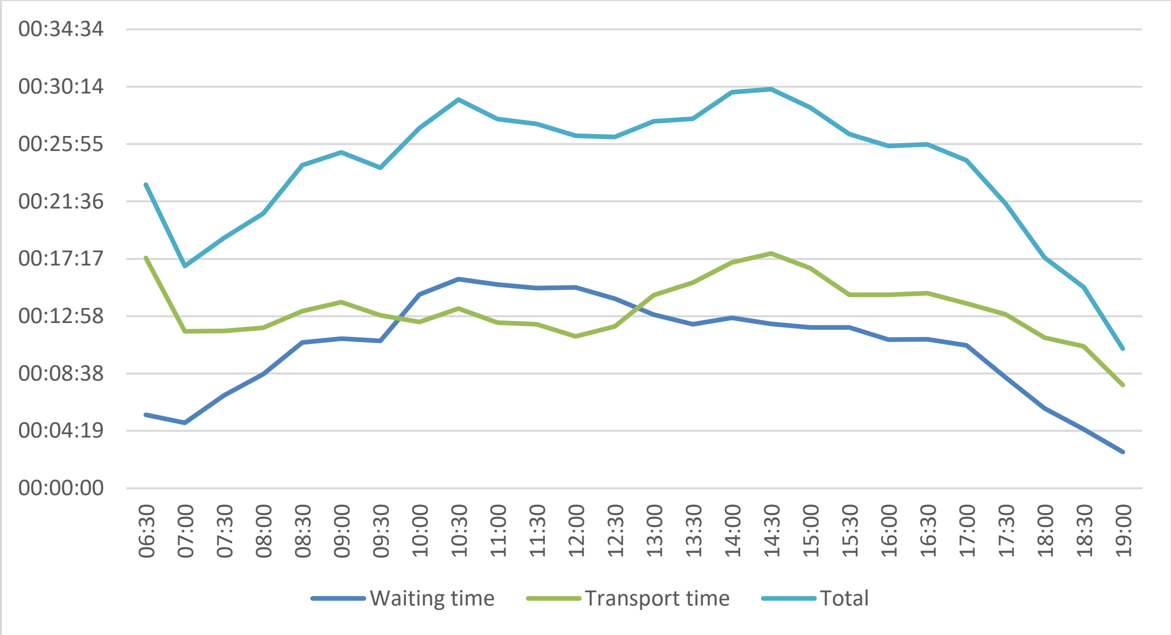

Figure 22: Waiting time, transportation time, and combined waiting and transportation time for supply.

The average waiting time is relatively low at the beginning and the end of the operating time, and is at the minimum at 2.7 minutes from 19:00 to 19:30, and a maximum of 15.7 minutes from 10:30 to 11:00. From 10:30 to 12:00, the average waiting time for supply exceeds 15 minutes. This is almost three times higher than the average estimated waiting time of 5.1 minutes from the simulations.

The average transportation time during the day varies ranges from a minimum of 7.8 minutes at 19:00 to 19:30, to a maximum of 17.7 minutes from 14:30 to 15:00. At the main part of the day, from 07:00 to 18:00, the average transportation time varies from 12.2 minutes to 17.7 minutes, which is a variation of 5.5 minute. These times exceeds the estimated average transportation times.

The combined waiting and transportation time reaches a maximum from 14:30 to 15:00 where it just exceeds 30 minutes, and the time greatly decreases towards the end of the day.

5.2.1.2 Disposal times

Disposal refers to the AGV transportation of containers *from* the customers back to the internal supplier. The four transportation schedules developed by Sykehusbygg estimated an average waiting time between 16 and 24.8 minutes for disposal. The average transportation time was only estimated for supply, which were between 11.4 and 11.7 minutes.

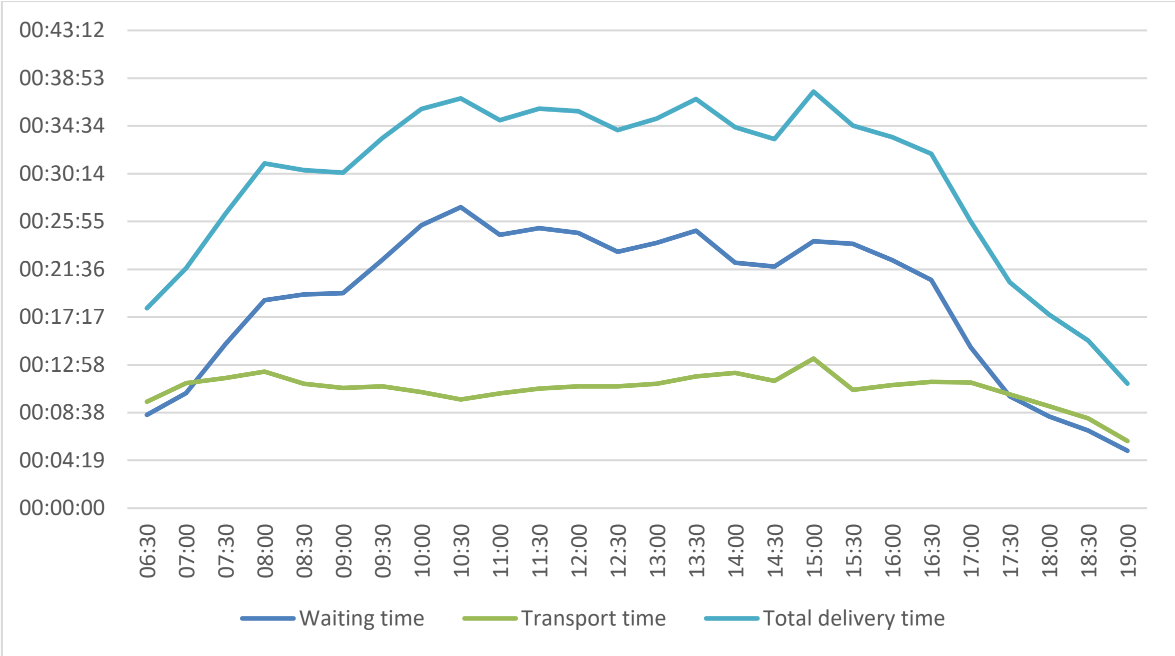

Figure 23: Waiting time, transportation time, and combined waiting and transportation time for disposal.

The average waiting time and transportation time for disposal is shown in Figure 23, as well as the combined waiting and transportation time. As the figure shows, the average waiting time remains over 20 minutes from 09:30 to 16:30, with a maximum of 27.2 minutes at 10:30 to 11:00. Notably, the maximum average waiting time for disposal is in the same period as the maximum average waiting time for supply, i.e. 10:30 to 11:00.

The average transportation time for disposal varies from 6.1 minutes at 19:00 to 19:30, to 13.5 minutes at 15:00 to 15:30, and remains relatively stable throughout the day. From 07:00 to 18:00, the average transportation time remains between 10.3 to 13.5 minutes, which is just above a three-minute variation.

5.2.2 Transportation capacity

Vehicles recharging is connected to the transportation capacity, in that the transportation capacity will decrease when more vehicles are recharging, because it reduces the number of operable vehicles.

For the AGVs, the recharging start time and the recharging duration can give a better understanding of the number of operable vehicles at different times during the day. Recharging start time refers to the time when a vehicle starts to recharge, and recharging duration refers to the duration a vehicle uses for one recharging session. The data retrieved on vehicle recharging activities are only based on one month, Mai 2018. This is contrasting to the other

AGV transportation data, which is retrieved over nine months, from September 2017 to Mai 2018.

St. Olav's Hospital count that a vehicle can usually conduct three transportations per hour, and they calculate with 20 AGVs per day instead of 21 vehicles, to account for repairs and maintenance. This would enable 60 transportations per hour. However, there are variations throughout the day in the transportation capacity since the vehicles regularly need to recharge. So, there will not be as much as 20 vehicles operable at all times. Figure 24 shows the average recharging start time, i.e. the number of vehicles starting to recharge for each half hour. The time interval in the graph is from 06:30 to 19:30 since this is the AGV operating time.

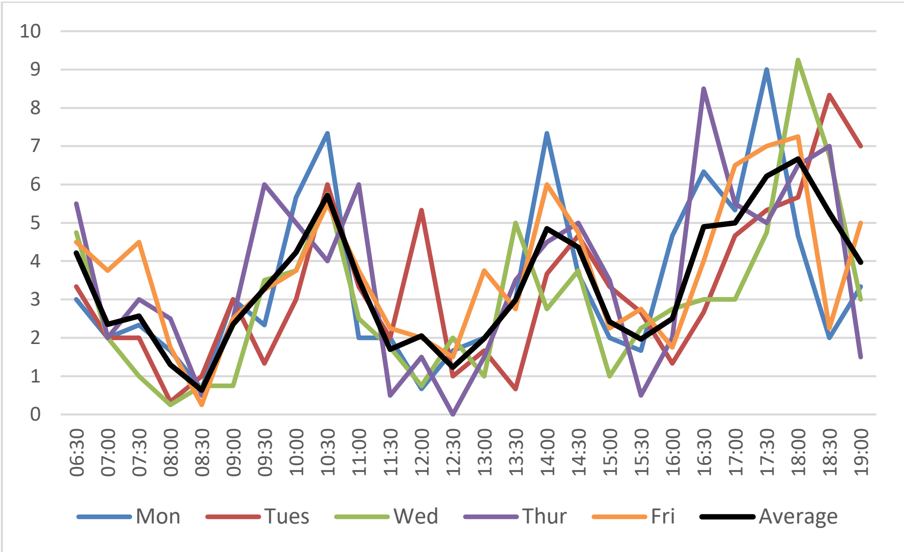

Figure 24: Recharging start time.

There is a peak at 10:30 to 11:00 in the recharging start time. This conforms to the vehicle's battery durability, which is around three or four hours. The AGVs are generally fully recharged at 06:30 because they recharge at night, and if a vehicle starts operating at this time it will have been active for four hours at 10:30, and will by this time usually start recharging. As identified in 5.2.1 Supply and disposal times, 10:30 to 11:00 is also the interval with the highest average waiting times. This can indicate that the increase in recharging start time – and the reduction in transportation capacity – results in increased waiting times for the containers.

There is a second peak at 14:00 to 14:30, which also gives a reduction in transportation capacity during this time. The last peak for recharging start time is at 18:00 to 18:30, which is the 30-minute period with the highest recharging number of 6.67 vehicles on average.

There are variations according to weekdays for the recharging start time. This may be because the data is only collected over a one-month period, but it also indicates that, although there is a clear daily seasonality, there are high variations when it comes to the vehicle recharging activities. There is also an increase in weekday variation throughout the day. This is arguably because the vehicles are fully recharged in the beginning of the operating time and each vehicle will then have approximately the same durability before needing to recharge. The recharging duration can vary according to the battery level at the recharging start time and the battery level at the recharging stop time (i.e. whether the vehicle uses enough time to fully recharge if there are transportation jobs waiting). The battery level will also be affected by how occupied the vehicle is when its operable. Thus, throughout the day, these factors will give increased variations for when the vehicles will recharge.

The average recharging duration for each half hour is presented in Figure 25. The interval is from 07:30 to 19:00 because the recharging durations outside of this period was influenced by the fact that the recharging durations at night is considerably higher than the recharging durations in the AGV operating time since there are no transportation jobs at night. The recharging durations outside of the AGV operating time were not deemed relevant for understanding the transportation capacity during the operating time.

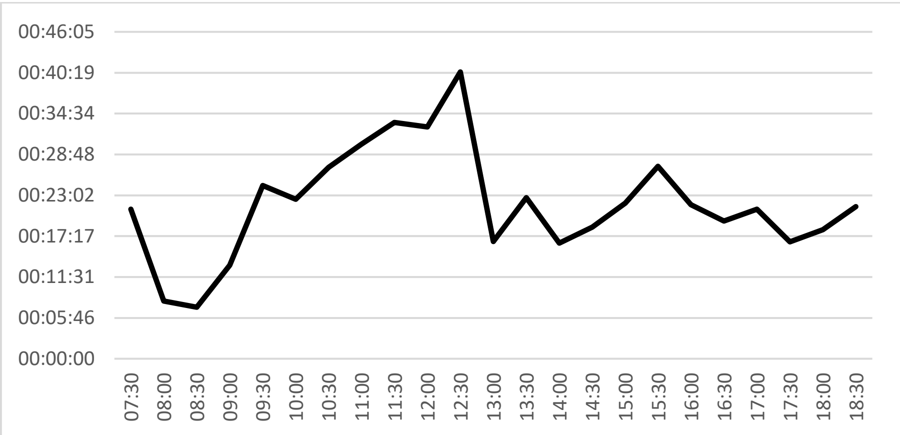

Figure 25: The average recharging duration.

The average recharging duration for each half hour varies from 7.3 minutes for vehicles recharging at 08:30 to 09:00, to 40.4 minutes for vehicles recharging at 12:30 to 13:00. This fits with the recharging start time and the fact that the vehicles start operating at 06:30 with a three to four hour durability, because the vehicles will then need more time to fully recharge. The average recharging duration for the entire time interval is 21.8 minutes.

5.2.3 Transportation volume

The transportation volume was analyzed to understand the daily seasonality of the transportation volume and to investigate whether the transportation volume is level throughout the day or if there are high variations. This section displays the total average transportation volume, the average transportation volume divided into supply and disposal, and the average transportation volume for each of the container groups also distinguishing between supply and disposal.

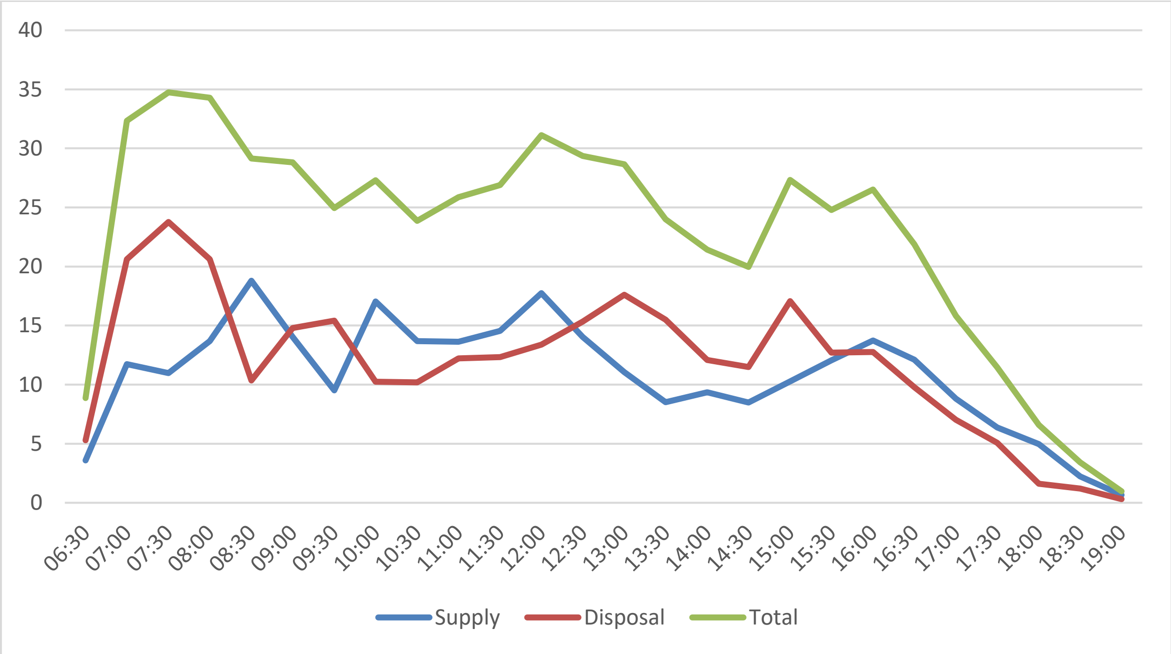

Figure 26: Average total transportation volume, and average transportation volume for supply and for disposal.

Figure 26 shows the average daily transportation volume for each half hour during the AGV operating time, as well as the average daily transportation volume for supply and for disposal.

As shown in the figure, the average total transportation volume exceeds 20 transportations per half hour from practically 07:00 to 17:00. The maximum average transportation volume is at 07:30 to 08:00 with 34.8 transportations.

The average transportation volume is similar for each weekday, even though there are small variations. The transportation volume for each weekday, and weekday variations for each container group, is shown in 9.6 Statistical analysis in the Appendix.

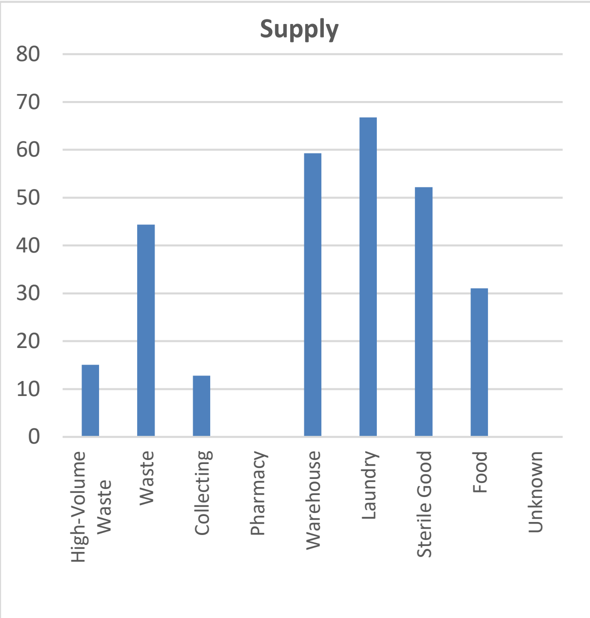

Figure 27: Daily transportation volume for supply of each container group.

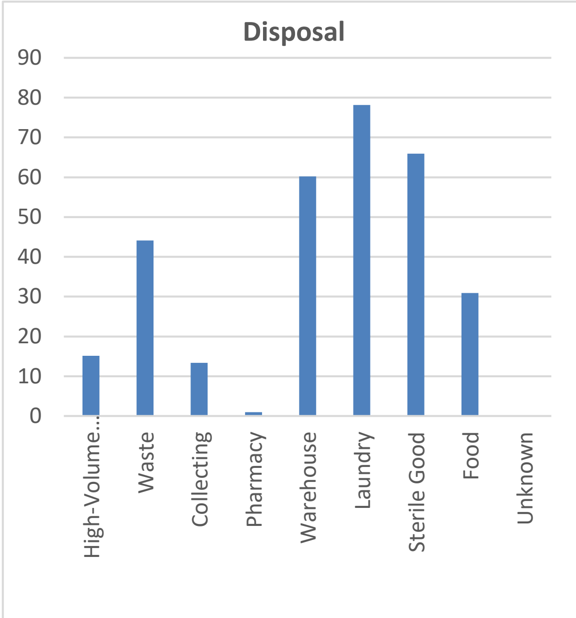

Figure 28: Daily transportation volume for disposal of each container group

Figure 27 and Figure 28 present the average daily transportation volume for each of the eight container groups divided into supply and disposal. It shows that Laundry has the highest transportation volume for both supply and for disposal, and the Warehouse containers have the second highest volume for supply while Sterile Goods have the second highest volume for disposal. Most of the container groups have approximately the same transportation volume for supply and disposal, apart from Sterile Good and Laundry containers where the volume for disposal is significantly higher than for supply. The reason for this is because the supply of some of these containers are performed manually, either in or outside of the AGV operating time, while the disposal can often wait to be transported by AGV.

When considering the total daily transportation volume for each container group, i.e. combining the supply and disposal, the Laundry containers have the highest average transportation volume of 145 transportations, while the Warehouse containers have 120 transportations and Sterile Good containers have 118 transportations. Waste containers have the fourth highest average transportation volume with 89 transportations, and Food containers have 62 transportations. High-Volume Waste containers and Collecting containers have 30 and 26 transportations respectively, while Pharmacy containers have one transportation per day on average.

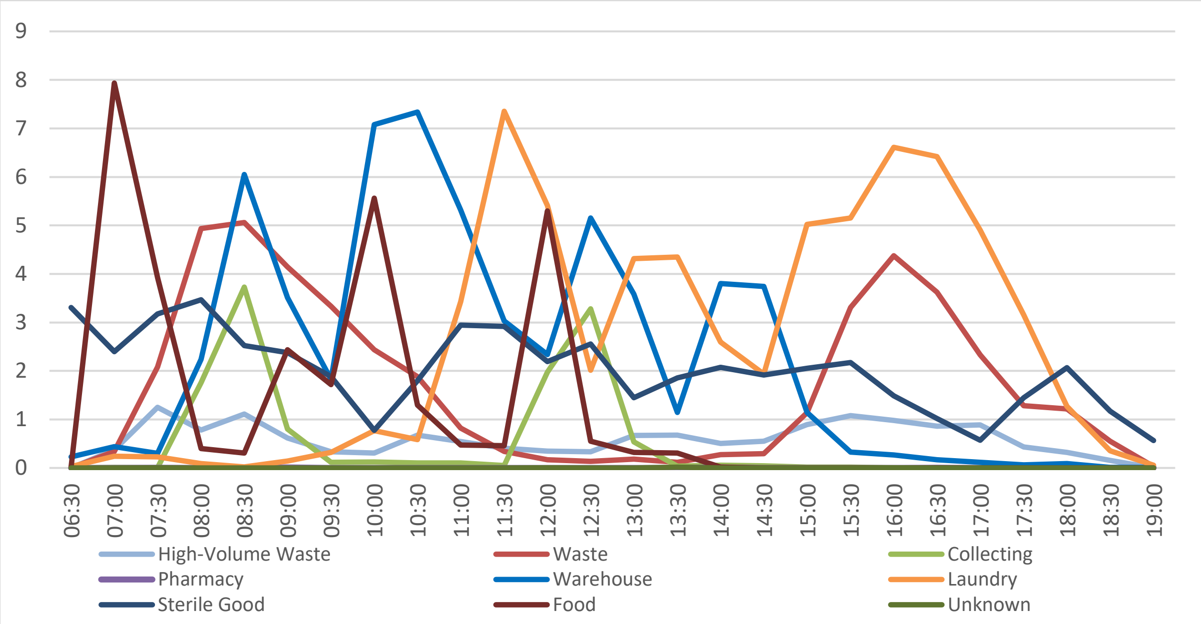

Figure 30:Average transportation volume for supply for each container group.

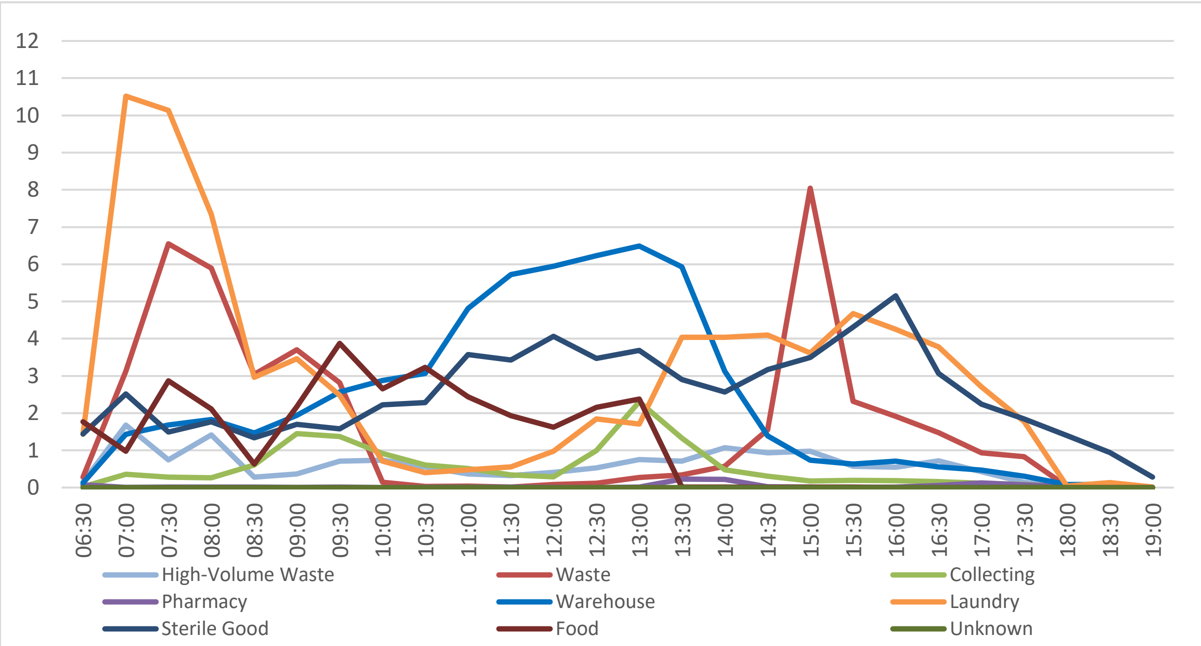

Figure 29: Average transportation volume for disposal for each container group.

Figure 30 and Figure 29 displays the average transportation volume for each container group at each half hour during the day, segregated into supply and disposal.

5.2.3.1 Warehouse containers

The Warehouse containers are transported from the Supply Center to the various hospital centers, and when they have been emptied, they are returned to the Supply Center. The AGV transportation schedule opens for transportation of supply for these materials from 07:00 to 19:00, and disposal from 07:00 to 18:00.

For the supply of Warehouse containers, as shown in Figure 30, there are four peaks in the transportation volume around 08.30, 10.30, 12.30, and 14.30. This matches with the replenishment plan from the Central Warehouse, which states four deliveries per day, i.e. four trailers, the first at 08:20 with a two-hour time interval. However, from the interviews and observations it is apparent that there can often be more deliveries. These extra deliveries may not be so apparent from the average transportation volume because they are more random and irregular compared to the four planned deliveries.

For the disposal of Warehouse containers, as Figure 29 shows, the average majority of transportations are performed from 11:00 to 14:00. For both supply and disposal, the are almost no transportations after 15:00.

5.2.3.2 Collecting containers

Collecting containers are transported from the Supply Center to the hospital centers, and returned to the Supply Center after they have been emptied. AGV transportation schedule opens for supply of these containers from 07:00 to 18:00, and disposal from 07:00 to 19:00.

For supply of Collecting containers, as seen in Figure 30, there are two clear peaks in the transportation volume. The peaks show that there are two times during the day where the supply of these containers are prioritized. Often the containers are disposed of shortly after the they are emptied, which can be seen in Figure 29.

5.2.3.3 Laundry containers

The Laundry containers are transported from the Supply Center to the hospital centers. These containers also carry dirty laundry that are transported from the hospital centers back to the Supply Center. The AGV transportation schedule is open for supply of clean laundry from 10:00 to 19:00, while the disposal of dirty laundry is open from 07:00 to 19:00. The replenishment plan for clean laundry states two transportations per day, but through the case study it is evident that there can also occur three deliveries during one day, which naturally increases the demand for transportation of these materials.

For supply of Laundry containers, there is an increase in the transportation volume from 10:30 to around 12:00. This is due to a daily delivery from the Laundry around 10:30. So, from around 10:30 there will usually be a high demand for containers to be transported from the Supply Center, both for Warehouse and Laundry containers, where both containers (as well as Collecting containers) use the same pickup- and delivery stations. The operators at the Supply Center will often prioritize consumer goods, so the laundry may either have to wait to be transported by AGV or be transported manually. It will usually be the personnel clothing that are affected when the AGV utilization is very high. According to personnel at the hospital, virtually 50% of the orders for personnel clothing are transported manually, which is around 25 % of the total volume from the Laundry. This can also be seen in Figure 30, where the hourly transportation volume of Laundry containers is, to a certain extent, negatively correlated to the hourly transportation volume of consumer goods, i.e. when the transportation volume of Warehouse containers increases, the transportation volume of Laundry containers declines, and opposite. There is another peak in the transportation volume around 16:00, which matches with the time for the final daily delivery from the Laundry. The total hourly transportation volume from the Supply Center remains at a high level for most of the day.

The trailers that arrive with clean laundry are to be transported back with dirty laundry, so there are usually disposals following the supply. For the disposal of Laundry containers, the transportation volume reaches is a maximum around 07:00 to 08:00, where Laundry containers are transported to the Supply Center. This enables these containers to be transported back to the Laundry with the first trailer arriving around 10:30. Just as the supply, the disposal is also to a certain extent negatively correlated with the Warehouse containers.

5.2.3.4 Food containers

The Food containers are supplied from the Supply Kitchen to the various hospital centers, and transported back to the Supply Kitchen after delivery. The AGV transportation schedule opens for transportation of food supply from 06:30 to 14:30, and disposal from 06:30 to 13:30.

For the supply of Food containers, there are several different transportations during the day. The replenishment plan from the Supply Kitchen states that around 07:30 there are transportations of groceries to the departments and baked goods to the cafes, around 10:00 and 12:30 there are transportations of lunch and dinner respectively, and around 13:00 there is a new transportation round for groceries to the cafés. This is reflected in Figure 30, apart from the transportation of groceries around 13:00. This may be because there is a lower volume and more inconsistency in the ordering of these products.

The average transportation volume for disposal is apparent, but at a low level from 06:30 to 13:30. As shown in the figures, and naturally because of the transportation schedule, there are practically no transportations for either supply or disposal after 13:30.

5.2.3.5 Sterile Good containers

The Sterile Good containers are transported from the Sterile Supply to the hospital centers, and returns the used sterile goods to the Sterile Supply. The AGV transportation schedule opens for both supply and disposal of sterile goods from 06:30 to 19:30.

For both supply and disposal, the average transportation volume of sterile goods stays between one and four transportations per half hour for the main part of the day, but especially for disposal, it declines around 16:00. From 06:30 to 16:00 in the replenishment plan of the Sterile Supply there are regular intervals of delivery to different operations departments. This correlates with Figure 30 since the transportation volume remains between one and four transportations per half hour for most of the day.

5.2.3.6 Pharmacy containers

The Pharmacy container are transported from the Hospital Pharmacy to the hospital centers, and returns emptied containers back to the Hospital Pharmacy.

As shown in the figures, there are practically no AGV transportations of these containers. The low transportation volume is, as previously stated, because these materials usually are transported manually, and the AGV transportations of these goods are generally only disposals. This material group will therefore have a small impact on the AGV transportation.

5.2.3.7 Waste containers

For the Waste containers the transportation is reverse of the other container groups in regards to supply and disposal, where the Waste container is first transported from a specific department to the Waste Disposal at the Supply Center, and then transported back to the same department shortly after it has been emptied. The AGV transportation schedule is open for disposal of these containers from 07:00 to 10:00 and from 15:00 to 18:00, and supply from 07:00 to 19:00.

This is seen in the transportation volume, where there are two peaks in these time intervals, which are similar for both supply and disposal. This is because after disposal, the containers must be quickly transported back to the specific departments. This is to prevent queues into the Waste Disposal since there are only two delivery stations at the there.

5.2.3.8 High-Volume Waste containers

The High-Volume Waste containers are, just as regular volume waste, transported from the hospital centers to the Waste Disposal, and back to the hospital centers when they are emptied. There are only eight designated containers that transport high volume waste. The transportation schedule for these containers is open from 07:00 to 19:00 for supply, and from 07:00 to 18:00 for disposal.

As the figures show, the average transportation volume for these containers is very scattered throughout the day since they can be are transportation whenever necessary.

5.2.4 Comparisons

Figure 31 shows the daily average for the transportation volume and the recharging start time compared to the waiting time and transportation time combining supply and disposal. The reason for comparing these measures is to identify any correlations. The analysis is based on data from the month of May 2018. This is because the recharging data is only retrieved for this month, so to make an accurate comparison, the other data was also retrieved from this month.

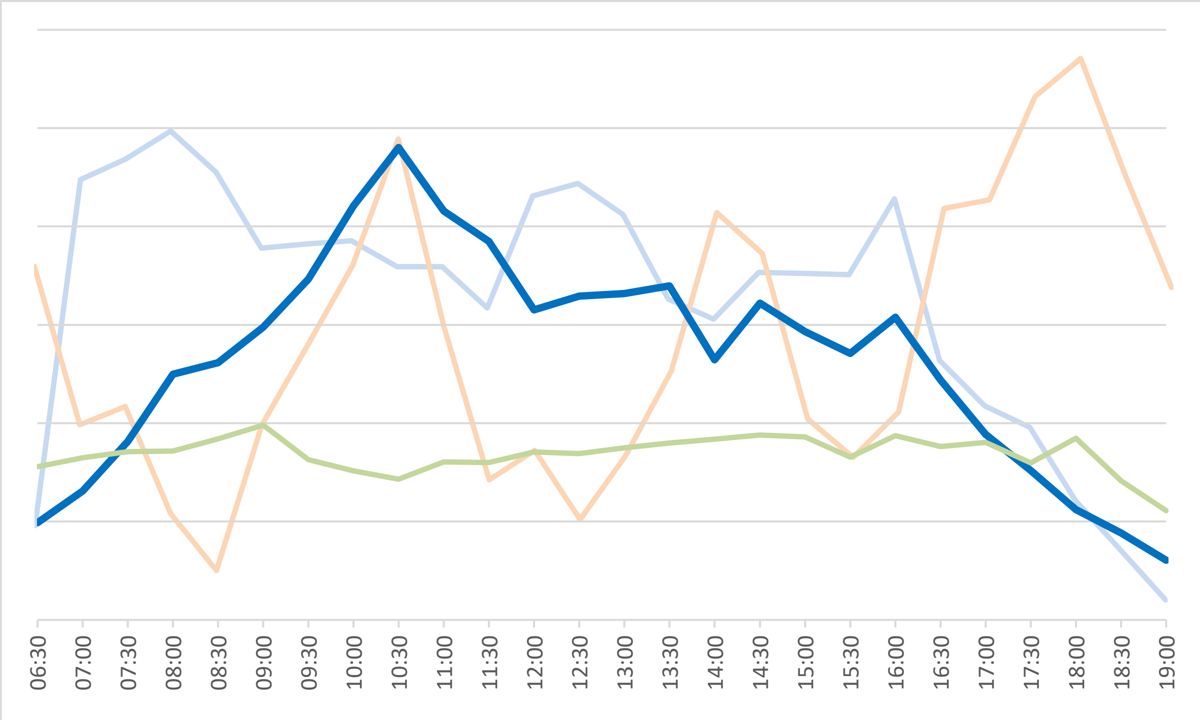

Figure 31: Comparing transportation volume (light blue) and recharging start time (light orange) with waiting time (dark blue) and transportation time (green) for the month of May.

5.2.4.1 Transportation volume vs. transportation capacity

From the figure there seems to be a negative correlation between the transportation volume and the recharging start time. This indicates that when the transportation capacity is declining, the transportation volume will also decline. This may be because when the transportation capacity starts to decline there is not enough operable vehicles to perform as many transportations as earlier. From the case study, it is likely to suggest that this scenario occurs at certain times, especially in the hours around 10:00. Another scenario is that when the transportation volume is declining, the vehicles will start to recharge. From the case study, it is apparent that this scenario will at least occur at the end of the day, where there are fewer transportation jobs to be performed, so the vehicles will start recharging.

5.2.4.2 Transportation time vs. transportation volume and transportation capacity

The transportation time remains at a relatively stable level through the entire operating time and remains under 14 minutes apart from the period at 09:00 to 09:30. From this analysis, the transportation time is not clearly correlated with the recharging start time, or with the transportation volume.

5.2.4.3 Waiting time vs. transportation volume and transportation capacity

As illustrated in the figure, the average waiting time has a much greater variation compared to the average transportation time, and is apparently more influenced by the transportation volume and the recharging start time. Before 10:00, there is a high transportation volume, which reaches a peak of 35.2 from 08:00 to 08:30. From around 08:30 until 10:30 the transportation volume is declining, however the waiting time is increasing in this same time interval and the recharging start time is also increasing. Because the transportation volume is decreasing, it can be argued that the increased waiting times is a result of the reduced transportation capacity due to increased recharging start time.

Also from the observations and interviews performed at the hospital, it was apparent that an issue occurs around 10:00 to 11:00. This is because a number of concurrent jobs usually happen around this time: The containers for lunch must be transported from the Supply Kitchen to the center kitchens around 10:00, and trailers from both the Laundry and the Central Warehouse commonly arrives around 10:30 to 11:00. In addition, the recharging start time reaches a peak at this time because the vehicles have been operating for three to four hours and need recharging. The concurrent jobs and the increase in recharging start time can pressure the operators to transportation materials manually. This usually affects the personnel clothing arriving from the Laundry. On average, approximately 50% of the daily deliveries of personnel clothing use manual transportation, which is 25% of the total deliveries from the Laundry. The transportation volume is not a direct reflection of the transportation demand. This may be especially relevant for the period from 10:00 to 11:00, but also for other parts of the day.

Towards the end of the operating time, there is a clear decline in both waiting time and transportation volume, and in the same time frame there is an increase recharging start time. This reflects that vehicles will move towards a recharging station when there are no jobs assigned to the vehicle.

The transportation volume *from* and *to* each hospital center is displayed and discussed in 9.6.1 Pickup and delivery locations in the Appendix.

6. Discussion

In this chapter the information found in the analysis is discussed in relation to the information found in the literature study. First, the various challenges for the AGV system is discussed. After this there is a discussion of possible measures for achieving timely delivery, which are presented in a framework.

6.1 Challenges

In a hospital supply chain there are high requirements for quality of services, also when it comes to timely delivery of materials. A lack of timely delivery can in worst case have negative consequences for the patients seeking treatment in the hospital. E.g. sterile goods used in the operation departments must be delivered on time to ensure availability for any planned or acute medical operations, and for the food supply there should be timely delivery to ensure that the patients receive their food on time, even though a high degree of timely delivery may give higher costs. The hospital supply chain is characterized as highly complex with multiple actors and stakeholders and there are various dependencies for each of the materials transported by AGV. This challenges the development of suitable solutions for achieving timely delivery.

The statistical analysis performed studies the transportation time and the waiting time for the AGV transportation. From the analysis, it is apparent that there are long waiting times at certain periods of the day, which can prevent timely delivery of materials. The analysis shows that the average transportation time for supply and disposal is relatively stable throughout the day, especially for disposal where there are only three minutes variation from 07:00 to 18:00. While the average waiting time for both supply and disposal has a variation over 12 minutes in the same time interval, and for the main part of the day exceeds what was estimated to be the average waiting time for the transportation schedules established by the hospital developers. This is especially evident for the waiting time for supply, where the average waiting time exceeds the average estimated waiting time of 5,1 minutes from 07:00 to 18:30.

A challenge in regards to the statistical data on waiting time is that the data only covers the waiting times from when a container is placed at a pickup station until it is picked up by AGV. However, the jobs will often have longer total waiting times because containers cannot be placed at a pickup station if all the stations are full. E.g. many of the containers delivered to the Supply Center from the Central Warehouse and the Laundry will usually be placed at the goods arrival for an uncertain amount of time before they can be placed at available pickup stations. This can lead to delays for many orders, which also creates delays for the personnel set to handle the delivered materials upon arrival. Thus, the overall waiting time is often higher than the waiting time that is found in the statistical analysis. However, quantitative data on the waiting time from when a container is ready to be transported until it is placed at a pickup station is not registered and is therefore difficult to determine. However, based on observations from the case study, it can be argued that when the waiting times retrieved from the statistical data is increasing, there will also be an increase in the total waiting times. This is because when a vehicle has a longer waiting time at a pickup station, this also gives longer waiting times for the vehicles waiting to be placed at a pickup station since they have to wait for an available station.

From the analysis, it can be argued that waiting time is influenced by transportation volume and transportation capacity. The analyses indicates that when the transportation volume is increasing or the transportation capacity is declining, or a combination of both, the waiting times will increase. It is apparent from the both the case study and the analysis that for the main part of the AGV operating time, and especially around 10:00 to 11:00, the transportation capacity and transportation volume reaches a level where it negatively affects the waiting time.

6.2 Possible improvement measures

To ensure timely delivery of materials by AGV, three main approaches are presented, which are developed based on findings in the case study and the analysis. The approaches are; levelling the transportation volume, reducing the transportation volume, and increasing the transportation capacity.

As seen in the analysis, the transportation volume can influence the waiting time, and an increased waiting time can prevent timely delivery. Thus, levelling the transportation volume or reducing the transportation volume are possible approaches for facilitating timely delivery.

Increasing the transportation capacity is also a possible approach because it would enable more transportations to be performed in a specific time period. As seen in the analysis, the waiting time is influenced by the recharging start time. When the recharging start time is increasing there will be a reduction in the transportation capacity, which results in longer waiting times.

Figure 32 presents a framework of potential improvement measures for facilitating timely delivery of materials internally transported by AGV. The framework is categorized into the three main approaches for timely delivery: Level transportation volume, reduce transportation volume, and increase transportation capacity. Thus, each measure presented in the framework are aimed at one of these approaches. The framework also distinguishes between three hierarchical levels. These are measures related to the AGV system, the hospital environment, and Supply Chain Management.

The framework is developed based on five frameworks that concern either AGV systems, which are presented in Figure 7 and Figure 8 (Bechtsis, Tsolakis, Vlachos, et al., 2017; Le-Anh & De Koster, 2006), and hospital supply chains (Gunasekaran, Patel, & McGaughey, 2004; Lapierre & Ruiz, 2007; Lega, Marsilio, & Villa, 2013). Compared to the other frameworks on AGV systems, the framework presented here aims specifically at AGV systems in hospitals and concerns measures for achieving timely delivery of materials in a hospital supply chain. A version with a bigger font size is shown in

9.7 Framework in the Appendix.

How	The AGV system	Hospital environment	Supply Chain Management
Level transportation volume	**Scheduling** Change AGV transportation schedule by separating the schedule for each container group more, rather than allowing transport of most container groups all day Perform more transportation jobs when there is little transportation. I.e. between 17:00 and 19:30. E.g. Warehouse, Laundry or Waste containers **Operating time** Expand AGV operating time (and AGV transportation schedule) **Priority rules** Give priority to different material types to enable transport of high priority materials	**Personnel** Expand personnel operating time to enable increased AGV operating time **Practices** Change healthcare practices to enable change in delivery time. E.g. practices such as hospital meal plans or medical schedules	**Centralize** Centralize decision making for the supply chain to give a comprehensive view **Integrate systems** Integrating ERP system with AGV system, allow for more offline scheduling where transportation can be scheduled in advance **Replenishment plans** Change plans for replenishment to allow for changes in transportation schedule **Data collection** Retrieve quantitative data on total waiting time and delivery precision
Reduce transportation volume		**Local inventory** Increase storage space at hospital to reduce procurement frequency **Container utilization** Increase container utilization by combining orders **Unnecessary replenishment** Examine the various order quantities to eliminate unnecessary replenishment. E.g. Replenishment of fabrics is sometimes excessive **Product criticality** Determine product criticality to establish replenishment practices for the different materials **Unit load** Specify unit or pack for all SKUs at the Central Warehouse	**Supply chain structure** Evaluate considerations regarding having activities in-house vs outsourcing of each material type. For consumer goods, evaluate considerations regarding having central warehouse vs. direct delivery from external supplier, and determine what should be stocked at warehouse. VMI for some materials. E.g. certain consumer goods **Data collection** Retrieve quantitative data on container utilization
Increase transportation capacity	**Vehicle properties** Change vehicle properties, such as vehicle type, mechanical parts, electronic devices, and power supply **Vehicle quantity** Increase the number of vehicles **Battery management** Increase the battery duration **Layout** Adjust guide path design, no. of lanes, recharging stations, parking stations Increase quantity of pickup- and/or delivery stations at areas with many pickups or deliveries. E.g. at Waste Disposal or goods arrival at Supply Center. **Deadlock resolution** Allow for more efficient throughput at areas with high traffic. E.g. goods arrival at Supply Center or at the area around Supply Kitchen and Sterile Supply. **Routing** Change vehicle routing, especially related to finding shortest path, reducing empty transportations, and prevent turns in elevator	**Elevators** Increase number of elevators at areas with high traffic **Obstacles** Prevent obstacles in transportation route	

Figure 32: Framework of improvement measures for facilitating timely delivery of materials transported by AGV in a hospital environment.

6.2.1 Level transportation volume

Levelling the transportation volume is one of the approaches for achieving timely delivery, as displayed in Figure 32. The overall average transportation volume per half hour is at the maximum between 07:30 and 08:00, with 35 transportations. The average transportation volume exceeds 20 transportations per half hour from practically 07:00 to 17:00. However, after 17:00 the transportation volume rapidly decreases, and there is only one transportation on average for the last half hour, which is from 19:00 to 19:30. This indicates that allocating more transportation jobs to the end of the day could reduce the transportation volume in other parts of the day. Today the schedule spans from 06:30 to 19:30 from Monday to Friday. However, there is also an option of expanding the schedule and, thus, the AGV operating time to achieve a more level transportation.

A measure for levelling the transportation is changing the transportation schedule. In the current transportation schedule, shown in 4.2.2.2 The AGV transportation schedule, transportation for most of the container groups is open for the main part of the day. However, it may be more beneficial to have more separated transportations where, at certain times, containers carrying the material with the highest urgency or criticality are transported and the less critical materials can wait. Making optimal adjustments to the transportation schedule would require approaches such as simulation-based optimization or optimization algorithms, however, adjustments to the seasonality of the daily transportation volume within the schedule is still achievable without changing the actual AGV transportation schedule.

Making adjustments to the transportation schedule could require adjustments in other parts of the supply chain, such as personnel operating time or various healthcare practices. As discussed in 5.1.1 Dependencies displayed in the control model, the AGV system is dependent on the replenishment plans for each of the materials transported by AGV. The replenishment plans are again dependent on different factors. So, for each material type, there are various dependencies that must be considered if adjustments are to be made to the supply of these materials.

Figure 33 displays the direct dependencies for the transportation schedule for each of the materials. This helps to understand the rigidity of the transportation of each material, where transportation of materials with more dependencies can be more challenging to change.

Material category	Container group	Material characteristics	Direct dependencies		
			Logistics personnel	Suppliers personnel	Healthcare practices
Consumer goods	**Warehouse container**	Consumer goods from central WH	x	x	
	Collecting container	Consumer goods from external suppliers	x	x	
		Residual orders of consumer goods	x	x	
Laundry	**Laundry container**	Personnel clothing	x	x	
		Fabrics	x	x	
Food	**Food container**	Lunch and dinner	x	x	x
		Groceries	x	x	x
		Other foods	x	x	x
Sterile goods	**Sterile Good container**	Sterile goods	x	x	x
Pharmaceuticals	**Pharmacy container**	Larger medical products	x	x	
Waste	**Waste container**	Larger and/or risk waste in regular volume	x		
	High-Volume Waste container	Large and/or risk waste in high volume	x		

Figure 33: Dependencies for the transportation schedule for each material type.

When changing the transportation schedule, for each of the materials there must be an evaluation of the benefits of changing the transportation against the costs and disadvantages of changing operating times.

The Laundry containers has the highest transportation volume, followed by the Warehouse containers. It is therefore apparent that changing the transportation of these materials could have a great impact on the AGV system. These materials are dependent on logistics personnel and suppliers personnel. The logistics personnel are the operators at the Supply Center in charge of moving the containers from the trailer to the pickup station for supply and moving the containers from the delivery station to the trailer for disposal, as well as the personnel at the hospital departments responsible for handling the materials upon delivery. Suppliers personnel are the personnel at the Warehouse and the Laundry that are responsible for delivering the materials to the Supply Center. The same dependencies are accurate for the Collecting containers, however the transportation volume for these containers is considerably lower than for Laundry and Warehouse containers, and will therefore have a smaller impact on the transportation volume.

The logistics personnel is the only dependencies of the transportation of Waste containers. That is, the logistics personnel handling the waste at the different hospital departments, as well as the personnel at the Waste Disposal. The high volume waste have the same dependencies as the regular volume waste.

The transportation of both Food and Sterile Good containers can be challenging to change because of the rigidness of the healthcare practices that are dependent on these goods. The Food containers are dependent on the meal times in all parts of the hospital, thus making it difficult to alter because it would affect the food supply to patients, personnel, and visitors. The transportation of the Food containers is also dependent on the personnel working at the Supply Kitchen, the center kitchens, the cafés, and the departments, as well as logistics personnel handling materials upon arrival. The transportation of Sterile Good containers is dependent on the medical operating schedules at the operation departments. It is also dependent on the personnel at the Sterile Supply and logistics personnel handling goods upon arrival.

For pharmacy containers, since there is very little AGV transportation of pharmaceutical products, the improvements in the supply of pharmaceuticals would not affect the AGV system to a considerable degree.

It is essential that any changes made to the transportation schedule are in fact beneficial changes, so this must be carefully evaluated. Also, today the transportation schedule cannot be determined in advance. AGV system only knows what is to be transported when button is pressed. Enabling offline scheduling would allow for a more level transportation volume.

The complexity of the hospital supply chain challenges the development of optimal solutions because it can be difficult to determine where the responsibilities are and to establish suitable collaborations. It can also be challenging to have a comprehensive view of a hospital supply chain, which makes it challenging to understand the current state and the core problems of the chain. A more centralized decision making would allow for determining which solutions that are best suited for the overall performance of the supply chain.

6.2.2 Reduce transportation volume

Various measures can be implemented for reducing the transportation volume, as shown in Figure 32. In the hospital supply chain, there is a challenge of product criticality. There are varying degrees of criticality for different hospital materials, and in some instances the consequences may be fatal if the material is not available at the right time. It is for example important to always have consumer goods used for emergency medical operations available at all times. However, through this study it is also evident that unnecessary replenishment may occur in certain instances, which results in a higher transportation volume. E.g. for the replenishment of fabrics, which is automatic unless personnel at the hospital departments notify the Laundry and change the order, the standard orders can on occasion be exaggerated compared to demand. If the cabinets are full when new laundry is delivered, the laundry must be treated as dirty laundry and will be sent back to the Laundry, which results in over processing and excessive transportation of these materials. Actively working towards to eliminating or reducing unnecessary replenishment would reduce the transportation volume.

The replenishment is also challenging considering the small inventory space in hospitals. This results in a more frequent replenishment, which also can lead to a higher transportation volume because the orders are less aggregated. An increased storage space at the hospital would reduce the ordering frequency and the transportation volume.

There is a challenge in regards to the container utilization. I.e. from the case study it is apparent that containers transported by AGV can often be half empty or less, and the contents will generally only be determined by the order size. So, if a department has ordered a small quantity of materials, an entire container will still be used. Aggregating orders and achieving higher container utilization would reduce the AGV transportation volume without reducing the quantity of materials delivered by AGV. However, there is no documentation of the actual utilization of each container.

It is important to find the most suitable supply structure for the hospital supply chain. For consumer goods, considerations must be made regarding having a Central Warehouse as opposed to direct delivery from supplier, for determining which materials to stock at the central warehouse. Vendor Managed Inventory (VMI) can also be considered for some materials. Establishing the most suitable supply structure can be cost beneficial, and it can also affect the transportation volume, because it can allow for a reduction in unnecessary replenishment.

For consumer goods there is uncertainty in the unit load for some materials from the Central Warehouse. When ordering, the personnel may not know whether a unit load is in packs or in single units because this is not specified in the ordering system. Thus, the order quantity may be much greater than what was intended. Specifying the unit load, which is the responsibility of the personnel at the Central Warehouse, can allow for more accurate replenishment and can reduce the transportation volume.

6.2.3 Increase transportation capacity

There are various measures related to increasing the transportation capacity, as shown in Figure 32. The measures that would have the most impact on the transportation capacity is arguably the vehicle quantity and the battery duration. Increasing number of vehicle is an alternative for increasing the transportation capacity, however, this alternative requires high costs. Increased battery duration would also increase the transportation capacity because it would increase the number of operable vehicles throughout the day. From the analysis, it can be argued that increased battery duration would result in a waiting time that is mainly dependent on the transportation volume. Figure 31 in the analysis indicates that if the recharging of vehicles where not a factor, the transportation volume at 07:30 to 08:00 could have been maintained throughout the day without the waiting times increasing.

There is also an alternative of implementing more pickup and delivery stations. This is maybe especially relevant for the Waste Disposal considering that there are only two pickups stations there. Increasing the number of pickup stations at the Waste Disposal may reduce the urgency of container pickup at these stations and thus reduce the need for giving priority to these stations. As a result, this could give increased (or at least equal) priority to transportations of other materials that may actually have a higher criticality in terms of timely delivery. E.g. the transportation of Sterile Good or Food containers. However, it must be considered whether the implementation of more stations would be beneficial if the number of vehicles remain the same.

Establishing more elevators could also be considered, but for the case of St. Olav’s Hospital, the elevators as a bottleneck seems to be more accurate for the *people* using the elevators, considering that the AGVs have first priority on the elevators. If obstacles occur in a vehicles path, the vehicle will not move until the obstacle is removed. So preventing obstacles can be a proactive measure for ensuring that a vehicle do not use unnecessary transportation time, and thus freeing up capacity for that vehicle.

6.3 Implementation of measures

Any measures performed must be beneficial for the overall performance of the hospital, where the aim is related to the quality of services given to the patient, as well as having cost efficient solutions.

The correlation of waiting time with transportation volume and transportation capacity indicates that there is a trade-off between vehicle utilization and waiting time. Vehicle utilization can increase either when transportation volume is increasing or when transportation capacity is declining. It can be cost efficient to have high vehicle utilization, but it can also result in increased waiting times. This trade-off must be considered for the investigation of the overall performance.

7. Conclusion

The conclusion deliberates on how the research questions were answered and what the outcome was, and discusses the practical contributions and contributions to the literature, as well as an explanation of limitations and suggestions for further research.

7.1 Research questions

Research question 1 aimed at finding characteristics and dependencies related to the AGV system at St. Olav's Hospital. It was answered by finding literature on the hospital supply chain and on AGV systems, and through the case study by finding the characteristics related to the AGV system. The control model methodology was used to more clearly present and discuss the characteristics and dependencies.

Research question 2 aimed at finding potential improvement measures related to the AGV system to facilitate timely delivery of materials at the hospital. It was answered by studying the findings from the case study and performing a quantitative analysis. A framework was developed to present the potential improvement measures that were discovered related to achieving timely delivery by AGV transportation. These measures where categorized into three approaches for achieving timely delivery, which are levelling the transportation volume, reducing the transportation volume, and increasing the transportation capacity. The measures were also hierarchically categorized into measures for the AGV system, the hospital environment, and supply chain management.

7.2 Contributions

In the context of research on AGV systems, this thesis adds to the research on AGV systems in hospitals, and gives a framework for possible measures for ensuring timely delivery of materials in hospitals. For the case company, the research on the AGV system gives a basis for further investigation into this field in order to establish improvements for the hospital, as well as for other similar cases. The measures are aimed at St. Olav's Hospital, but they can also be found relevant in other hospital supply chains where AGVs are used for internal transportation, because hospital supply chains often have similarities.

7.3 Research limitations and further research

A limitation is that even though there are clear problems related to timely delivery at St. Olav's Hospital, quantitative data does not exist on the actual degree of timely delivery. This makes it challenging to determine which materials that are the most affected and at what times during the operating time this occurs. However, information retrieved from the case study, as well as from findings in the analysis, helped to provide an understanding of this. Another limitation is that there may be validity issues related to the information retrieved in the case study by interviews and observations, since this is one of the disadvantages of using these research methods.

Considering that logistics has a high impact on both performance and costs for the hospital supply chain, further research should be conducted on logistics in hospitals in general, as well as the structure of hospital supply chains, such as performing in-house activities as opposed to outsourcing, and having a central warehouse as opposed to direct delivery from supplier. Further research should also be conducted into the scheduling of AGVs in a hospital environment, as well as establishing common practices and standards for internal transportation of materials in hospitals. Also, offline scheduling of AGV transportation should be studied, which would allow for scheduling in advance and could enable a more level transportation volume. Research can also be conducted on inventory management and particularly product criticality for hospital materials. This can help establish suitable solutions for replenishment. In addition, research on measures for improving container utilization can be conducted to help reduce the transportation volume while maintaining the same volume of replenishment.

8. Literature:

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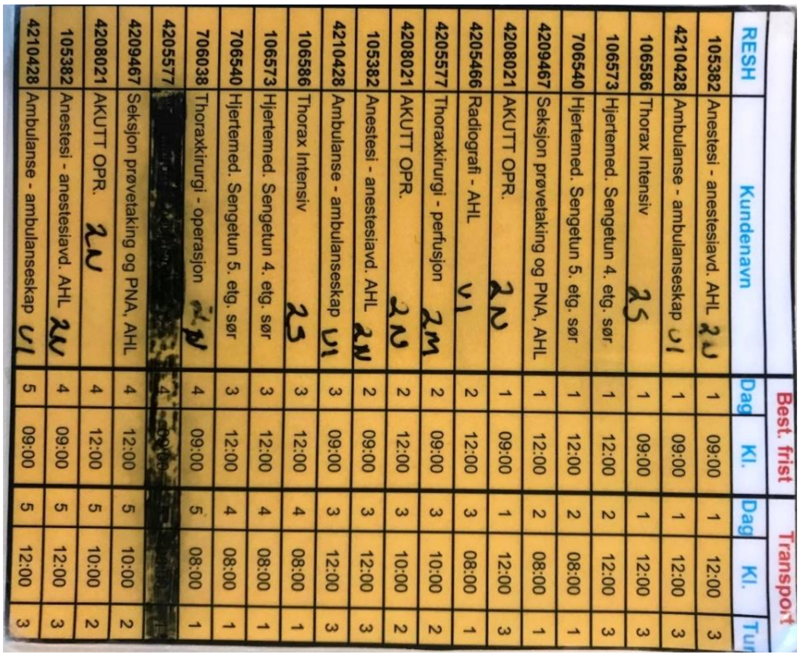
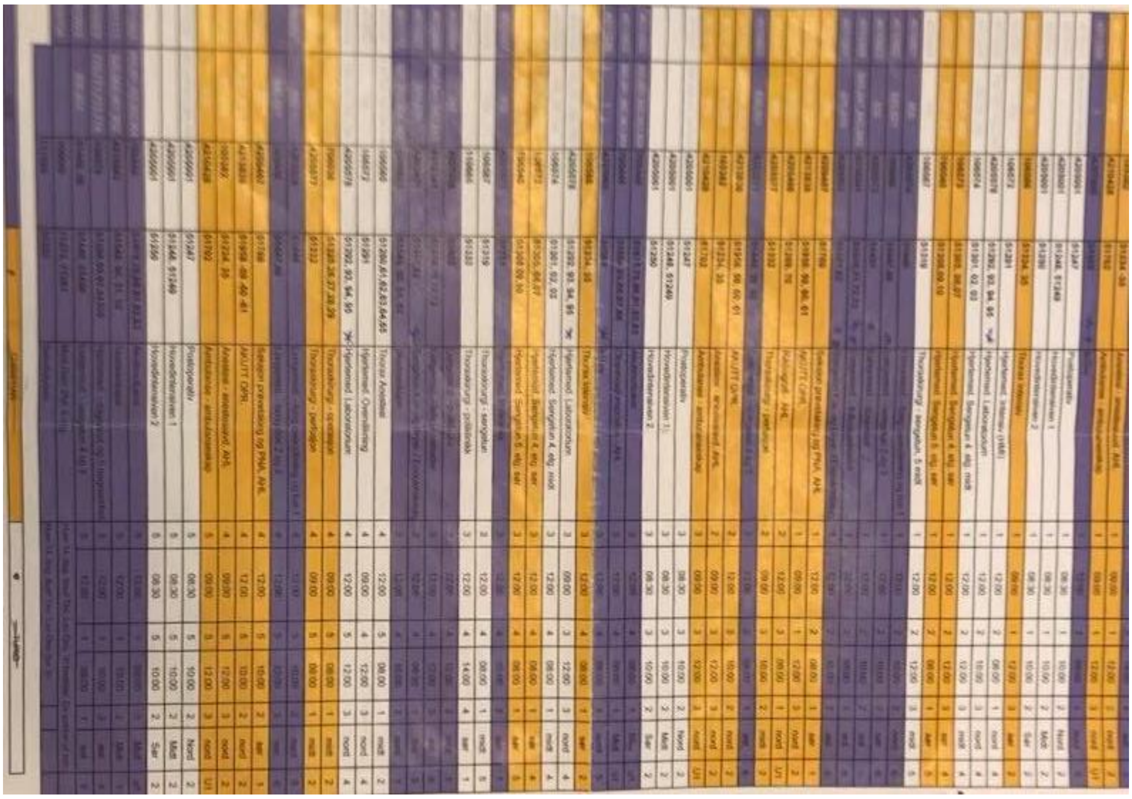
9. Appendix

9.1 Consumer goods



RESH	Kundenavn	Best. frist Dag	Best. frist Kl.	Transport Dag	Transport Kl.	Tur
105382	Anestesi - anestesiavd. AHL 2N	1	09:00	1	12:00	3
4210428	Ambulanse - ambulanseskap U1	1	09:00	1	12:00	3
106586	Thorax Intensiv 2S	1	09:00	1	12:00	3
106573	Hjertemed. Sengetun 4. etg. sør	1	12:00	2	12:00	3
706540	Hjertemed. Sengetun 5. etg. sør	1	12:00	2	08:00	1
4209467	Seksjon prøvetaking og PNA, AHL	1	12:00	2	08:00	1
4208021	AKUTT OPR. 2N	1	09:00	1	12:00	3
4205466	Radiografi - AHL U1	2	12:00	3	08:00	1
4205577	Thoraxkirurgi - perfusjon 2M	2	09:00	3	10:00	2
4208021	AKUTT OPR. 2N	2	12:00	3	10:00	2
105382	Anestesi - anestesiavd. AHL 2N	2	09:00	3	12:00	3
4210428	Ambulanse - ambulanseskap U1	3	09:00	3	12:00	3
106586	Thorax Intensiv 2S	3	12:00	4	08:00	1
106573	Hjertemed. Sengetun 4. etg. sør	3	12:00	4	08:00	1
706540	Hjertemed. Sengetun 5. etg. sør	3	12:00	4	08:00	1
706038	Thoraxkirurgi - operasjon	4	09:00	5	08:00	1
4205577	[redacted]	4	[redacted]	5	[redacted]	2
4209467	Seksjon prøvetaking og PNA, AHL	4	12:00	5	10:00	2
4208021	AKUTT OPR. 2N	4	12:00	5	10:00	2
105382	Anestesi - anestesiavd. AHL 2N	4	09:00	5	12:00	3
4210428	Ambulanse - ambulanseskap U1	5	09:00	5	12:00	3



9.2 Laundry

Texi	Mat & Cafe	<u>Gjennomsnittelig mengde med AGV vogner levert St. Olav</u>	Utenfor Øya
45	5	*(Det er plass til 45 vogner på bilen)*	25
47	3	*(Hvis det er mer enn 90 vogner kreves 3 turer)*	25
46	4		29
42	4		22
45	4	***106,5***	25,25

Texi	Mat & Cafe		Utenfor Øya
37			3
55			2
41			4
40			4
43,25		***102***	3,25

Texi	Mat & Cafe		Utenfor Øya
40			18
33			19
38			16
36			14
36,75		***81,5***	16,75

Texi	Mat & Cafe		Utenfor Øya
38	5		24
43	6		20
34	3		21
37	6		20
38	5	***83,75***	21,25

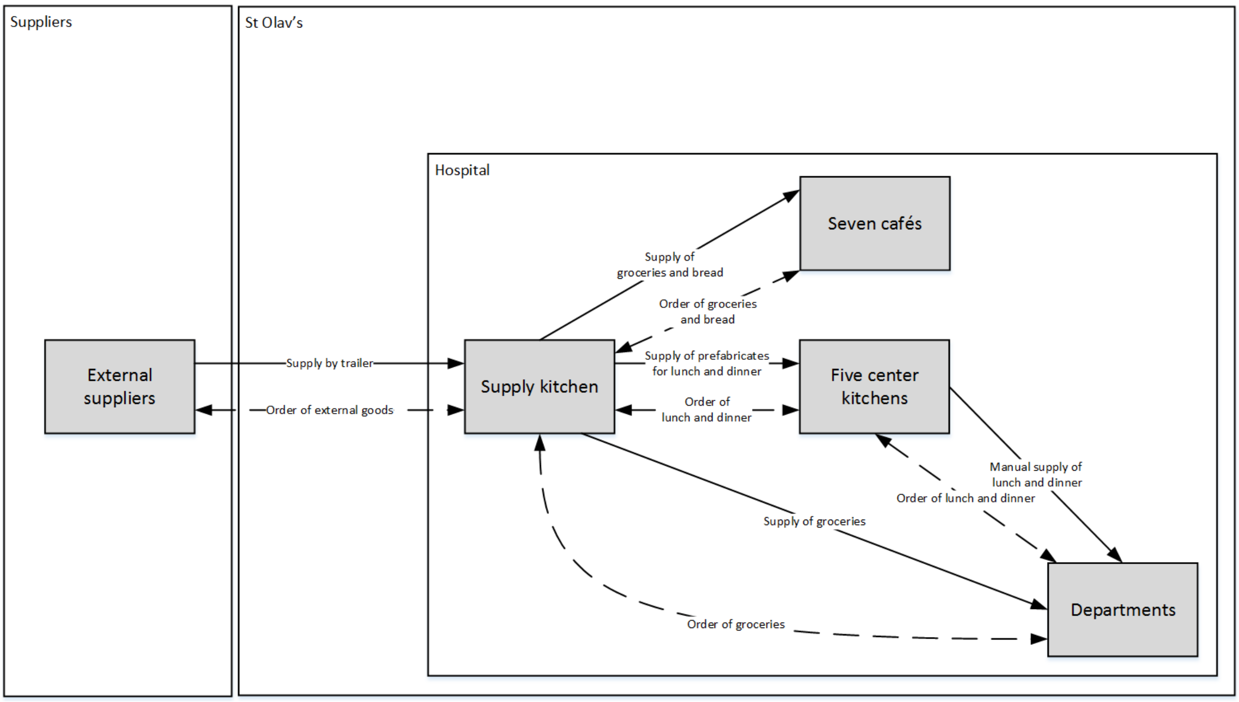
Texi	Mat & Cafe		Utenfor Øya
41			
40			
35			
41			1
39,25		***105***	1

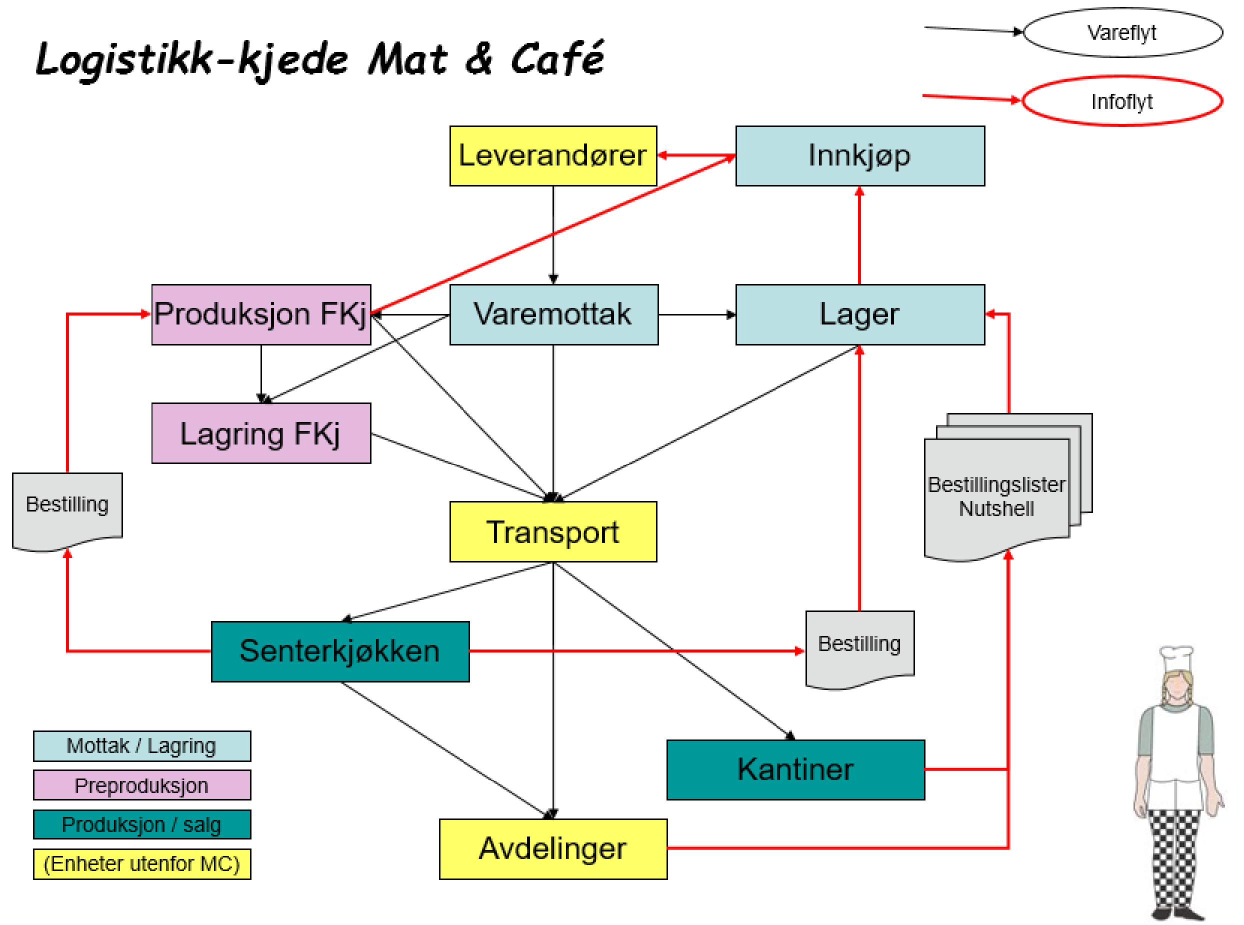
9.3 Food

Driftsplan kjøkken Revidert 06.11.2017 / T.Våg | 84 vogner i utvalget

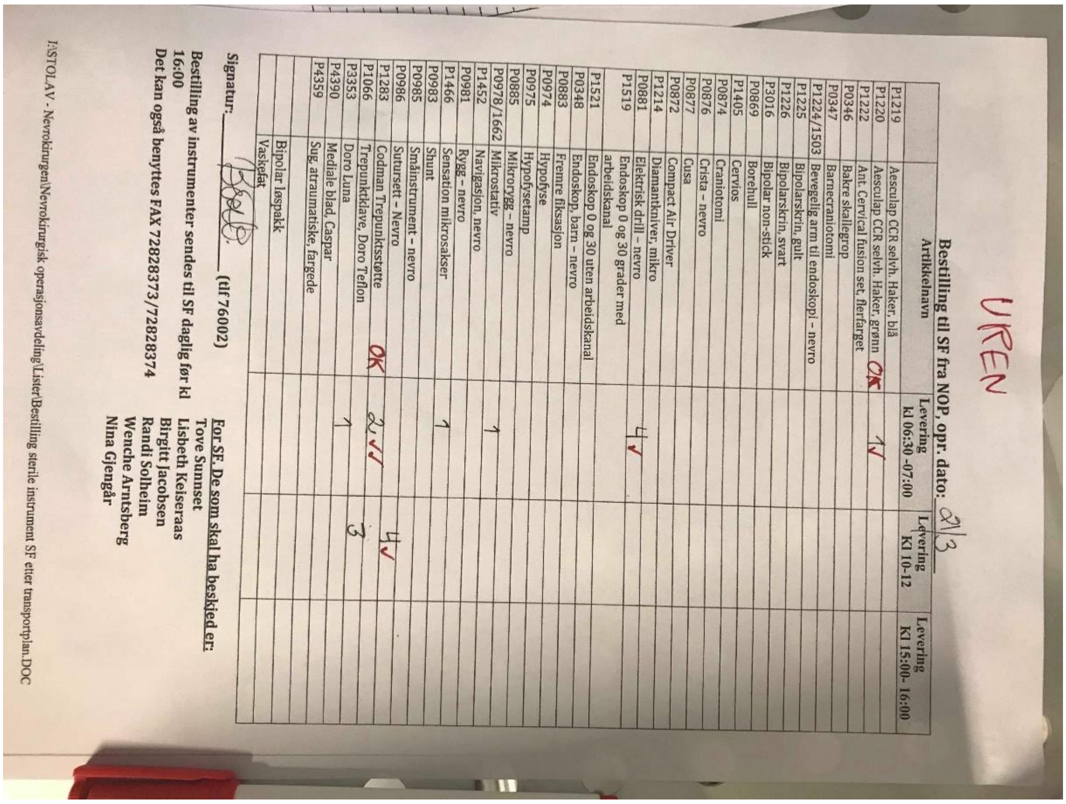
Transportplan AGV

Dag	Senter	Mottaker	Leveranse	Agv ut fra kl	Siste agv senest	Totalt antall Antall vogner (ca)	Fordelt på mottakere Antall vogner (ca)	
Ma-fre	AHL	Café	Brødvarer	07:15	07:45		1	
Ma-fre	Gastro	Café	Brødvarer	07:15	07:45		1	
Ma-fre	Bevegelse	Café	Brødvarer	07:15	07:45		1	
Ma-fre	Kunnskap	Café	Brødvarer	07:15	07:45		1	
Ma-fre	Kvinne-Barn	Café + avdelinger	Brødvarer	07:15	07:45		1	
Ma-fre	Nevro	Café + avdelinger	Brødvarer	07:15	07:45	17	1	
Ma-fre	Labb-inn	Café	Brødvarer	07:15	07:45		1	
Ma-fre	AHL	Avdelinger	Kolonial	07:15	07:45		3	Max-tall
Ma-fre	Gastro	Avdelinger	Kolonial	07:15	07:45		4	Max-tall
Ma-fre	Bevegelse	Avdelinger	Kolonial	07:15	07:45		2	Max-tall
Ma-fre	Kunnskap	Avdelinger	Kolonial	07:15	07:45		1	
Ma-fre	AHL	Senterkjøkken	Lunsj	09:30	10:15		1	
Ma-fre	Gastro	Senterkjøkken	Lunsj	09:30	10:15		1	
Ma-fre	Bevegelse	Senterkjøkken	Lunsj	09:30	10:15		1	
Ma-fre	Kvinne-Barn	Senterkjøkken	Lunsj	09:30	10:15	10	1	
Ma-fre	Nevro	Senterkjøkken	Lunsj	09:30	10:15		1	
Ma-fre	Kvinne-Barn	Avdelinger	Kolonial	09:30	10:15		3	Max-tall
Ma-fre	Nevro	Avdelinger	Kolonial	09:30	10:15		2	Max-tall
Ma-fre	AHL	Senterkjøkken	Middag	11:45	12:45		1	
Ma-fre	Gastro	Senterkjøkken	Middag	11:45	12:45		1	
Ma-fre	Bevegelse	Senterkjøkken	Middag	11:45	12:45	5	1	
Ma-fre	Kvinne-Barn	Senterkjøkken	Middag	11:45	12:45		1	
Ma-fre	Nevro	Senterkjøkken	Middag	11:45	12:45		1	
Ma-fre	AHL	Café	Kolonial	12:45	13:30		2	Max-tall
Ma-fre	Gastro	Café	Kolonial	12:45	13:30		2	Max-tall
Ma-fre	Bevegelse	Café	Kolonial	12:45	13:30		1	
Ma-fre	Kvinne-Barn	Café	Kolonial	12:45	13:30	10	2	Max-tall
Ma-fre	Kunnskap	Café	Kolonial	12:45	13:30		1	
Ma-fre	Nevro	Café	Kolonial	12:45	13:30		1	
Ma-fre	Labb-inn	Café	Kolonial	12:45	13:30		1	
							42	


Suppliers
St Olav's
Hospital
External suppliers
Supply by trailer
Order of external goods
Supply kitchen
Seven cafés
Supply of groceries and bread
Order of groceries and bread
Supply of prefabricates for lunch and dinner
Order of lunch and dinner
Five center kitchens
Manual supply of lunch and dinner
Order of lunch and dinner
Supply of groceries
Order of groceries
Departments


Logistikk-kjede Mat & Café
Vareflyt
Infoflyt
Leverandører
Innkjøp
Produksjon FKj
Varemottak
Lager
Lagring FKj
Bestillingslister Nutshell
Bestilling
Transport
Senterkjøkken
Bestilling
Kantiner
Avdelinger
Mottak / Lagring
Preproduksjon
Produksjon / salg
(Enheter utenfor MC)

9.4 Sterile goods



UREN

Bestilling til SF fra NOP, opr. dato: 21/3

	Artikkelnavn	Levering kl 06:30 -07:00	Levering Kl 10-12	Levering Kl 15:00- 16:00
P1219	Aesculap CCR selvh. Haker, blå			
P1220	Aesculap CCR selvh. Haker, grønn OK	1✓		
P1222	Ant. Cervical fusion set, flerfarget			
P0346	Bakre skallegrop			
P0347	Barnecraniotomi			
P1224/1503	Bevegelig arm til endoskopi – nevro			
P1225	Bipolarskrin, gult			
P1226	Bipolarskrin, svart			
P3016	Bipolar non-stick			
P0869	Borehull			
P1405	Cervios			
P0874	Craniotomi			
P0876	Crista – nevro			
P0877	Cusa			
P0872	Compact Air Driver			
P1214	Diamantkniver, mikro			
P0881	Elektrisk drill – nevro	4✓		
P1519	Endoskop 0 og 30 grader med arbeidskanal			
P1521	Endoskop 0 og 30 uten arbeidskanal			
P0348	Endoskop, barn – nevro			
P0883	Fremre fiksasjon			
P0974	Hypofyse			
P0975	Hypofysetamp			
P0885	Mikrorygg – nevro			
P0978/1662	Mikrostativ	1		
P1452	Navigasjon, nevro			
P0981	Rygg – nevro			
P1466	Sensation mikrosakser	1		
P0983	Shunt			
P0985	Småinstrument – nevro			
P0986	Sutursett – Nevro			
P1283	Codman Trepunktsstøtte OK	2✓✓	4✓	
P1066	Trepunktklave, Doro Teflon		3	
P3353	Doro Luna	1		
P4390	Mediale blad, Caspar			
P4359	Sug, atraumatiske, fargede			
	Bipolar løspakk			
	Vaskefat			

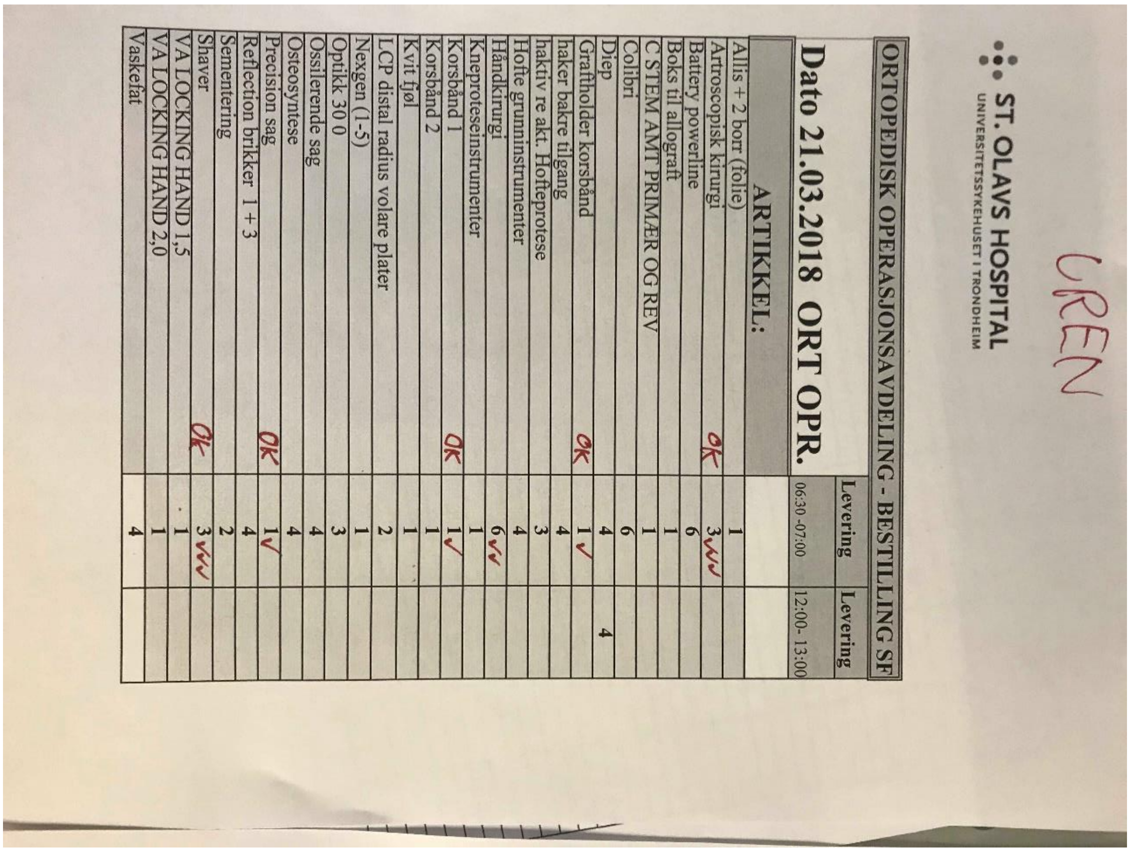
Signatur: [signature] (tlf 76002)

Bestilling av instrumenter sendes til SF daglig før kl 16:00

Det kan også benyttes FAX 72828373/72828374

For SF. De som skal ha beskjed er:
Tove Sunnset
Lisbeth Keiseraas
Birgitt Jacobsen
Randi Solheim
Wenche Arntsberg
Nina Gjengår

I:\STOLAV - Nevrokirurgen\Nevrokirurgisk operasjonsavdeling\Lister\Bestilling sterile instrument SF etter transportplan.DOC



UREN

ST. OLAVS HOSPITAL
UNIVERSITETSSYKEHUSET I TRONDHEIM

ORTOPEDISK OPERASJONSAVDELING - BESTILLING SF

Dato 21.03.2018 ORT OPR.		Levering 06:30 -07:00	Levering 12:00- 13:00
ARTIKKEL:			
Allis + 2 borr (folie)		1	
Artroscopisk kirurgi	OK	3✓✓✓	
Battery powerline		6	
Boks til allograft		1	
C STEM AMT PRIMÆR OG REV		1	
Colibri		6	
Diep		4	4
Graftholder korsbånd	OK	1✓	
haker bakre tilgang		4	
haktiv re akt. Hofteprotese		3	
Hofte grunninstrumenter		4	
Håndkirurgi		6✓✓	
Kneproteseinstrumenter		1	
Korsbånd 1	OK	1✓	
Korsbånd 2		1	
Kvit fjøl		1	
LCP distal radius volare plater		2	
Nexgen (1-5)		1	
Optikk 30 0		3	
Ossilerende sag		4	
Osteosyntese		4	
Precision sag	OK	1✓	
Reflection brikker 1 + 3		4	
Sementering		2	
Shaver	OK	3✓✓✓	
VA LOCKING HAND 1,5		1	
VA LOCKING HAND 2,0		1	
Vaskefat		4	

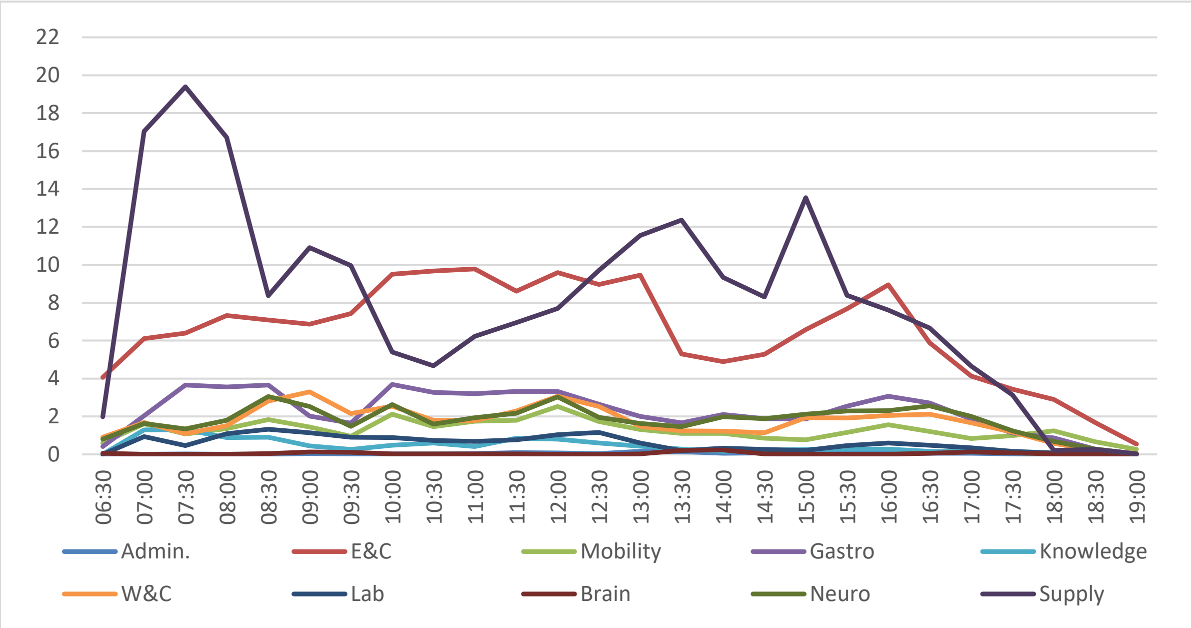
9.5 Waste

Avfallsmengder 2017		
	KG	Tonn
Risikoavfall	371507	371,5
Risikoavfall patologi	9211	9,2
	380718	380,7
Total mengde farlig avfall	434834	434,8
Container nr 5 Restavfall manuelt	191380	191,38
container nr 7 papp manuelt	87260	87,26
Ca Mengde som går i avfallsuget	1300000	1300
Total mengde avfall	2918744	2918,7
Noen kommentarer til tallene		
Det mest av risikoavfall kommer med AGV og ca 2/3 av patologien.		
Det kommer også en del avfall som EE-avfall og trevirke og metall med AGV		
Det meste av pappen kommer med AGV		
Det meste av avfallet som kommer med AGV løftes minst 2 ganger.		

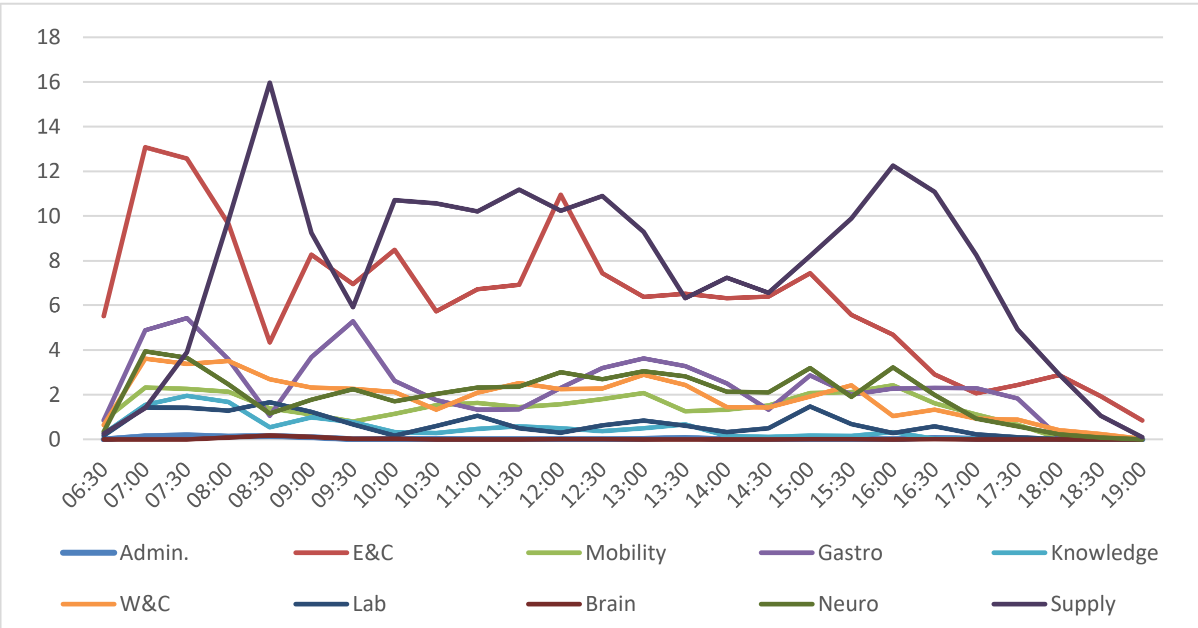
9.6 Statistical analysis

9.6.1 Pickup and delivery locations

The analyzations presented here show the transportation volume *from* and *to* each hospital center at every half hour of the daily AGV operating time.



Average transportation volume from each hospital center.



Average transportation volume to each hospital centers

These figures illustrates the average transportation volume *from* each hospital center, and the average transportation volume *to* each hospital center. From the figures, it is evident that the largest transportation volumes are from the Supply Center and the E&C Center. In both centers there are suppliers transporting materials to the various hospital departments, which gives a high transportation volume for these centers. The Supply Center has the highest transportation volume, both from and to the center. For this center, the transportation volume constitutes of 33.6 % of the total transportation volume *from* the centers, and 35.8 % of the total transportation volume *to* the centers. The transportations for this center consists of Waste and High-Volume Waste containers transported to and from the Waste Disposal, as well as Laundry, Warehouse, and Collecting containers transported to and from the goods arrival. There is a high transportation volume to the Supply Center around 07:30, which is due to dirty laundry being transported from the various hospital centers for delivery to the Laundry service.

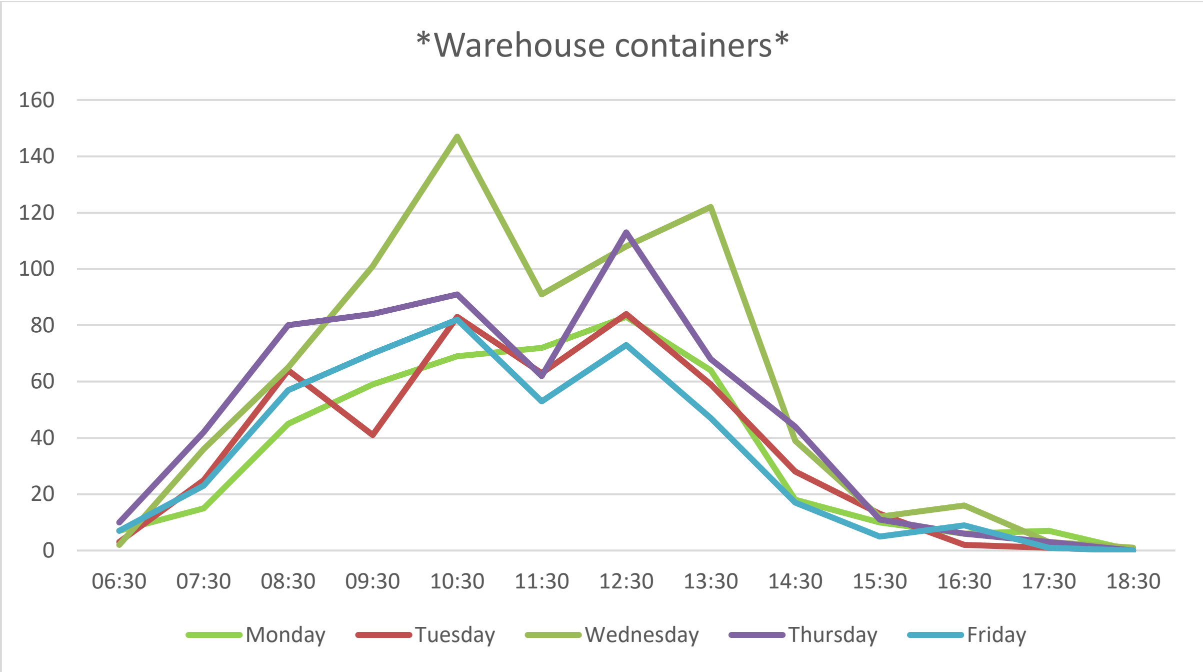
The second largest transportation volume is for the E&C Center. The transportation volume from this center constitutes of 27.6 % of the total transportation volume *from* the centers, and 28.5 % of the total transportation volume *to* the centers. This consists of transportations to and from the various clinical hospital departments, but the main share is for the Supply Kitchen and the Sterile Supply. These suppliers are situated in U1 at the E&C center. The main reason for the peak in transportations from this center around 07:30, is most likely because of the transportations of baked goods and groceries from the Supply Kitchen, which occurs between 07:15 and 07:45.

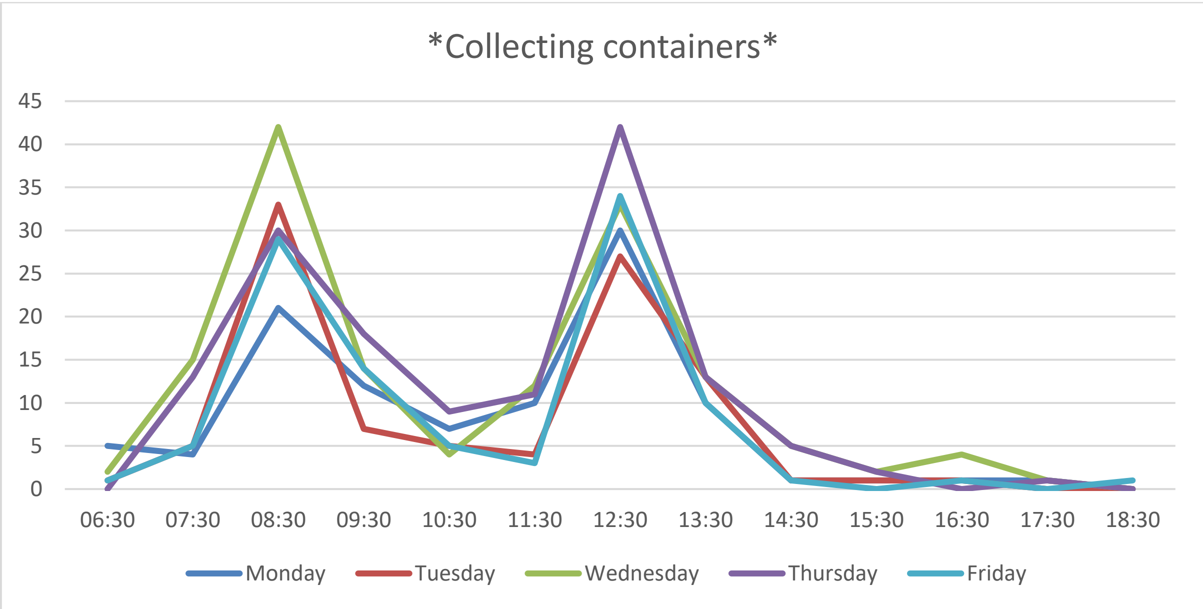
The centers with the highest volumes after the Supply Center and the E&C Center are the Gastro Center, the Neuro Center, the W&C Center, and the Mobility Center. These centers combined constitute of 33.6 % of the total transportation volume *from* the centers, and 30.9 % of the total transportation volume *to* the centers. These are all clinical centers with operation departments that creates demand for a variety of materials.

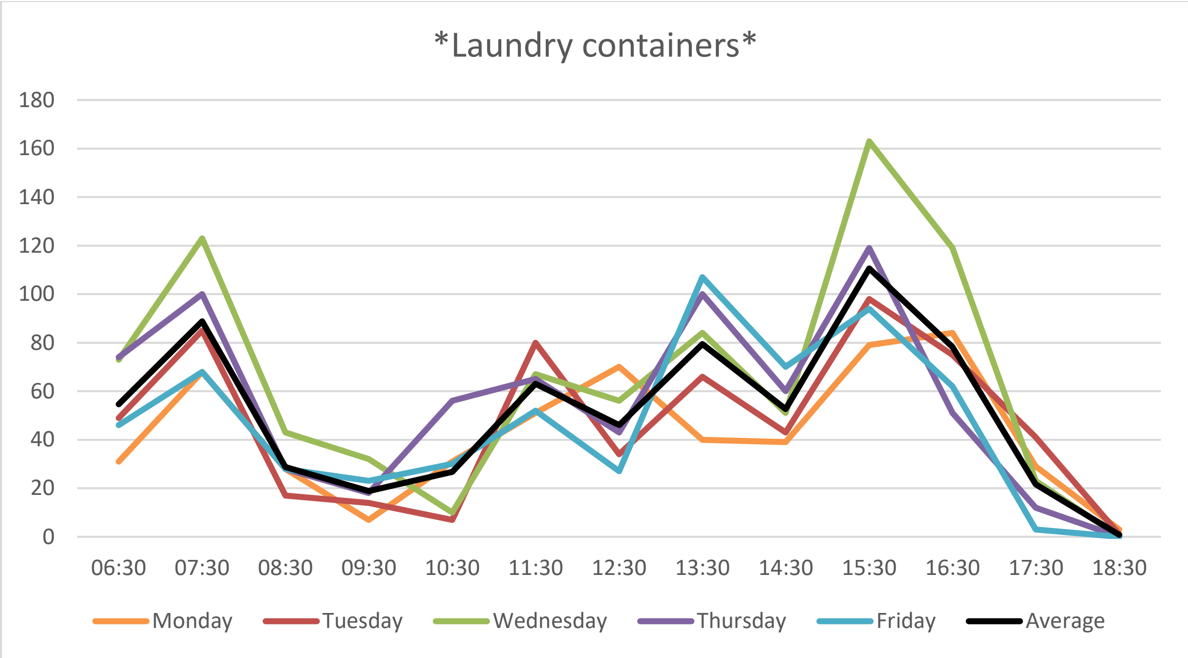
For the Knowledge Center, the Lab Center, the Admin. Center, and the Brain Center, the combined transportation volume only constitutes of 5.2 % of the total transportation volume *from* the centers, and 4.9 % of the total transportation volume *to* the centers.

9.1.2 Tranportation volume for each container dividing into weekdays

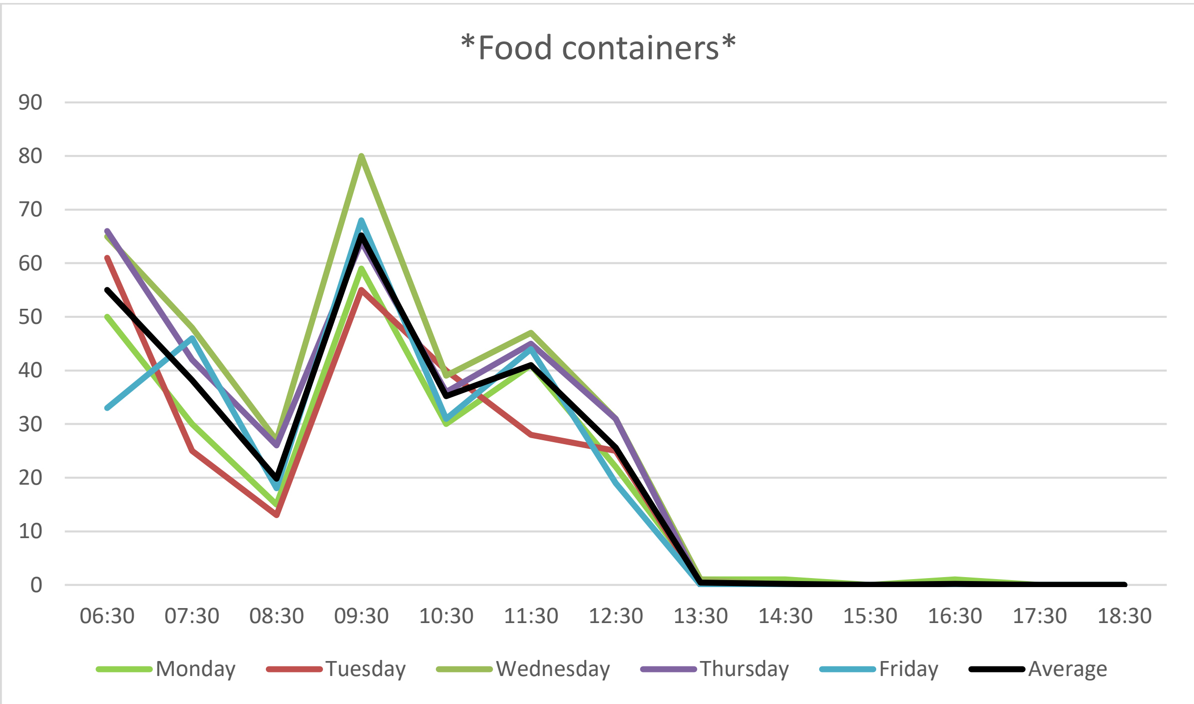
Statistical data of transportation volume for each material type for the entire period (november)


Warehouse containers
160
140
120
100
80
60
40
20
0
06:30
07:30
08:30
09:30
10:30
11:30
12:30
13:30
14:30
15:30
16:30
17:30
18:30
Monday
Tuesday
Wednesday
Thursday
Friday

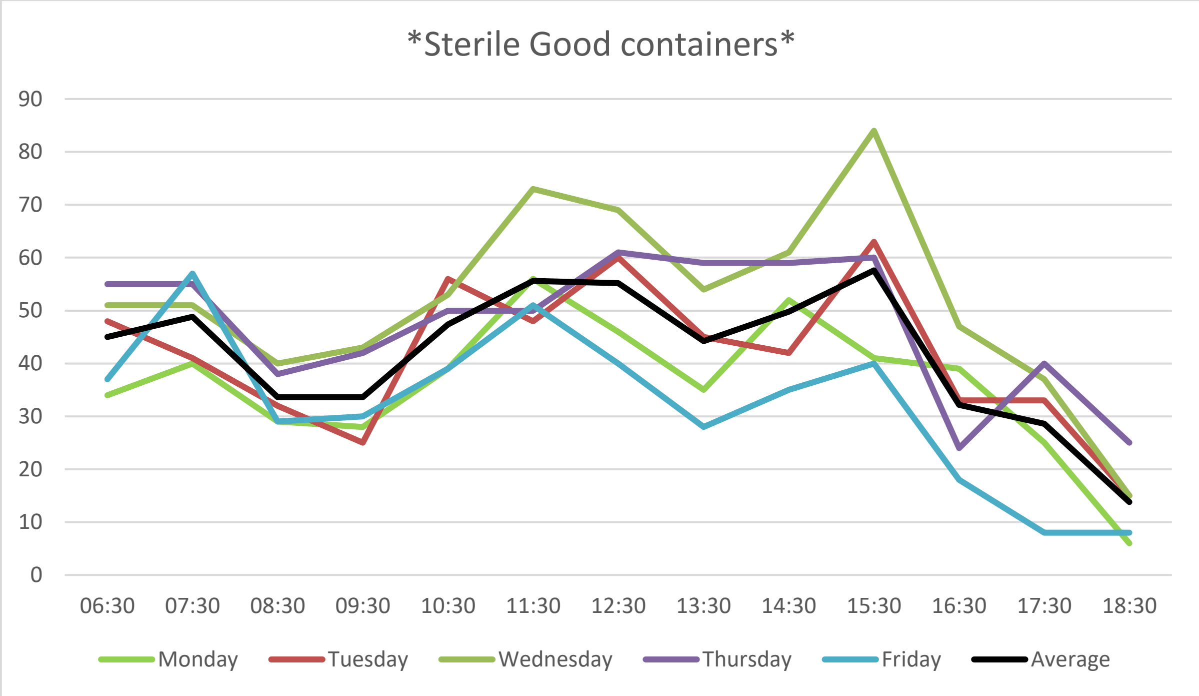

Collecting containers
45
40
35
30
25
20
15
10
5
0
06:30
07:30
08:30
09:30
10:30
11:30
12:30
13:30
14:30
15:30
16:30
17:30
18:30
Monday
Tuesday
Wednesday
Thursday
Friday



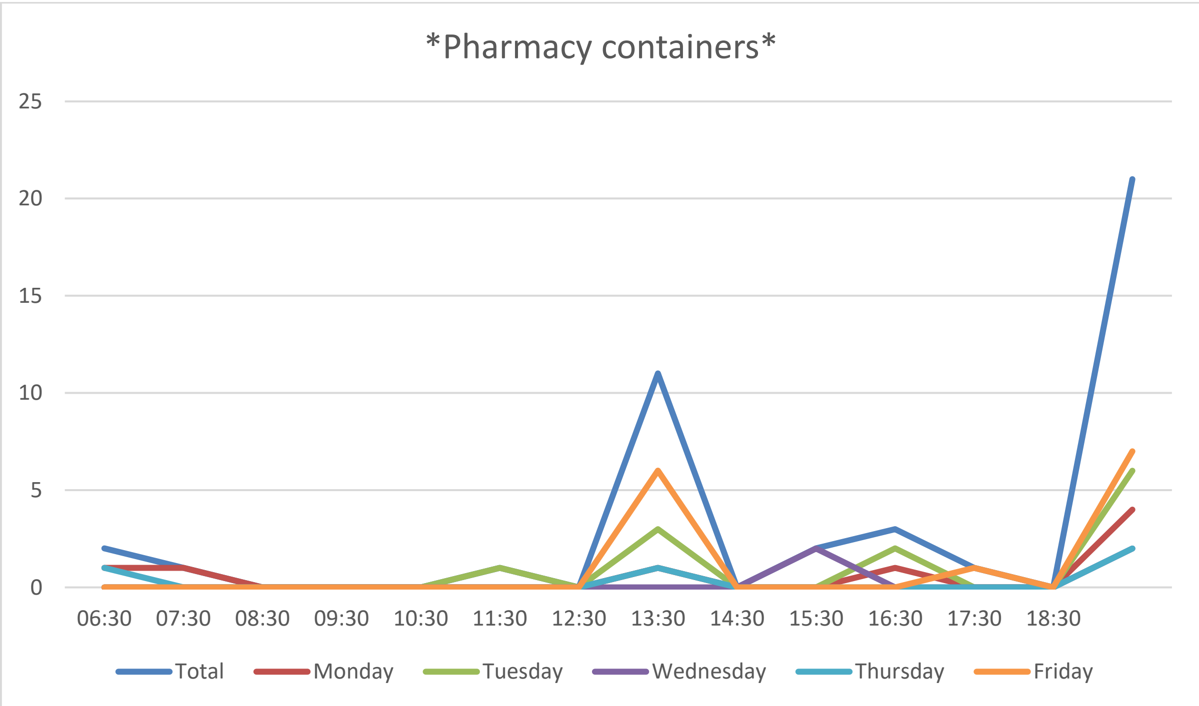
Laundry containers
180
160
140
120
100
80
60
40
20
0
06:30
07:30
08:30
09:30
10:30
11:30
12:30
13:30
14:30
15:30
16:30
17:30
18:30
Monday
Tuesday
Wednesday
Thursday
Friday
Average



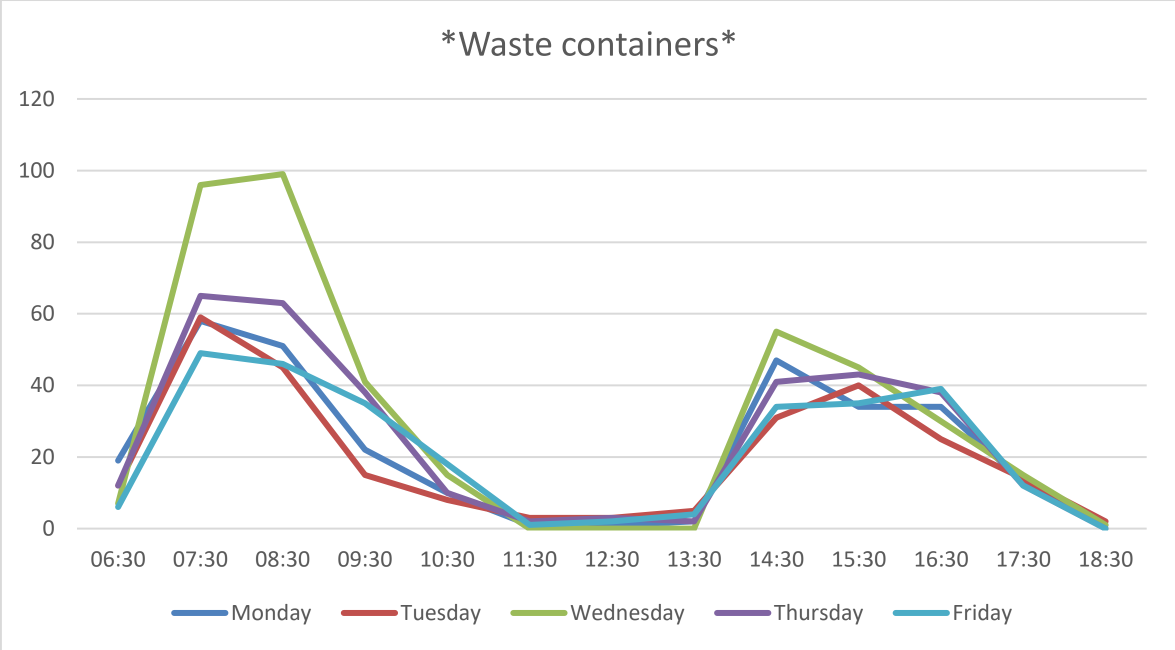
Food containers
90
80
70
60
50
40
30
20
10
0
06:30
07:30
08:30
09:30
10:30
11:30
12:30
13:30
14:30
15:30
16:30
17:30
18:30
Monday
Tuesday
Wednesday
Thursday
Friday
Average



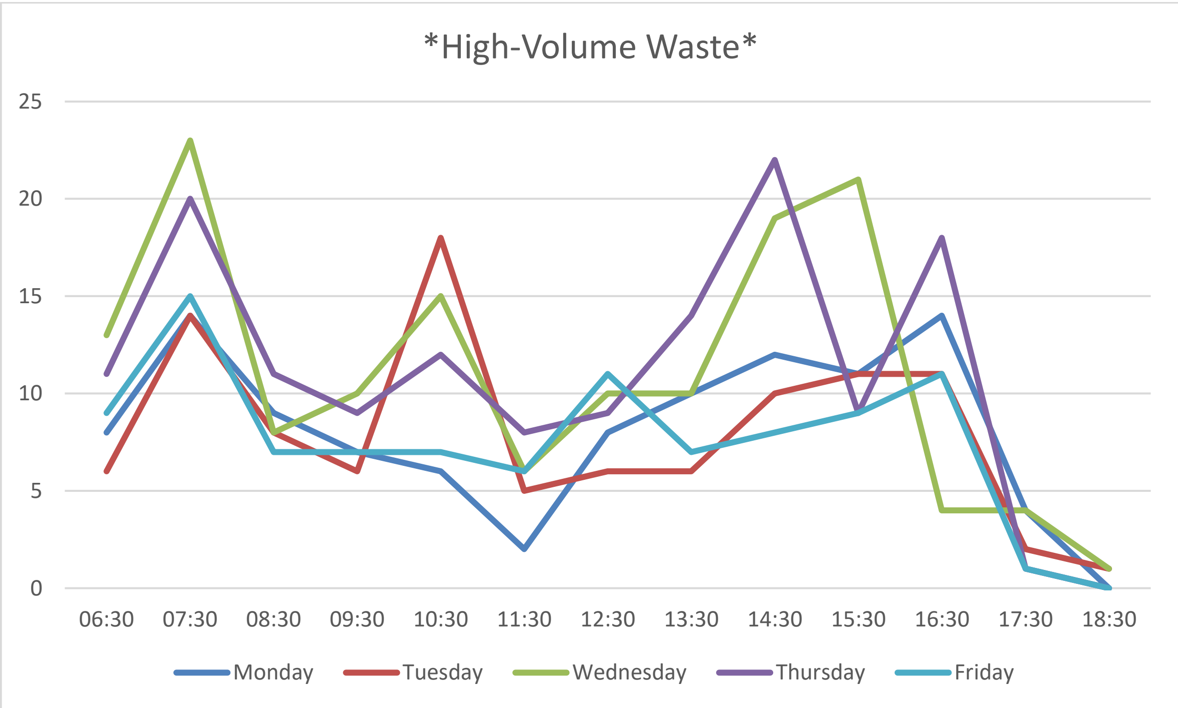
Sterile Good containers
90
80
70
60
50
40
30
20
10
0
06:30 07:30 08:30 09:30 10:30 11:30 12:30 13:30 14:30 15:30 16:30 17:30 18:30
Monday Tuesday Wednesday Thursday Friday Average



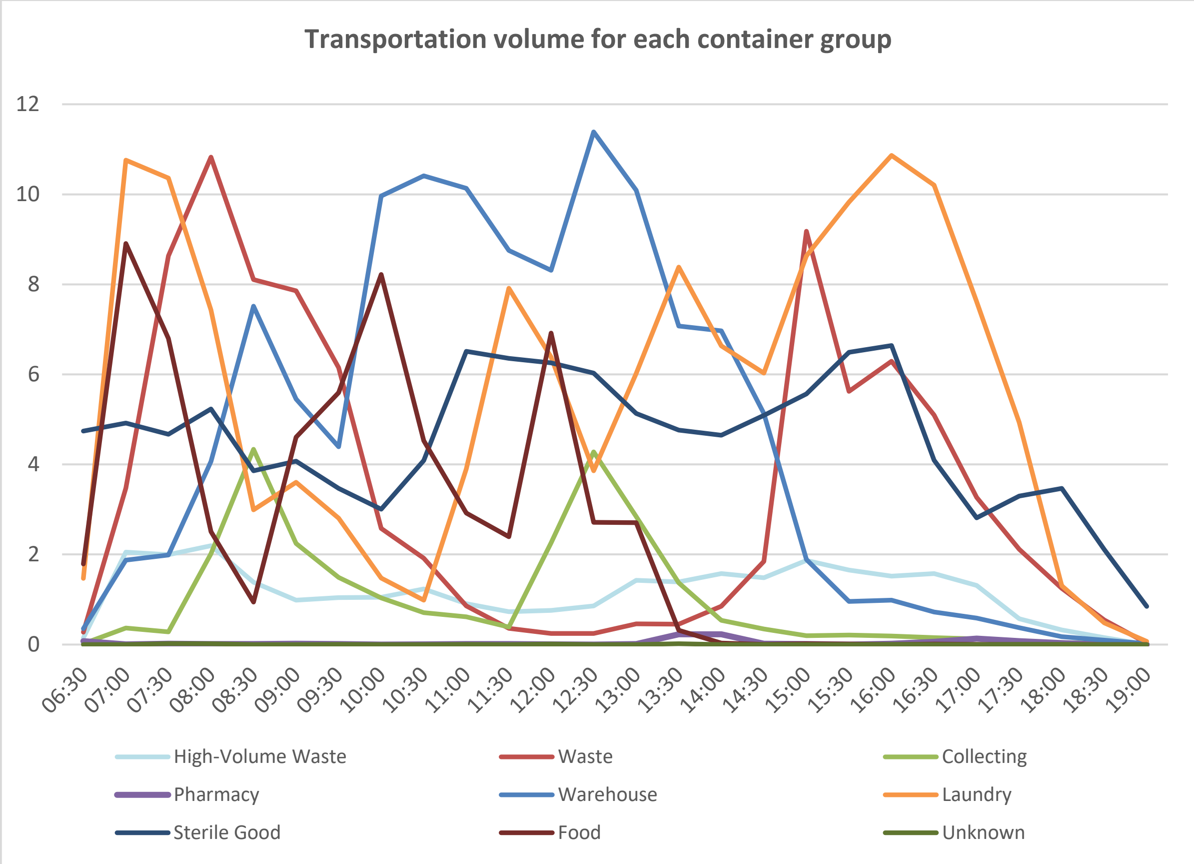
Pharmacy containers
25
20
15
10
5
0
06:30 07:30 08:30 09:30 10:30 11:30 12:30 13:30 14:30 15:30 16:30 17:30 18:30
Total Monday Tuesday Wednesday Thursday Friday

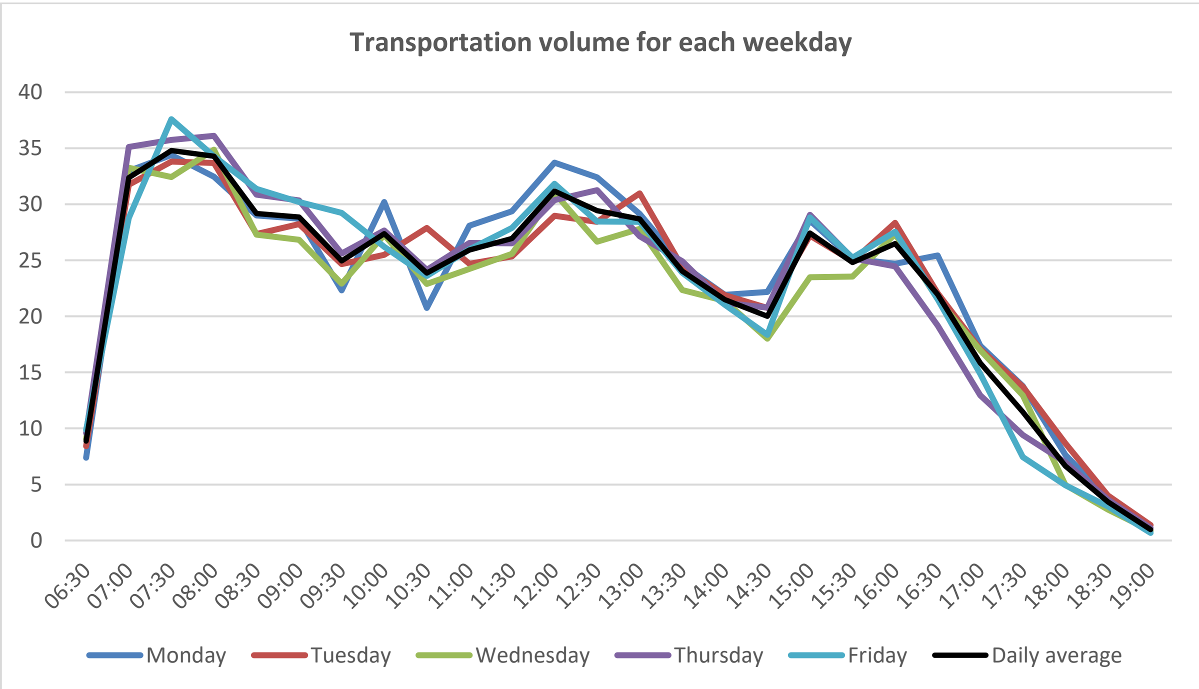


Waste containers
120
100
80
60
40
20
0
06:30 07:30 08:30 09:30 10:30 11:30 12:30 13:30 14:30 15:30 16:30 17:30 18:30
Monday Tuesday Wednesday Thursday Friday



High-Volume Waste
25
20
15
10
5
0
06:30 07:30 08:30 09:30 10:30 11:30 12:30 13:30 14:30 15:30 16:30 17:30 18:30
Monday Tuesday Wednesday Thursday Friday


Transportation volume for each container group
12
10
8
6
4
2
0
06:30
07:00
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
18:30
19:00
High-Volume Waste
Waste
Collecting
Pharmacy
Warehouse
Laundry
Sterile Good
Food
Unknown


Transportation volume for each weekday
40
35
30
25
20
15
10
5
0
06:30
07:00
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
18:30
19:00
Monday
Tuesday
Wednesday
Thursday
Friday
Daily average

9.7 Framework

How	The AGV system	Hospital environment	Supply Chain Mgt
Level transportation volume	**Scheduling** Change AGV transportation schedule by separating the schedule for each container group more, rather than allowing transport of most container groups all day Perform more transportation jobs when there is little transportation. I.e. between 17:00 and 19:30. E.g. Warehouse, Laundry or Waste containers **Operating time** Expand AGV operating time (and AGV transportation schedule) **Priority rules** Give priority to different material types to enable transport of high priority materials	**Personnel** Expand personnel operating time to enable increased AGV operating time **Practices** Change healthcare practices to enable change in delivery time. E.g. practices such as hospital meal plans or medical schedules	**Centralize** Centralize decision making for the supply chain to give a comprehensive view **Integrate systems** Integrating ERP system with AGV system, allow for more offline scheduling where transportation can be scheduled in advance **Replenishment plans** Change plans for replenishment to allow for changes in transportation schedule **Data collection** Retrieve quantitative data on total waiting time and delivery precision

Framework (cont.)

How	The AGV system	Hospital environment	Supply Chain Mgt
Reduce transportation volume		**Local inventory** Increase storage space at hospital to reduce procurement frequency **Container utilization** Increase container utilization by combining orders **Unnecessary replenishment** Examine the various order quantities to eliminate unnecessary replenishment. E.g. Replenishment of fabrics is sometimes excessive **Product criticality** Determine product criticality to establish replenishment practices for the different materials **Unit load** Specify unit or pack for all SKUs at the Central Warehouse	**Supply chain structure** Evaluate considerations regarding having activities in-house vs outsourcing of each material type. For consumer goods, evaluate considerations regarding having central warehouse vs. direct delivery from external supplier, and determine what should be stocked at warehouse. VMI for some materials. E.g. certain consumer goods **Data collection** Retrieve quantitative data on container utilization

Framework (cont.)

How	The AGV system	Hospital environment	Supply Chain Mgt
Increase transportation capacity	**Vehicle properties** Change vehicle properties, such as vehicle type, mechanical parts, electronic devices, and power supply **Vehicle quantity** Increase the number of vehicles **Battery management** Increase the battery duration **Layout** Adjust guide path design, no. of lanes, recharging stations, parking stations Increase quantity of pickup- and/or delivery stations at areas with many pickups or deliveries. E.g. at Waste Disposal or goods arrival at Supply Center. **Deadlock resolution** Allow for more efficient throughput at areas with high traffic. E.g. goods arrival at Supply Center or at the area around Supply Kitchen and Sterile Supply. **Routing** Change vehicle routing, especially related to finding shortest path, reducing empty transportations, and prevent turns in elevator	**Elevators** Increase number of elevators at areas with high traffic **Obstacles** Prevent obstacles in transportation route	