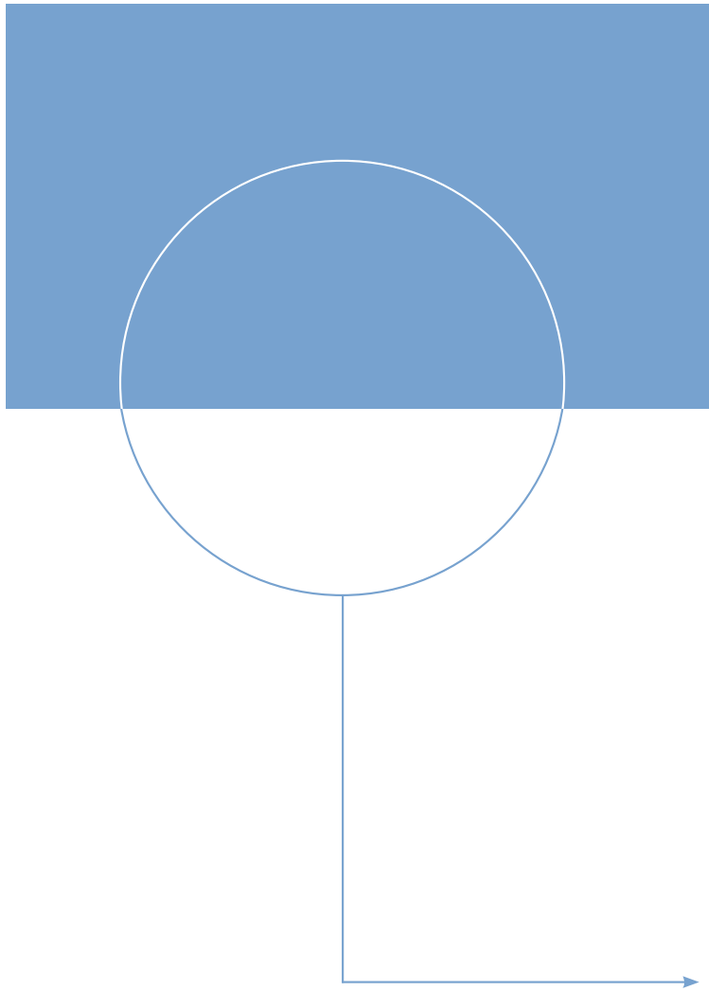

Master's thesis

2022

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Resource Sharing in Hospital Laboratories

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Resource Sharing in Hospital Laboratories

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Global Manufacturing Management
Submission date: June 2022
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Preface

This report concludes our master's thesis in Production Management, which is a part of the Global Manufacturing Management study program at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU). The master's project was conducted in the spring of 2022, whereas a project carried out in the fall of 2021 laid the foundation for the direction of this thesis.

Research conducted in this thesis aims to investigate resource sharing in hospital laboratories. Thus, we would like to acknowledge the staff at the department of Pathology, the department of Medical Genetics, and the department of Medical Biochemistry at St. Olavs Hospital for their cooperation and contribution to this thesis.

We would also like to thank our supervisors, Marco Semini and Aili Biriita Bertnum, for guidance, feedback, encouragement, and positivity throughout this thesis. Our discussions and knowledge generation have truly formed the outcome of this project. We would like to recognize you for your engagement in this project, as it has made it a fun and knowledgeable experience.

Roy Kenneth Berg & Stian Bergstøl

Trondheim, June 2022

Abstract

This thesis aims to investigate resource sharing in hospital laboratories. Hospital laboratories are experiencing increased pressure to organize and improve the effectiveness and efficiency of their processes, and there has been identified a gap in the literature on how to manage shared resources in hospital laboratories. The hospital laboratory operations can be viewed as a production environment that intends to efficiently supply test answers to patients. Thus, this thesis operates from an operations management and logistics perspective.

The objective of this thesis is to investigate alternatives for shared resources and their implications on hospital laboratory logistics and operations. To reach this objective, three research questions have been developed and answered:

- **RQ1**: *What are the alternatives for resource sharing in hospital laboratory processes?*
- **RQ2**: *What are the effects on laboratory performance when sharing these resources?*
- **RQ3**: *How can resource sharing complexity be managed?*

RQ1 has been answered with knowledge obtained through a case study at laboratory departments at St. Olavs Hospital. A conceptual simulation model has been developed, which in combination with the case study and a literature study has helped answer RQ2. Finally, answers to RQ3 have been identified through discussions of findings in literature, the case study, results from the conceptual simulation model, and logical reasoning.

The results show that shared resources have great potential in hospital laboratories. It has been identified that sharing resources can decrease throughput time, WIP, and costs, while it could increase utilization. Moreover, it could have both a negative and positive impact on quality, depending on how the shared resource is managed. Thus, in general, sharing resources could be viewed as an opportunity and not only a restriction.

This thesis contributes to the knowledge of how to use and manage shared resources in hospital laboratories. Moreover, findings can be generalized to other industries with similar characteristics.

Sammendrag

Denne oppgaven har som hensikt å undersøke ressursdeling i sykehuslaboratorier. Sykehuslaboratorier opplever økt press til å organisere og forbedre effektiviteten til sine prosesser. Det har blitt identifisert et forskningshull om hvordan man kan håndtere delte ressurser i sykehuslaboratorier. Oppgaven ser på sykehuslaboratorier som et produksjonsmiljø med hensikt i å effektivt levere testsvar til pasienter. Derfor er vinklingen til denne oppgaven fra et driftsledelses og logistikk-perspektiv.

Målet med denne oppgaven er å undersøke alternativer for delte ressurser og deres implikasjoner på driften og logistikken i sykehuslaboratorier. For å nå dette målet har det blitt formet tre forskningsspørsmål (FS) som senere blir besvart:

- **FS1**: Hvilke alternativer for ressursdeling eksisterer i sykehuslaboratorieprosesser?
- **FS2:** Hvilken effekt har det på laboratoriedriften å dele slike ressurser?
- **FS3**: Hvordan kan kompleksiteten ved deling av ressurser bli håndtert?

FS1 er besvart med kunnskap innhentet gjennom casestudie ved laboratorieavdelinger ved St. Olavs Hospital. Det er utviklet en konseptuell simuleringsmodell som i kombinasjon med casestudiet og litteraturstudiet har bidratt til å besvare FS2. Til slutt er kompleksiteten en delt ressurs medfølger belyst, og svaret på FS3 kommer fra diskusjon av funn i litteraturen, case studiet, resultater og logiske resonnementer.

Resultatene viser at å dele ressurser har et stort potensial i sykehuslaboratorier. Det har blitt identifisert at deling av ressurser kan redusere gjennomløpstid, varer i omløp og kostnader, mens det kan øke utnyttelsen av maskiner. Dessuten kan det ha både negativ og positiv innvirkning på kvaliteten, avhengig av hvordan den delte ressursen styres. Derfor kan deling av ressurser også sees på som en mulighet og ikke bare som en begrensning.

Oppgaven bidrar til ytterligere kunnskap om delte ressurser i sykehuslaboratorier. Dessuten er det grunner til å si at enkelt funn kan generaliseres til sykehuslaboratorier generelt, men også andre bransjer med lignende egenskaper.

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Abbreviations

ATO	Assembly-to-order
DNA	Deoxyribonucleic Acid
DMB	Department of Medical Biochemistry
DMG	Department of Medical Genetics
DP	Department of Pathology
EHDS	European Health Data Space
EOQ	Economic Order Quantity
ERN	European Reference Network
MTO	Make-to-order
NGS	Next Generation Sequencing
NTNU	Norwegian University of Science and Technology
PCR	Polymerase Chain Reaction
RNA	Ribonucleic Acid
RQ	Research Question
SMED	Single-Minute Exchange of Die
WIP	Work-In-Process

1. Introduction

This chapter aims to present the background and motivation for the research conducted in this thesis. Moreover, the objective, research questions, scope, and thesis structure will be presented.

1.1 Background

The healthcare sector is experiencing increased pressure to organize and improve the effectiveness and efficiency of their processes due to demographic development, increased amount of admitted patients, budget restrictions, unnecessary investments, poor use of resources, space restrictions, shortage of workforce, government regulations, rising healthcare costs, and increased demand for high-quality care. (van Sambeek et al., 2010; Jørgensen and Jacobsen, 2012; Lakshmi and Iyer, 2013; Pitt et al., 2015; Bhat et al., 2016; Luo, 2017; Bittencourt, et al., 2018; Crema and Verbano, 2021).

All these factors are of great concern for decision-makers in healthcare. Thus, it is important that the healthcare sector is operating efficiently with the given resources and budgets to provide the necessary service for increasing demand. One opportunity is to improve the performance of clinical efficiency and patient safety through resource optimization (Rechel et al., 2010; Pitt et al., 2015; Crema and Verbano, 2021). Furthermore, delivering high-quality healthcare involves patients having appropriate access to healthcare services. Additionally, to achieve efficient and effective patient flow, there needs to be a high throughput of patients, minimal waiting times, short length of stay, little overtime, sufficient utilization of staff and equipment, and moderate idle times (Lakshmi and Iyer, 2013). According to Van Sambeek et al., (2010) it is important to optimize the already existing logistics system to achieve efficiency. Thus, the healthcare sector can become more effective with the use of logistics (Jørgensen and Jacobsen, 2012) and operations management.

The pressure on healthcare managers to increase efficiency has led to a bigger focus on systems modeling and simulation as assisting tools in decision-making processes (Pitt et al., 2015). When trying to manage the main problems in hospital systems, the more traditional research methods are often not sufficient. This is due to the many dependent variables resulting in experiments and control trials not being adequate. The traditional methods are often too risky and expensive (van Sambeek et al., 2010), leading to an increased need for methods to analyze such complex environments. Constructing models and running simulations is a method that was originally designed for more traditional production industries; however, it has been widely

adopted within healthcare (Brailsford et al., 2009; Jørgensen and Jacobsen, 2012; Crema and Verbano, 2021). Tough, Pitt et al. (2015) state that the healthcare sector lags behind other industries that have been successfully using simulation for a long time. Nevertheless, they also point out that its use in health care could prove to be just as successful.

Simulation could help with the understanding of complex systems and enable predictions of consequences from different scenarios. The focus when conducting simulation research within the healthcare sector is often related to design, scheduling, planning, resource utilization, and process improvement, which can be used as support for decision making in operations management (van Sambeek et al., 2010; Jørgensen and Jacobsen, 2012). As hospital environments can be described as highly complex, it is difficult to simulate the whole system accurately (Jørgensen and Jacobsen, 2012). Thus, to support the results from the simulation in this thesis, additional qualitative discussions are conducted.

The increased pressure on the healthcare sector will also affect the hospital laboratories. For hospital laboratories, there is additional pressure due to the increased availability of hospital laboratory resources to the public, the growth in internet access, and doctors ordering tests to reassure patients (Freyer and Hanna, 2009; Mrazek et al., 2020). Furthermore, according to Plebani (2015), the hospital laboratories are especially affected due to their role in conducting the different analyses. The different analyses are becoming even more complex due to new medical knowledge and technological innovation.

1.2 Motivation for research

Gonçalves et al. (2013) point out how complex processes are created due to departments being organized by medical skill rather than by processes in which patients are cared for. Being organized like this could result in lost control of processes and have a negative effect on process efficiency. Within each process, there is a set of resources necessary to conduct the process. Due to this organization, departments can have the same processes and thus the same resources. It is therefore interesting to investigate if sharing resources could solve some of the challenges affecting the hospital laboratories.

A shared resource can be described as a resource where multiple flows meet and join before splitting and going their separate ways (Rechel et al., 2010). Moreover, Vissers and Beech (2005) mention how shared resources in the healthcare sector are resources that are shared between different specialties. According to Rutledge et al. (2010) and Bittencourt, et al. (2018) sharing resources could solve limitations related to space restrictions. Freitag et al (2016) imply how sharing resources should be implemented when there is an increased need for resource efficiency. Moreover, they state how there are two opportunities for sharing of resources; (1) when having overcapacity and offering the idle resources to other companies or departments, and (2) when several companies/departments are investing together in a certain resource that would be underutilized or too expensive for one company/department to buy. Vissers and Beech (2005) also mention how there can be several options for acquiring shared resources, as reasons can be improved quality, better control of existing resources, or saving costs. Additionally, Anderson et al. (2017) points out that sharing resources can be critical when having a scarce number of resources available and when they are difficult and expensive to obtain.

Hospital laboratories are offering important services for both hospitals and patients. Moreover, they are experiencing a big increase in demand due to the previously mentioned factors. As having shared resources is often unavoidable (Vissers and Beech, 2005), how they affect the hospital laboratory operations are important to consider. As understood from the literature, a shared resource often occurs due to restrictions on operations. According to Broekhuis and Van der Vaart (2005), sharing resources is creating more complexity. Increased complexity will put additional pressure on the hospital laboratory as it already experiences increase demand, shortage of workforce, government regulations, and increased focus on high-quality care. Thus, a hospital laboratory is selected as the case company in the thesis.

Both in literature and practice, there has been an increased focus on healthcare research within management science and operations management (Hans et al., 2012; Hicks et al., 2015; Benitez et al., 2019; Bertnum et al., 2020). Most of the research focuses on test procedures and the clinical aspects of hospital laboratory operations, rather than the operations management and logistics perspectives. The research on hospital laboratory operations is scarce, especially operations with shared resources. From an operations management and logistics perspective, one can view the hospital laboratory operations as a production environment. This thesis will investigate the applicability of operations management and logistics within a hospital laboratory. Thus, this thesis will contribute to filling the gap in research related to shared resources in hospital laboratory processes.

1.3 Thesis objective and research questions

The objective of this thesis is to investigate alternatives for shared resources and their implications on hospital laboratory logistics and operations. To reach this objective, three research questions have been developed, intending to give a better understanding of shared resources in hospital laboratories, the effects on logistical performance, and how to manage resource sharing complexity. To answer the research questions, a literature study, a case study, and a simulation model have been conducted, which will be further explained in chapter 2. The research proposed will be relevant for hospital laboratories and industries operating in similar environments. The research conducted should fulfill the objective and answer the following proposed research questions:

RQ1: What are the alternatives for resource sharing in hospital laboratory processes?

This research question aims to identify the different alternatives for sharing resources in hospital laboratories. The research questions will be answered through a case study and are supported by the literature. The identified resources are part of the foundation to answer RQ2 and RQ3

RQ2: What are the effects on laboratory performance when sharing these resources?

Different performance indicators for hospital laboratories will be identified through a case and literature study. This research question aims to investigate how the alternatives for resource sharing identified in RQ1 will affect the performance indicators. This will be achieved through discussions of the literature, the case study, and the results from the simulation model.

RQ3: How can resource sharing complexity be managed?

Several triggers for increased complexity when sharing resources will be identified based on the literature and the case study. This research question aims to present how to manage this complexity. This will be accomplished through discussions based on knowledge gained from the literature study, case study, and results from the simulation model.

1.4 Research Scope and structure

Hospital laboratories are the focus of this thesis, which is a specialized service in the healthcare sector. Hospital laboratories serve a broad specter of different analyses, while this thesis will focus on certain hospital laboratory departments that are performing genetic analysis. Hence, the processes investigated are limited to laboratories focusing on certain genetic analyses. The literature study is limited to literature that has relevance to shared resources in hospital laboratories and environments with similar logistical characteristics.

The thesis will focus on hospital laboratories from a logistics and operations management perspective. Hence, the processes investigated are further limited to the physical flow of patient samples. This means that the focus is from when a sample enters the laboratory system until it exits the system. Interpretation of patient DNA is the last station for all departments and happens after the patient samples are done with all necessary processing steps, thus it is not part of the scope to investigate.

The thesis focus on how to manage shared resources without going unrealistically outside the given restrictions. This means that the thesis will not include suggestions for facility expansions due to how it will result in an increased and unrealistic cost that will not be assessed. Moreover, the technical aspects of the facility (e.g., ventilation systems) will not be considered due to how it is outside the scope of operations management and logistics. It is known that there are requirements for ventilation and various restrictions within the hospital laboratory, however, this is left out of scope. All suggestions and discussions will be limited to the existing layout and machines in the laboratory departments. The discussion will be limited to assessments that can potentially free up both capital and space, as both factors are restricting the laboratories at St. Olavs today.

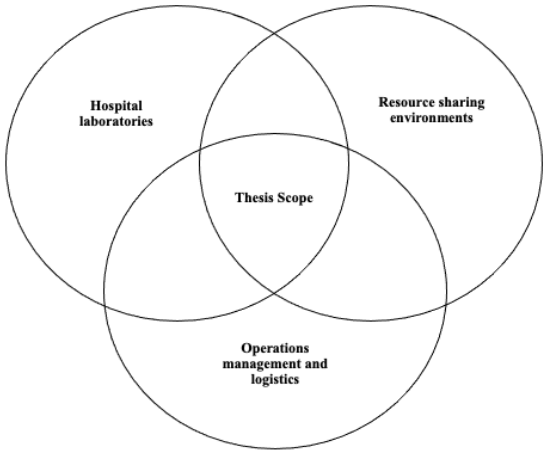

Figure 1: Thesis Scope

Table 1: Thesis structure

Chapter 1: **Introduction**	The introduction presents the research background, motivation, objectives, research questions, scope, and structure of the thesis.
Chapter 2: **Methodology**	The research methodology describes what methods were used and how they were used. It describes methodology in general, in addition to literature study, case study, interviews, and simulation.
Chapter 3: **Theoretical and literature study**	The theoretical background will present the relevant research found on the topic and will help answer the research questions presented in the introduction. It will be further used to substantiate the discussions. The theoretical background consists of relevant literature from the healthcare sector. Moreover, relevant literature from other industries is also included.
Chapter 4: **Case Study**	The case study describes the hospital laboratory operations in detail, with information collected from semi-structured interviews and visitations. The case study will supply the necessary information to construct a realistic model of the laboratory. Additionally, it will be used to highlight the real-life problem described in the introduction.
Chapter 5: **Case company analysis**	Here, observations from the case study will be elaborated, and **RQ1** will be answered. Furthermore, what scenarios to investigate with the simulation model is presented.
Chapter 6: **Model Construction**	The model construction chapter will describe in-depth decisions relevant to the construction of the model system. This includes the input data to the model, necessary assumptions implemented, descriptions, experiments, and validation of the model.
Chapter 7: **Results**	This section will present the output from the simulation model.
Chapter 8: **Discussion**	The discussion will use the results in combination with findings in the literature to answer **RQ2** and **RQ3**. Additionally, limitations to the thesis will be discussed.
Chapter 9: **Conclusion**	The conclusion will summarize the findings in the thesis and if the objective was fulfilled. Additionally, possibilities for further work are presented.

2. Methodology

This chapter aims to describe the methodology used to address the objective and research questions proposed in this thesis. Research methodology is the description of what methods were used and how reliable the results were. When conducting research, choosing the most suitable methods to investigate the research questions is an important issue (Karlsson, 2010; Busetto et al., 2020). There is no clear distinction between quantitative and qualitative methods, hence, research often consists of both qualitative and quantitative methods. Qualitative methods are often revolved around constructivism, interpretation, and perception, while quantitative methods are often mathematical and statistical tools used to analyze data (Karlsson, 2010). Therefore, one can interpret the main difference between the two methods to be the use of text or numbers.

The methods used in this thesis will be described to assure the reader that the research is reliable. In this thesis, both qualitative and quantitative methods, where literature study, case study, and simulation will be described.

2.1 Literature Study

To assist in answering the research questions, a literature study was conducted. The literature study was conducted with a logistics and operations management perspective, which influenced the type of articles that were identified. The goal of the literature study was to identify already existing research, clarifying the gap in existing literature in relevance to the thesis topic.

When conducting academic research, it is important to acquire an overview of the existing literature within the field the thesis is intended to cover. At the beginning of the thesis work, it is common to start with a broad area of interest and open research questions to get a general idea of what literature is available (Karlsson, 2010). As the research questions are rather open and connected to the literature study, it is expected that they change and adapt throughout the literature study (Karlsson, 2010). As the research progressed and the information gathered increased, the knowledge of existing literature increased, and the focus of the thesis got narrower. This helped to shape specific research questions and objectives relevant to topics of interest. This highlights how the research process continuously adapts and amends from the original plan to correspond to the opportunities that arise throughout the process.

When searching for scientific literature, the four databases Google Scholar, Scopus, Science Direct, and Oria were used. Using multiple databases resulted in the literature search being more thorough, identifying a wide range of scientific articles. Additionally, it reduced the possibility of missing relevant articles. However, due to factors such as paywalls, only free articles, or articles accessible through the NTNU license were accessed, limiting the literature search. Both Norwegian and English articles were identified. As the search progressed and more insight into the available literature was obtained, more detailed search terms were used to further narrow it down. Since the thesis has a due date in June, the literature search is limited to articles published before June 2022. Articles with high credibility were identified to make sure the information found was reliable and applicable.

Articles with research from more traditional manufacturing industries which could apply to the problems described in this thesis were used in addition to articles that directly involved research in the healthcare sector. The reason for identifying both literature from traditional manufacturing and the healthcare sector was due to the scarce amount of literature found regarding shared resources in the healthcare sector. Principles from other industries could be applicable to hospital laboratories. Hence, research from other industries could assist in finding solutions to the management of shared resources in hospital laboratories. The titles and keywords of articles were checked against the search term used, to see if it was relevant. When relevant and credible articles were found the contents were skimmed through, where the abstract and conclusion were mainly read to get a general understanding of the contents. If the article identified were relevant, it was saved and read more thoroughly to find out how it could contribute to this thesis. Then, the relevant parts of the article were analyzed and included as part of this thesis.

Figure 2 highlights the keywords used to search for literature. The different keywords were separated into main keywords and sub-keywords. The sub-keywords were further divided into level 1 and level 2. This structure intends to first identify more general literature to gain knowledge of the field of interest. This resulted in a more thorough literature search, as it helped the researchers identify new areas of interest to investigate. Then, to gain more detailed knowledge more directly related to the problems presented in this thesis, level 1 and level 2 sub-keywords were added to the main keywords. A combination of level 1 and 2 was also applied, in addition to the main keywords, to acquire more detailed literature from a logistics and operations management perspective. The keywords were combined logically, enabling the researchers to obtain a great amount of relevant literature.

Keywords		
Main keywords	**Sub-keywords**	
	Level 1	**Level 2**
Material flow	Healthcare	Operations management
Shared Resources	Hospital(s)	Logistics
Scheduling	Laboratory	
Performance indicators	Production	
Layout	Manufacturing	
Capacity		
Scalability		
Prioritization		
Batching		

Figure 2: Keywords used in the literature search

After identifying relevant articles, a cited reference and citation search were conducted, creating a snowball effect. Since this was done on relevant and credible articles, it resulted in a larger amount of credible literature being available for analysis. Using citation search as a method creates an overview of a particular field, where one can identify how ideas have been critiqued and discussed (Karlsson, 2010). This creates a "two-way" search, where relevant articles are identified and used to see what other work has cited them. This quickly creates a substantial literature search, building on article after article and creating a snowball effect. One can identify work that has cited the identified article, but also what other work the identified article has cited, hence, a "two-way" method. Furthermore, conducting a citation search can uncover unencountered parts of the available literature and provide new perspectives on the topic (Karlsson, 2010). However, citation searches are often only useful for publications that are over 2 years old due to the lead time of journal articles, resulting in it taking 2 years before a paper appears as a reference (Karlsson, 2010). Using this method is best when having a clear and firm understanding of the works in the field (Karlsson, 2010), hence, it was utilized when the literature reached a more mature stage.

As the literature study matured, it became clearer and clearer how shared resources in hospital laboratories lack research. Hence, literature from other industries was applied to build a solid foundation of theory for discussions later in this thesis. The literature study has provided this thesis with relevant knowledge of topics related to the research questions presented in the introduction. To illustrate the "real-world" relevance of the problems presented, a case study was conducted to further strengthen the results of this thesis.

2.2 Case Study

A case study in this thesis is relevant due to:

- The use of an operations management perspective, which is common in case studies
- The necessity of new insights into problems
- The need for why and how questions
- The possibility of allowing the researchers to understand the processes
- Obtaining input to create a simulation model

Within operations management, case research is one of the most powerful methods to apply. This method can be both quantitative and qualitative, hence, it can be used for a wide range of research. Case research could create new insights and the development of new theories while being a method of high validity. In addition, the researchers themselves are being exposed to real problems enriching their knowledge and experience. However, there are several challenges related to case research as it is time-consuming, skillful interviewers are necessary, and to ensure accurate research one needs to be careful when concluding from a restricted set of cases. (Karlsson, 2010)

The case study is a section of analysis within case research. Case studies can be used for exploration, theory building, testing, and extension. It has been recognized as being well suited for investigating the how and why questions. Before developing a case study, it is key to have research questions, however as previously stated, these research questions are likely to adapt and change. Nevertheless, they will still serve as the foundation for the study and help guide the collection of information in the right direction. The fact that the research questions are fluid and can evolve during the study can also be a strength, as it will allow the development of more knowledge. As there are a given set of available resources, having fewer case studies will allow for greater in-depth observations. Hence, conducting single in-depth case studies can result in more in-depth examinations. However, there are also limitations to single in-depth cases, as it is difficult to draw generalizable conclusions when having only one case. There is also the possibility of misinterpreting a single incident and exaggerating data. Having single incidents and exaggerating data also exists in other case research but are mitigated due to having a larger number of cases to compare with. (Karlsson, 2010)

2.2.1 Selecting case company

Since it was necessary to acquire in-depth information (Karlsson, 2010) on different processes at hospital laboratories, a single-case study is preferred. With in-depth information, the simulation model to be developed will serve as a solid foundation of information to build upon, which further strengthened the reason for choosing a single-case study. Other reasons for choosing a single-case study are the availability of companies who is relevant to the topic of this thesis. It was identified how St. Olavs Hospital had relevance to the thesis topic and problem formulation, which made it logical to involve them in a case study. The following will describe the relevance of St. Olavs Hospital in this thesis.

The clinic of laboratory medicine at St. Olavs Hospital consists of six departments: Immunology and Transfusion Medicine, Clinical Pharmacology, Medical Biochemistry, Medical Genetics, Medical Microbiology, and Pathology. The different departments have their own focus and operations, and all departments are conducting genetic analysis. The challenge for the laboratories is that different departments were recently relocated and merged on the 5th floor at the *laboratoriesenter*. Previously, the departments have been separated from each other both in terms of physical location and lack of cooperation. This has led to a longer period where the departments are operating for themselves and invested separately in equipment without any overview of the other departments. The choice of merging opens several operational and economic opportunities for the departments, both separately and as a collective.

Before deciding which departments to include in this thesis, a preliminary presentation with three departments was carried out. At this meeting, the leaders of each department, the researchers, the co-supervisor, and the main supervisor were present. The purpose of this presentation was to present and discuss a potential case study investigating shared resources in hospital laboratory processes. It was identified that a common process between some of the departments was DNA/RNA isolation. One of the departments attending the meeting stated how they do not conduct DNA/RNA isolation; thus, they were excluded from the potential case study. Moreover, the remaining two departments identified how a third department not attending the meeting also conducts a DNA/RNA isolation process. Therefore, a third department was included. This selection of departments was conducted to have the best possible foundation to answer the objective of this thesis.

The relevant departments that were included in the case study were the department of Pathology, the department of Medical Genetics, and the department of Medical Biochemistry. All these departments stated how they see the potential of sharing the DNA/RNA isolation

process of their operations. Hence, the preliminary meeting focused on the DNA/RNA isolation process, which ended in the realization that the station can be shared between the three departments. More detailed descriptions will be given in the case study chapter. Hence, the observations and semi-structured interviews were conducted with these three departments, as they were the departments relevant to the topic of this thesis.

Moreover, due to the researchers' supervisors having a connection to St. Olavs Hospital, it was logical to pursue them as a case company. The case study was conducted at the laboratories for genetic analysis at St. Olavs Hospital in Trondheim. Additionally, the case study enabled the researchers to get a clearer understanding of their problems and the relevance of shared resources in hospital laboratories. To understand problems that are on a detailed level in their processes, information regarding material flow and organization of the departments were necessary. Throughout the case study conducted in this thesis, there have been several meetings, visitations, and semi-structured interviews. The visit to different departments consisted of semi-structured interviews and observations. The case study was structured as follows:

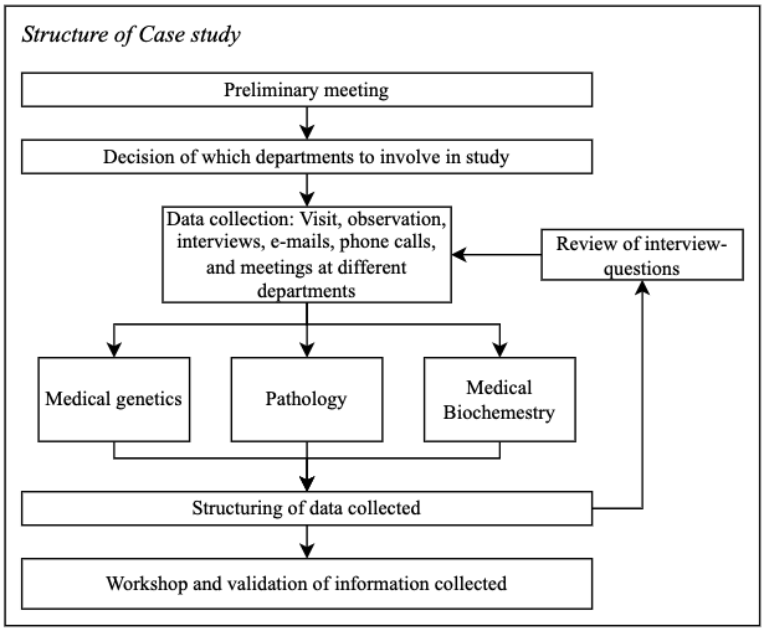

Figure 3: Structure of case study

The use of these methods has allowed the researchers to collect relevant information to help answer the proposed research questions. As highlighted in Figure 3, each department has been treated separately. This means that visits and interviews of departments were not necessarily conducted on the same day, highlighting how case studies can be time demanding (Karlsson, 2010), as it depends on the availability of the company in relevance to the case. However, this

allowed the researchers to review the interview guide between the visit to different departments, change or add questions, and make sure that all the necessary information were gathered. This strengthened the case study, minimizing the possibility of missing information. This did not mean that the departments were visited multiple times if questions were forgotten, but they were rather communicated through e-mail to get the answers needed.

2.2.2 Data collection

To collect the necessary data, semi-structured interviews and visitations with observations and meetings were conducted. When visitations and observations were carried out, they usually started with a meeting. This meeting was intended to get an introduction to the department, general and detailed information about their processes, and ask questions from the interview guide. This was followed by observations of the environment in which the different departments are operating, where additional questions were asked. A description on how the semi-structured interview and observation was carried out follows.

Semi-structured interview

Qualitative methods are usually conducted orally and not written to preserve the interactive component of the method (Mann, 2016). However, during the visit to the different laboratories, as much information as possible was written down. The perk of being two researchers is the fact that one can focus on taking notes while the other continues the conversation. According to Mann (2016) interviews, in general, can be categorized into three categories: Structured interviews, semi-structured interviews, and unstructured interviews. A completely structured and formal interview is much more directed by the interviewer and will stick to a pre-defined question list and answers rather than a conversation and will in practice function as an oral questionnaire (Mann, 2016). Moreover, Mann (2016) identifies how interviews can be divided into two extremes, where semi-structured interviews are somewhere between the two extremes. Interviews can be structured as follows (Mann, 2016):

Structured	Unstructured
Formal	Informal
Directive	Non-directive
Less conversational	Conversational

Semi-structured interviews can be described as a conversation where there is an exchange with informal character, where the goal is to gain the necessary insight into a person’s subjective

experience, opinions, and motivation (Busetto et al., 2020). Semi-structured interviews were conducted due to the nature of the case study, where rather than just conducting an interview, questions would be asked in combination with observing the different processes. It is then logical to think that new questions would arise through the observation, hence a semi-structured interview would be best suited. What characterizes a semi-structured interview from other interview formats, is that the interviewer often relies on a guide instead of a script. It is still important to follow the structure of the pre-defined interview guide as there may be a need for comparison between several interview objects. The guide will also help the interviewer to ensure that the most important information is covered. Semi-structured interviews benefits from that there are room for deviations and unexpected, but relevant, topics to be taken up (Busetto et al., 2020). Hence, a guide was created to ensure that the researchers asked the correct questions but were allowed to ask additional questions if necessary.

The DNA/RNA isolation station was identified in the preliminary meeting as a potentially shared resource. Hence, each of the three departments was asked the same questions. The advantage of asking all three departments the same questions is the reliability of the answers collected. Additionally, the different departments might have different information to share which could be key to the result of this thesis. Moreover, as the simulation model needs input to be as reliable as possible, the same questions were asked to ensure that enough input was collected to run a realistic model. A conceptual model was made before the interview guide was developed. This assisted in the development of the questions, as it affected what questions were necessary to ask to ensure the realistic construction of a simulation model.

The interview guide is found in appendix A. As pointed out by Busetto et al. (2020), the pre-defined interview guide is often derived from the literature study, previous research, data collection, document study, or observations (Busetto et al., 2020). The questions listed in the interview guide are based on prior knowledge obtained on the mentioned methods from Busetto et al (2020) when the project thesis was conducted last semester. Additionally, a large portion of the literature study was conducted before the semi-structured interviews were performed. This resulted in additional questions being added, based on problems highlighted by other researchers. In advance of the visitation of different departments, the interview guide was discussed with the co-supervisor and supervisor to ensure the quality of the questions. To further ensure the correctness and reliability of the information gathered, the researchers structured the collected information right after the visits were done, to ensure nothing was forgotten.

Observations

The researchers were followed through the flow of each department at the laboratory by personnel with the required knowledge. This allowed the researchers to ask questions at certain steps in the material flow, which was necessary for input to the simulation model. Moreover, it allowed the researchers to get a "real-life" perspective of laboratory operations, putting the research questions into context.

Observation is a great method to gain insight and experience the actual behavior of a given setting. Busetto et al (2020) divide observations into two types; participants and non-participants. When visits to the laboratories at St. Olavs Hospital were carried out, the researchers conducted a non-participant observation which implies that the observer is "on the outside and looking in". In these types of observations, the observer is not a part of the situation and is trying to avoid influencing the setting by their presence. This means that the researchers did not take part in the process, but rather observed how it was performed. The objective was to experience the physical behavior and take pictures of relevant functions in the laboratory.

According to Busetto et al (2020), written notes can be taken during or after the observation, depending on the feasibility and acceptability. Since a semi-structured interview was carried out, notes were written down throughout the tour of the laboratories. These notes were both answers to possible questions and general observations from the researchers. The interview guide and floor plan were printed out in advance, as it was both feasible and acceptable to take notes during the visit. These notes were later used to develop a simulation model of the laboratory. They were also used as a checkbook to make sure all questions were answered and to identify the need for additional questions to be asked when observing the next department. Questions missing answers were later asked through phone calls and a workshop. Additionally, the observations helped to minimize the distance between the researchers and the actual case. This makes it possible to discover topics that the researchers did not realize were relevant and gain deeper insight into the real-world dimensions of the researched problem (Busetto et al., 2020). Hence, the observations helped shape the focus of the thesis and influenced the research questions presented in the introduction.

Workshop

At the end of the case study, a workshop was held with the involved personnel at the different laboratory departments at St. Olavs Hospital, where the results from the thesis were presented. The workshop was held to ensure the researchers had the correct understanding, which further strengthened the discussion and conclusion of this thesis. The quantitative information collected was verified to ensure that the simulation model was developed based on correct information. The workshop also spiked discussions in relevance to the thesis topic and further work. How and why verification of the simulation model and results were conducted are further explained in section 2.3 and 6.3.

2.3 Simulation

Simulation is a common method used in operations management, and is central in this thesis, as it is the method used to investigate shared resources in hospital laboratories. Simulation as a tool is a model-based quantitative research method with developed models consisting of relationships between control variables and performance variables, which are tested or analyzed. The method can be classified as a rational knowledge generation approach, where there are assumptions that allow the development of objective models explaining the behavior of real-life processes. With model-based quantitative research, it is possible to develop models that can predict and explain future states. This means that with this method one is not only limited to explaining current observations. (Karlsson, 2010)

Health sciences are one of many sciences (engineering, management, mathematical, military, social, transportation, and telecommunications) where simulation is highly applicable (Fishman, 2001). These are all complex systems where other analytical methods may not provide the necessary information to solve a problem, hence, simulation is the preferred method. A hospital laboratory can be categorized as a complex system, meaning that simulation is a highly relevant method. Simulation is an experimental method that can be characterized by being computer-based, mathematical, and quantitative (Campuzano and Mula, 2011). Moreover, simulation can describe very complex real-life processes and can be used to investigate and observe both existing systems (without altering them) and systems that do not exist, before implementing changes (Campuzano and Mula, 2011; Bangsow, 2012; Henchey et al., 2013).

Simulation can also be referred to as axiomatic research, where the research is dependent on available methods within the fields of mathematics, statistics, and computer science. Axiomatic research is often driven by the model that has been developed. With this method, the goal is to attain solutions from a developed model and make sure the solutions provided are insightful and relevant to the research questions. Axiomatic research gives insight and enhances knowledge about the behavior of variables within the developed model, however, these are based on assumptions of other variables in the model. So, reasonable assumptions need to be made and stated to clarify the behavior of the variables. The research can also provide knowledge of how to change different variables, making it possible to investigate different scenarios. (Karlsson, 2010)

When using model-based quantitative research methods, a goal is often to identify and develop different policies, actions, and improvements, find optimal solutions and strategies, and compare different scenarios. This is prescriptive research, which is what axiomatic research typically is. However, axiomatic research could also be descriptive, which is primarily focusing on analyzing the model, resulting in a better understanding of the model characteristics. As this thesis aims for a more prescriptive type of research, the main method is the use of model-based quantitative research methods using axiomatic research. (Karlsson, 2010)

The process can be described through four steps: conceptualization, modeling, model solving, and implementation (Karlsson, 2010). First, through conceptualization, a model of the problem is made. Here, decisions on the variables to be included in the model, and the scope of the problem and model are addressed. The steps when developing a model could vary, but often a limited model is developed first and as time goes on more detail is added where the model gives inadequate answers (Fishman, 2001). Conducting the development of the model in this way reduces debugging and computing times, additionally, it makes for more sensible use of time for model development.

Initially, a model was developed to ensure that the researchers got familiar with the simulation software. This included going through tutorials, becoming familiar with different functions, and ensuring that FlexSim as a simulation software was sufficient for this thesis. Moreover, when developing the model logic, information regarding laboratory processes was collected from the co-supervisor and based on information from a study conducted in another laboratory. This logic was implemented due to its potential relevance for the final model to be developed. Additionally, it ensured that potential questions of input needed to run the model were discovered before visiting the different laboratory departments, making sure that necessary input information was collected. After observations and interviews were finished, a conceptual model was developed based on the information collected. The information gathered from interviews, observations, phone calls, meetings and workshop were necessary to make sure that the model was as realistic as possible. The final model logic is described in more detail in chapter 6.

Secondly, modelling of the system is initiated (Karlsson, 2010). Here, the model is built and relationships between variables are defined. The conceptualized model was further developed to ensure that all information were included correctly. Different actors operating in the system were defined, and the material flow were implemented. This also included parameters such as sample volumes, set-up times, processing run times, and available workhours. The model logic

was defined so that the actors in the systems interacted as supposed with their surroundings. Moreover, different performance indicators were identified through discussions with personnel at the laboratory departments. These performance indicators would then shape what data to collect from the simulation.

Thirdly, the model is run, where mathematics plays a central role in acquiring results (Karlsson, 2010). The time-lapse for how long the simulation would run were defined based on how long it would be necessary to run to get enough results to analyze. The model was observed during simulation, to ensure that no errors occurred and that the model worked as it was supposed to. The model was run several times to collect enough data to compare different scenarios.

Finally, the results are implemented. After completing the four steps, the cycle can start over again (Karlsson, 2010), as shown in Figure 4. As the research is axiomatic prescriptive research, different solutions will be presented and compared. However, due to the scope of this thesis, the implementation of results will not be part of the process. Moreover, as visualized in Figure 4, the different stages of model development interact with each other. Therefore, during the development, the researchers often went back to the problem situation and compared it to the simulation model, making sure that the model was correct. Hence, there were a lot of interactions between the problem situation, conceptual model, and scientific model. Only leaving out the implementation of the solution as it is not part of the scope.

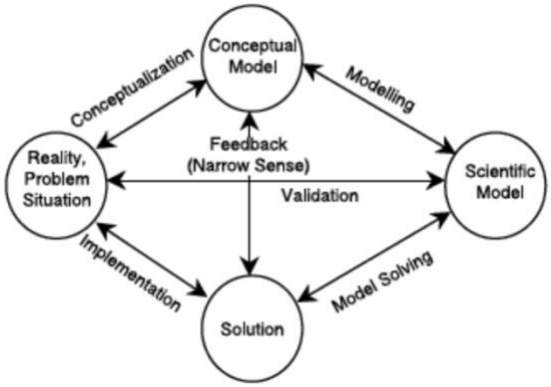

Figure 4: Research Model (Mitroff et al., 1974)

Axiomatic research is often used when a problem is too complex for formal mathematical analysis, hence, it is important to justify the use of this method. As hospital laboratories can be categorized as complex systems with uncertain demand, an approach such as axiomatic research is logical. Simulation is then a viable option to construct a replica of the real-life

system, enabling the researchers to conduct a more in-depth analysis of different scenarios without altering the actual system.

The simulation software used in this thesis is FlexSim, which is a discrete event simulation program. FlexSim gives the opportunity of making a visual simulation of a system, and thereby the possibility of presenting the model to the healthcare personnel and get a validation of the construction of the model. A discrete event simulation could be described as a system that is following an event list to shape the data of interest (Ross, 2013), where the event is occurring instantaneously causing the state to move from one value to another (Cassandras and Lafortune, 2006). The state can be described as events taking place over time, meaning that it evolves through time. Additionally, the state should describe the system behavior in a measurable way. Being a discrete simulation means that the state is discrete and are only allowed to move to a different value at discrete points in time, rather than continuously with time. When developing the model, time handling is important to consider. Pidd (2004) states how discrete event simulation is a method that uses next-event technique. When using next-event technique the model is only updated when it is known that a state will change. This technique has two advantages. The first advantage is that the time increment adjusts automatically, avoiding unnecessary checking of the state of the model, while the second advantage is that the technique makes it clear when events occur in the simulation (Pidd, 2004).

Often when simulating a discrete event system, the main objective is to investigate the performance of the system regarding throughput time, buffer occupancy, delay, resource utilization and system loss (Fishman, 2001). Hence, following the research from Fishman (2001), discrete event simulation is highly relevant for this thesis.

Healthcare decision-makers are becoming more accepting of discrete-event simulation as a tool for improving operations and reducing costs (Jacobs, 2006). The advantages and disadvantages can be directed towards discrete event systems in healthcare. Using discrete-event simulation in healthcare enables the researchers to construct complex models and to evaluate the efficiency of existing healthcare systems. The method allows the researchers to ask “what if?” questions to develop new solutions (Jacobson, 2006). However, due to the complexity of operations within the healthcare sector, simulation studies need to carefully formulate the problem statement to achieve success. This is due to the detailed information necessary, to know what involves in the problem to be solved.

There are both advantages and disadvantages when using discrete-event simulation. In literature, there is a common consensus on what the advantages and disadvantages are. Hence, a summary of findings in Fishman (2001), Cassandras and Lafortune (2006), Jacobsen (2006), Kråkenes et al. (2007), Compuzano and Mula (2011), Bangsow (2012), Henchey et al. (2013) and Pitt et al. (2015) will be presented. Table 2 intends to investigate what advantages and disadvantages there are with discrete event simulation, and how it would affect the work done in this thesis. When choosing the right method, advantages and disadvantages need to be identified. The disadvantages were especially important to discuss, as they could potentially have effects on the results of this thesis. Many of the different disadvantages and how they have been managed have been argued for throughout this section.

Table 2: Advantages and disadvantages of discrete event simulation

Advantages	**Disadvantages**
Can describe complex real-life systems.	Does not generate a closed set of solutions.
Allows for testing of scenarios before implementation.	Time-consuming.
Investigate systems without altering them.	Could be cumbersome.
Cheap and accurate.	Requires accurate data from the physical world and information on all interactions.
Results in enhanced understanding of the system in focus.	Difficult to find the right balance between structural detail and the need to make the model receptive to problem-solving.
Forces a bigger focus on the need for detail and relevance.	Limitations in detailed information about the real-life case will make the model less realistic.
Increases the speed at which an analysis can be conducted. It can compress time, simulating years of activity in a much shorter time. It can also expand time, enabling the investigator to study detailed changes in the system.	The necessity of detailed information. • It is more time-consuming the more detail is necessary. • Having more detail in the model could also result in more time used when trying to find the root cause of errors. • More detail could also increase the execution time of the model.
Easy to change system modifications and could result in a framework for testing different solutions.	There is no guarantee that the model will produce a useful result.
It is easier to manipulate and enables greater control over sources of variation, than in the real-life system.	Round-off errors can occur in computer simulations.
After running the simulation, situations, where data were not collected can be identified. Reprogramming enables the simulation to run over again with the same initial conditions, collecting the necessary data.	The results that a model produces are only approximations to the true values in the real-life system. When using the model to predict future performance, it is necessary to have proper qualifications to make sure the results are viable.
The possibility of stopping the simulation and reviewing it and resume the simulation when done.	Could be difficult to develop generic and standardized approaches.
Easy to cooperate with analytical methods when investigating the results.	

Moreover, the margin in error when designing models within healthcare is much more limited (Jacobson, 2006). Therefore, a workshop showcasing the simulation model were conducted. Here, hospital laboratory personnel could give feedback to both results and the simulation model, making sure that both the model construction and results made sense. Especially due to simulations including future scenarios, feedback was necessary to validate the results.

When conducting axiomatic research, the scientific quality of the results could be lower due to how only results with some statistical substance can be reached (Karlsson, 2010). Furthermore, finding generalizable solutions could be difficult through discrete event simulation. However, the results will still be a valid contribution to discussions in relevance to the described system and established research questions. Furthermore, it is essential to justify the solution to be tested, hence, the solutions are based on findings from the literature study. The results from the simulation model will be discussed together with the case study and literature study.

3. Theoretical and literature study

This chapter will contribute the necessary theoretical background to understand the problem presented in chapter 1. It will present the existing literature on different topics that are relevant to this thesis. The chapter starts with an introduction to the healthcare sector and hospital laboratories from a logistics perspective. Then, literature on shared resources in general and their consequences are presented in section 3.2. Section 3.3 investigates different topics from logistics and operations management. In this section, the theory on layout and its importance for process flow are presented, to clarify its relevance in managing shared resources. This is then followed by capacity management, explaining how all resources have a certain capacity and how to manage this. Then scalability is presented, explaining its relevance for hospital laboratories and how it affects operations management. Furthermore, why prioritization happens and how other industries have coped with it are elaborated. Thereafter, theory on batch sizes and line balancing will contribute to the knowledge of how it could affect effectiveness and efficiency in hospital laboratories. Finally, chapter 3.4 will investigate and identify performance indicators relevant in hospital laboratories.

3.1 Introduction to the healthcare sector

This section will introduce hospitals and hospital laboratories. The central processes will be introduced from a logistics perspective to provide additional understanding of the environment in which this thesis takes place. Additionally, the characteristics of laboratories conducting genetic analysis will be presented.

Hospitals are complex organizations (Figure 5), and as identified by Gonçalves et al. (2013), this is mainly due to departments being organized by their medical skills/specialization, and not by the processes in which patients are cared for. This could result in lost control of processes, which could affect the quality and efficiency of the hospital. Furthermore, operations management can contribute to the improvement of the efficiency of the healthcare sector. Many healthcare organizations have started to implement principles and techniques from more traditional manufacturing industries, enabling them to meet the ever-growing demand (Gonçalves et al., 2013).

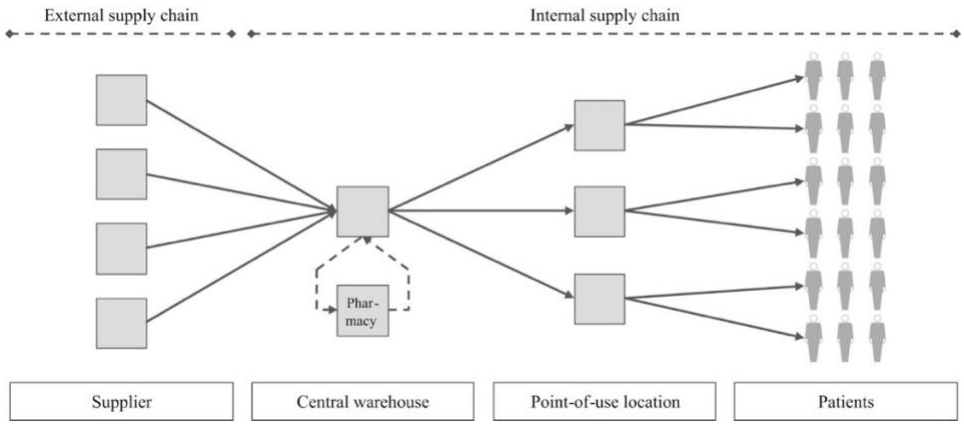

Figure 5: Illustration of a hospital supply chain (Volland et al., 2017)

There are many definitions of hospital logistics in the literature. Serrou and Abouabdellah (2016) define hospital logistics as "patient satisfaction requirements through an optimization of the various functions of the hospital" (Serrou and Abouabdellah, 2016, p.2950). While Frichi et al. (2018) define it as "a set of design, planning and execution activities which enable the purchase, inventory management and replenishment of goods and services surrounding the provision of medical services to patients" (Landry and Beaulieu, 2002 as cited in Frichi et al., 2018, p. 1233). In later years logistics has evolved to become a vital part of the hospital supply chain (Volland et al., 2017; Jawab et al., 2018), where it is responsible for the provision of material resources to different actors in the hospital supply chain (Frichi et al., 2018). Hospital logistics can be characterized as having a division of labor, non-standard processes, and a lack of information (Đapić et al., 2015). As Đapić et al. (2015) point out, a consequence of these characteristics is that decision-makers have to deal with the challenge of ensuring that resources are available every day.

Logistics in hospitals are essential in improving efficiency and quality of care (Serrou and Abouabdellah, 2016; Frichi et al., 2018), moreover, a large number of hospital costs are linked to logistics activities (Volland et al., 2017; Jawab et al., 2018). Logistics in hospitals is an important part of hospital management (Volland et al., 2017; Jawab et al., 2018), and every hospital needs logistics (Đapić et al., 2015). However, it has not been given high priority in the past (Volland et al., 2017). This could be due to hospital management often focusing on clinical activities and neglecting logistics activities (Frichi et al., 2018). More recently, logistics have been gaining focus and are being implemented as an important part of hospital management. Logistics have great potential in hospitals, as healthcare expenses can be reduced through logistical procedures (Serrou and Abouabdellah, 2016; Jawab et al., 2018) where logistics costs are the second biggest cost after personnel costs (Volland et al., 2017).

There are a great number of different services within a hospital, however, unlike in more traditional manufacturing industries, it is often not possible to predict the patient mix and demand for materials (Đapić et al., 2015). Moreover, Frichi et al. (2018) identify how better management of hospital logistics could result in improved quality of care. More specifically in terms of using information systems, reducing waiting times, improving human resources availability, improving material resource availability, and improving physical access to healthcare services.

Furthermore, logistics in hospitals can be divided into goods and people (Đapić et al., 2015). Figure 6 shows how it can be divided into three categories, *hospital logistic groups, hospital logistic criteria,* and *hospital logistic fields.* As the scope describes, hospital laboratories are the focus of this thesis. Hence, an introduction to hospital laboratories will be provided.

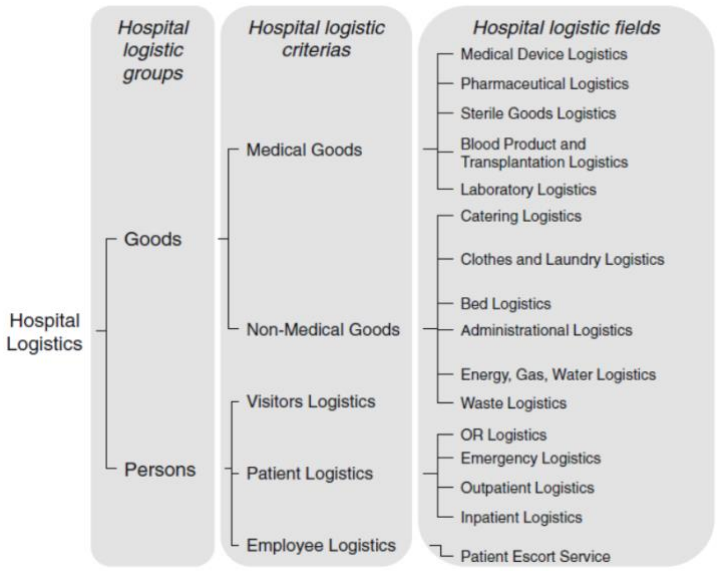

Figure 6: Logistics in hospitals (Đapić et al. (2015) adapted from Kriegel (2012))

Hospital laboratories

In healthcare, clinical laboratories are essential, as treatment and diagnostics depend on how accurate and prompt laboratory tests are. As personalized care becomes a more popular method, the complexity of tests conducted in clinical laboratories increases (Plebani, 2015). Plebani (2015) states how the clinical laboratory is the center of diagnostic medicine. This is due to its involvement in providing crucial information for the diagnosis, prognosis, monitoring of disease, screening, prevention of disease, and the decision of treatment (Schimke, 2009; Plebani, 2015). Furthermore, laboratories are key in medical decision-making, providing crucial information to patients (Plebani, 2015). There are mainly two reasons to order laboratory testing, for diagnostics and control. With diagnostics, the reason is to identify

diseases or types of disease (St. Olavs Hospital, 2017). These tests are often ordered due to uncertainty of patient diagnosis based on health records and clinical examinations. While control is conducted to surveil changes in patients with known conditions and to find out why potential changes occur (St. Olavs Hospital, 2017).

Plebani (2015) identifies how hospital laboratories act as independent silos, having little to no relationship with clinics. Additionally, the advances in technology have caused a significant expansion of test capacity and the number of possible tests to be conducted. However, laboratories have experienced redundancy and little focus on clinical effectiveness due to operating as independent silos (Plebani, 2015).

Hospital laboratories can be divided into centralized testing and point-of-care testing (POCT) (Schimke, 2009). Centralized testing in centralized laboratories are laboratories that deliver high-quality results, while POCT is conducted by clinical staff, enabling testing to be moved closer to the patient. POCT laboratories have the advantage of enabling shorter turnaround times, however, clinical staff is limited, limiting the possibilities of POCT laboratories. The growing demand and need for cost reduction are affecting the hospital laboratory as well as the healthcare sector in general. Due to this, the centralization of hospital laboratories was started to improve both service and quality (Schimke, 2009). Thus, patient-centered analysis moved more and more towards centralized laboratories (Schimke, 2009; Plabani, 2015). Furthermore, the hospital laboratory processes can be divided into the *pre-analytical phase, analytical phase,* and *post-analytical phase*. Moreover, they can be further divided into the *pre-laboratory phase*, *laboratory phase*, and *post-laboratory phase* (Figure 7).

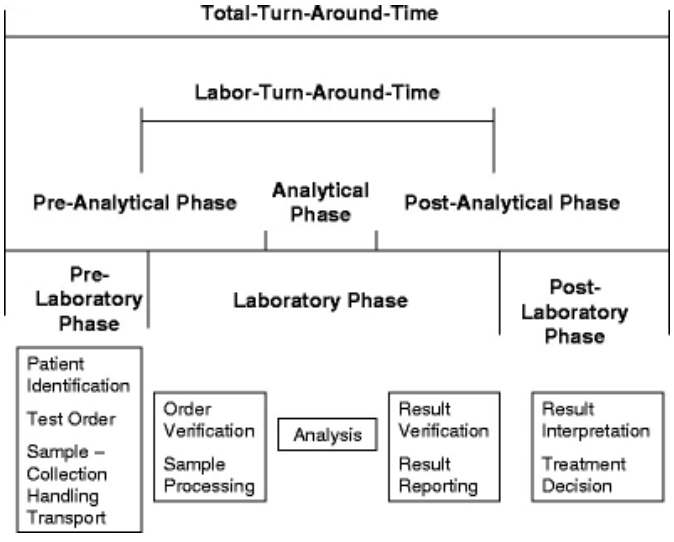

Figure 7: Laboratory processes (Schimke, 2009)

The pre-analytical phase involves steps that are conducted outside of the laboratory; however, it also includes steps that are directly connected to the laboratory. Hence, it is part of both the pre-laboratory phase and laboratory phase. Processes conducted outside of the laboratory are the collection of information regarding patient identification, ordering of tests, collection of samples, and preparation of sample transportation. These processes are usually performed by physicians and nurses. The remaining processes are conducted by laboratory staff. The activities conducted in the laboratory phase of the pre-analytical phase are verification of orders and sample processing. The analytical phase is where the actual analysis of patient samples is conducted and is part of the laboratory phase. The post-analytical phase includes verification of results and reporting of results, which is a part of the laboratory phase. Furthermore, it includes result interpretation and decisions regarding treatment, which is part of the post-laboratory phase.

Hospital laboratory characteristics

The hospital laboratory characteristics were developed through a project as preceding work to this thesis. The characteristics were developed based on a document study in combination with theory, which relies on information provided by USAID (2009), Rutledge et al. (2010), Helsedirektoratet (2016), St. Olavs Hospital (2018), Bertnum et al. (2020) and Midt-Norge et al. (2021). The characteristics are presented in Table 3:

Table 3: Hospital laboratory characteristics

Variable	Aspect	Characteristics
Product	Commodities	Reagents, consumables, durables & equipment
	Uniqueness	High: Personalized, DNA
	Shelf life	Varies: Depends on sample features
	Test complexity	Varies between 20-50 commodities per test.
	Quality	High: Precise treatment
Market and customers	Demand	Medium: Increasing phase
	Uncertainty	Seasonality, limited influence
	Income	Budgetary supported
	Budget	Competition with other sections within healthcare
	Investment	Long term
	Geographical distance	Local and regional
	Customers	Health professionals, patients, healthcare institutions.
	Customer contact	Not existing, operating as Backoffice

	Test urgency	Varies, determined by patient status
	Customer Influence	Could be high, due to sensitive information
	Patient groups	Often small groups due to rare diseases
	Service level	High: Fast, detailed, and accurate
Production and development	Volume	Total volume is high. Low volume per variant.
	Variety	High, customization
	Process complexity	Some are established, others are new
	Processing	Batch based
	Production strategy	MTO/ATO
	Storage	External location, never destroyed
	Research	High degree of innovation and development
	Utilization of resources	Low
	Equipment	Varies, but are often outdated
	Machine cost	Contract: High
	Maintenance cost	Contract: High
Information flow	Communication	There is potential for improvement in communication between departments
	External sections	Mail, both paper and electronic
	Notification	Notification by Email when analysis can start
	Healthcare platforms	ERN & EHDS for international information sharing and storage
Restrictions	Space	Limited possibilities for space expansions
	Budget	Limited budgets
	Employees	Need for specialized expertise
	Safety	Need to follow specifications for a safe testing environment
	Ethics	Laws for storing and sharing personal information

3.2 Shared Resources

There exists a variety of definitions for the term “resource”. To understand shared resources, one needs to understand what resources are first. Vissers and Beech (2005) define resources as objects that are used in production and that are not changed or consumed throughout the process. Each resource has a capacity, which is the highest amount of “something” it can achieve, and it refers to the resource's ability to achieve production. APICS identifies a resource as anything that adds value to a service or goods creation, production, or delivery. This indicates that resource is a broad term that can include all from machines within a production facility, to the production facility itself. It all depends on the characteristics of the situation in focus.

Shared resources are a typical characteristic of hospitals, as it is difficult to avoid due to the required infrastructure and specialized staff (Vissers and Beech, 2005). Wu et al. (2016) define a shared resource as a resource that can be shared between different departments, while Zhao et al. (2021) mention it as a factor that characterizes the strategies of companies through decreasing or increasing the resource amount. Schönberger et al. (2016) identify a shared resource as a resource that is cooperatively managed by two or more actors. In the perspective of a whole network, a shared resource is a common capacity source involved in two or more networks (van Donk and van der Vaart, 2005). Research by Gansterer and Hartl (2020) focuses on shared resources in collaborative vehicle routing. They identify how there are often inefficiencies in logistics, where there is underutilization of existing resources such as trucks being half full. Sharing resources (trucks) will then reduce these inefficiencies (Gansterer and Hartl, 2020). Essentially, it is a collaboration of the use of the same resource, meaning that multiple flows are utilizing the same resource for their operations.

Curjssen et al. (2007) mention how the main motivation to enter collaboration of resources is to reduce costs and increase efficiency by taking advantage of the synergy effects of sharing resources. These synergy effects could be economies of scale, a skilled labor force, and higher research and development level. Moreover, entering into cooperation could also cause a greater customer value with a lower cost (Cruijssen et al., 2007). Shared resources could cause potential cost reductions (Muñoz-Villamizar et al., 2015), this is especially true if one goes from having two resources to one common resource, cutting fixed costs. However, as Arashpour et al (2016) point out, the real challenge is to find an optimal production sequence. Freitag et al. (2015) and Kück et al. (2016) mention how increased flexibility and efficiency could be achieved with the use of shared resources, this is further argued by Freitag et al. (2016)

addressing that resource sharing has one central aim of changing capacities to increase resource efficiency to meet the current demand.

Sharing information about what capacity and demand are expected at the shared resource increases the efficiency of the available resource (Schönberger et al., 2016). Xu (2013) identifies that collaboration involves sharing information, resources, opportunities, and risks to increase profits and improve efficiency. Moreover, Meller et al. (2012) highlight that collaboration can result in improved utilization and lower cost. As hospitals are experiencing increased demand and trying to fulfill it with a restricted number of resources, sharing resources could be seen as an opportunity to improve operations. Thus, it is not enough to just minimize costs but to encourage cooperation (Luo, 2017).

Furthermore, van Donk and van der Vaart (2005) identifies that having shared resources limits the possibilities of integration and point out that the coordination of capacity is important. Additionally, sharing resources will increase the complexity of flows (Broekhuis and Van der Vaart, 2005). As Anderson et al. (2017) point out, when having shared resources, one needs to avoid resource conflicts as this adds to the complexity and will make planning and control more difficult. The changeover time for switching from one job to another increases this complexity (Ferrell et al., 2020), as it is difficult to find the optimal sequence of jobs. Wilson and Platts (2010) investigated mix flexibility, which is a company's ability to change between current products being produced (Slack, 2005). They pointed out that a shared resource is involved in multiple production flows would need a higher requirement of mix flexibility, further implying that shared resources increase production complexity. Furthermore, Dockery et al. (2014) investigated laboratory design and identified that where the shared resource is located affects the workflow and material flow. The layout should be designed to centralize the shared resource, locate labs next to production areas, and co-locate labs using the shared resource.

Shared resources can reduce risky and capital-heavy investments and enable flexible adaptions to demand fluctuations, however, shared resources could result in increased costs related to the organization and coordination of the resource (Freitag, 2016). Moreover, in addition to the increased complexity that follows shared resources, occupying a shared resource could also heavily affect other companies/departments that are depending on the resource (Freitag, 2016). This indicates that if a faulty happens at the shared resource it will impact all the other downstream production processes and material flows of the other companies/departments. Hoekstra and Romme (1992) highlight how shared resources, in general, should be avoided. This is unless the advantages, such as leveling of overcapacity/under-capacity, and economies

of scale, outweigh the disadvantages such as increased complexity, creation of stocks, and longer lead times. Sharing machines could cause a focus on measuring machine utilization and productivity. This often leads to a wrong focus, where the batch sizes are suitable to increase the machine performance rather than the performance of the whole process (Duggan, 2013).

3.3 Logistics and Operations Management Perspectives

This section will introduce layout, capacity management, scalability, prioritization, batching, and material and process flow, from an operations management and logistics perspective.

3.3.1 Layout

Choosing a layout is the decision of the physical structure inside a plant. A layout can be defined as "the configuration of departments, work centers, and equipment, with particular emphasis on the movement of work (customers or materials) through the system" Stevenson (2011, p.248). This decision will have a significant impact on both the flow of work through the processes and the ability to synchronize production with demand (Anupindi et al.,2012). The importance of a layout can be divided into three main arguments: "(1) they require substantial investments of money and effort; (2) they involve long-term commitments, which makes mistakes difficult to overcome; and (3) they have a significant impact on the cost and efficiency of operations" (Stevenson, 2011, p.248). Based on research conducted by Slack et al. (2010), Tompkins et al. (2010), and Joseph (2006), operational and organizational factors of layout have been listed in Table 4.

Table 4: Layout - Operational vs Organizational factors

Operational	**Organizational**
Inherent safety and staff condition	Improve customer satisfaction
Minimize customer dissatisfaction	Improving visibility for effective management
Obtain smooth and clarity of flow	Management coordination
Effectively utilize people, equipment, space, and energy	Support the organization's vision through partnerships and communication
Minimize material handling distance/cost	Support organization's vision through improved material handling, material control, and good housekeeping
Avoid bottlenecks	Maximize return on investments (ROI) on all capital expenditures
Be adaptable and promote ease of maintenance	Provide for employee safety, job satisfaction, energy efficiency, and environmental responsibility
Long term flexibility	Assure sustainability and resilience
Reduce WIP	

According to Tompkins et al., it is not reasonable to believe that the layout solution will meet all objectives that are listed. As we can see in Table 4, some sources focus on how the layout solution can fit the other actors in the supply chain, while others have a more focus on the performance internally for the given plant. Hence, when discussing different solutions, it is important to be aware of the importance and carefully evaluate the performance of each alternative by using the appropriate criteria.

Layout types

There are four main groups of layout solutions: Fixed-position-layout, Process layout, Cell layout, and Product layout. According to Slack et al. (2010), these four can be separated by two main parameters: volume and variety. Figure 8 shows the relationship between the mentioned layout types and the given parameters.

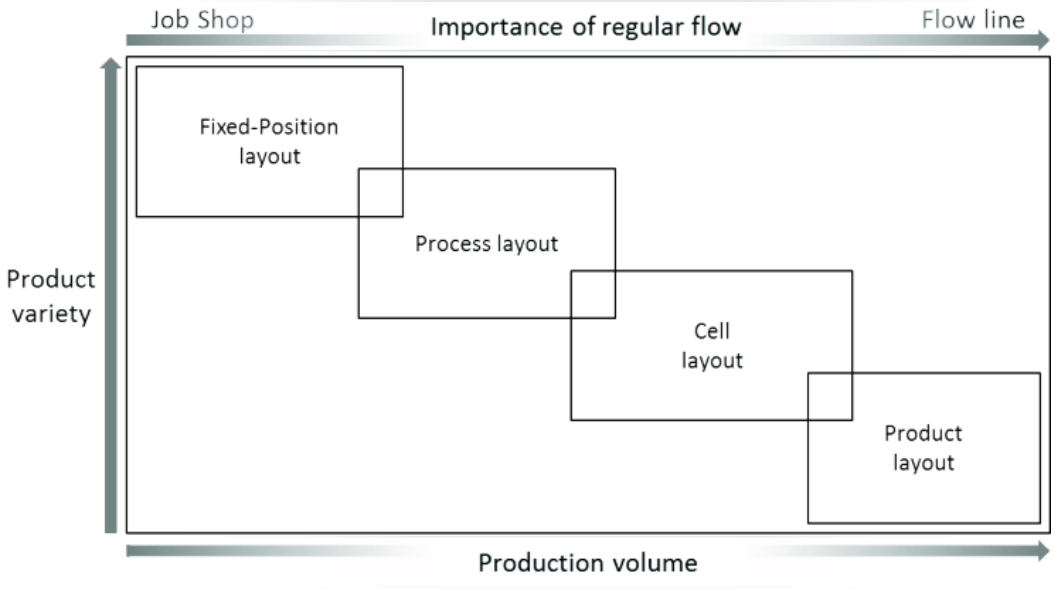

Figure 8: Layout types

Both fixed-position and product layout is not suited for hospital laboratories due to their characteristics creating a mismatch. For large and heavy products, it would be logical to have a fixed-position layout, as it is extremely cumbersome to move the product around inside a facility. Therefore fixed-position layout is mostly used in ETO environments (Monga and Khurana, 2015). Furthermore, Product layout is feasible for high volume production with a low degree of variation where most of the stages are standardized (Stevenson, 2011). Thus, the following will go into further detail regarding the process and cell layout.

Process layout is characterized by grouping processes or resources with similar functions together. A Process layout is ideal for job shops that process a wide variety of products with

smaller volumes. The physical structure is departments where different operations are performed, and it is mainly the products that are moved from one operation to another. (Monga and Khurana, 2015)

Cell layout refers to workstations that perform operations on a given product or product family and are grouped to form a cell. Each cell can be seen as a miniature version of a product layout that can be categorized as the same product family. This layout often requires the same machine in more than one cell and duplicating such machines often leads to high investment costs. This solution is often suitable for high volumes where the factory is producing more than one single product. (Anupindi et al., 2012; Monga and Khurana, 2015)

Table 5 is a collection of advantages and disadvantages for different layout types adapted from Slack et al. (2010) and Stevenson (2011).

Table 5: Advantages and disadvantages of layout types

Layout types	**Advantages**	**Disadvantages**
Process layout	High mix and product flexibility	Can have very high WIP or customer queuing (batch)
	Relatively robust in the case of disruptions	High facility and equipment utilization
	Relatively easy supervision of transforming resources	Complex flow can be difficult to control
	General-purpose equipment is often less costly	Accounting, inventory control and purchasing is more complex
	Possible to use individual incentive systems	Special attention necessary for each product/customer
Cell Layout	Gives a compromise between cost and flexibility for relatively high-variety operations.	Requires multiskilled employees and redefining of jobs
	Fast throughput time	Can require more equipment
	Potential good staff motivation	Requires fast change over time
	Smooth flow and minimal transportation	Can give lower equipment utilization, due to duplication
	Minimal WIP and lead time	Costly equipment and vulnerable to shutdowns
	High productivity and quality	Can be costly to rearrange existing layout.

In addition, it may be appropriate to set up a cell of very flexible resources that is assigned a large variety of low-volume parts. Then the focus for that cell will be on flexibility to produce a variety of low-volume products, and so the rest of the plant can focus on the high-volume products efficiently. Furthermore, the resources available play a central role in such decisions. It is inefficient to set up a cell to handle a variety of products with different workflow, requirements, and high changeover times if the resources are not flexible enough. In cellular layout, resources are dedicated to specific cells, and it is therefore not convenient for others to use them. Consequently, the possibility of resource sharing that is easily accessible for a process layout is lost. This loss of resource sharing can be countered with flexible and cross-functional resources. Cells without flexible resources can be justified only if production volume is sufficiently high. (Anupindi et al., 2012)

3.3.2 Capacity Management

As resources have a certain capacity (Vissers and Beech, 2005), managing the capacity is an important part of managing shared resources. High performance in the healthcare sector is key when managing the increasing demand (Lakshmi and Iyer, 2013; Bittencourt, et al., 2018), meaning that waiting in the system is important to avoid. As demand is increasing, healthcare systems need additional capacity (Fagefors, 2021). Capacity management does not mean maxing out the utilization of existing resources, but to find the right position between waiting time (responsiveness) and utilization (efficiency) (Terwiesch et al., 2011). Patrick and Puterman (2008) highlight three reasons for waiting to occur in healthcare systems:

1. Capacity does not meet demand
2. Capacity or demand is not well managed
3. Due to the variability in demand for healthcare service

This is a strong indicator of how managing capacity could increase the performance of the system. McLaughlin (2017) identifies capacity as the highest amount of output a process or resource can produce, while Terwiesch et al. (2011) mention capacity as the highest number of customers that can be served per unit of time. Bittencourt et al. (2018) investigate hospital capacity, stating that capacity in healthcare is usually measured regarding resources aiming to deal with the variety. Balancing capacity with demand is something that has been a challenge for a long time due to the difficulty of predicting demand behavior and is especially difficult to accomplish in the service industry (Jack and Powers, 2009). Moreover, in the service sector, it is difficult to control and determine service rates, balancing the capacity with demand is often referred to as capacity management (Klassen and Rohleder, 2002). Furthermore, capacity

management can be defined as a reaction to demand (Klassen and Rohleder, 2002; Jack and Powers, 2009), while Smith-Daniels et al. (1988) highlight capacity management as decisions associated with the allocation of critical resources such as facilities, equipment, and personnel. With capacity management, hospitals can correct lost revenue, delays, inefficiencies, and dissatisfaction among patients (Lima et al., 2021).

A consequence of shared resources is increased process complexity. Lantz and Rosen (2016) identify how increased complexity results in measuring capacity output when there is a mixture of products being more complicated. Bamford and Chatziaslan (2009) identify how complexity in operations is a deciding factor in capacity management. They argue that having a better understanding of the resources available in the operation could result in better management of capacity, resulting in decreased profit loss and fewer unnecessary investments. Luo (2017) investigates capacity sharing in hospitals, identifying that waiting is the result of a mismatch between capacity and demand. This mismatch might lead to insufficient management of demand, possibly increasing delivery times of test answers to patients. Furthermore, this mismatch is the outcome of not having enough needed resources, the need being too high or not having resources and their needs being synchronized. This highlights the need for a balance between capacity and demand.

Capacity will impact how demand is managed and the performance of the operations in a laboratory (Smith-Daniels et al., 1988; Patrick and Puterman, 2008; Demirel et al., 2015; Luo, 2017). Dockery et al. (2014) imply that there are often no procedures of how to level the flow of goods entering the lab and how the capacity in labs is often misunderstood. The consequence of not having control of this capacity is misusing laboratory space, consuming excess resources, and adding additional stress on the laboratory system. As indicated by Patrick and Puterman (2008), this results in longer waiting times. In addition to longer waiting times, the operational effectiveness will be reduced, and more waste will be added to the system (Dockery et al., 2014).

The ratio between demand and capacity could have positive and negative consequences (Klassen and Rohleder, 2002). Wait times and queues will be short when capacity is remarkably greater than demand, resulting in better customer satisfaction (Klassen and Rohleder, 2002; Patrick and Puterman, 2008). However, due to demand variability, some resources will be idle part of the time, resources will be underutilized, and costs will be high (Patrick and Puterman, 2008; McLaughlin, 2017). Costs will be high due to having idle staff, equipment, or facilities increasing the costs without increasing the revenue (McLaughlin,

2017). If the capacity is remarkably lower than demand, the existing resources will be fully utilized, but patients will experience long waiting times and could find another service provider, resulting in increased costs (Klassen and Rohleder, 2002; Fomundam and Herrmann, 2007; Patrick and Puterman, 2008; Mclaughlin, 2017). In queuing systems, reducing the customer waiting time (patients in healthcare) and increasing resource utilization are conflicting goals (Fomundam and Herrmann, 2007).

Capacity management strategies

In capacity management, it is important to consider the manufacturing strategies and sales plans as inputs to decisions and acknowledge the timing of capacity changes (Coker and Helo, 2016). Strategies could be to lead, lag, or track the demand level (Olhager et al, 2001). Lead and lag strategies are related to decisions within the manufacturing strategy, managing the capacity relative to the long-term demand. Chase and level strategies are related to sales and operations planning, which revolves around decisions related to the utilization of existing capacity relative to demand. Moreover, Olhager and Johansson (2012) separate between capacity strategy (long-term) and planning strategy (medium-term).

A leading strategy means to time the capacity so that you always have enough capacity to meet demand, while a lagging strategy implies that demand is always equal to or greater than capacity. Additionally, there is a third approach, tracking, which sets the capacity level at the average demand over a given period (Olhager et al., 2001; Slack et al., 2010**;** Olhager and Johansson, 2012). The medium-term strategies involve level, chase, and demand. A level strategy means that one can ignore the fluctuations in demand and maintain constant activity levels. A chase strategy implies modifying capacity to handle the demand fluctuations, this can be done with the use of capacity or utilization as the lever. With a demand strategy, the aim is to influence demand to fit the capacity available, however, as previously mentioned, this is often not possible in the healthcare sector. Additionally, these strategies can be mixed to find a better fitting solution (Slack et al., 2010).

As matching capacity to demand is key in healthcare due to the possible consequences of not fulfilling demand, strategies influencing capacity and demand must be established. However, influencing demand is not possible in healthcare (McLaughlin, 2017). How balancing capacity and demand is performed, is different from service industries to other industries. There are fewer opportunities in service industries such as healthcare, compared to more traditional manufacturing industries (Fagefors et al., 2020). Typical capacity management strategies could be scheduling employees, using part-time or on-call employees, cross-trained staff, using

overtime, use of customer participation, or staffing pools (Klassen and Rohleder, 2002; McLaughlin, 2017; Fagefors et al., 2020).

Fagefors et al. (2020) point out that there is a need for flexibility in healthcare systems due to variations in capacity and demand. To cope with variation in both capacity and demand, Fagefors (2021) highlights how there are reactive and proactive tools to create short-term flexibility. Capacity pooling is a proactive tool where capacity can be assigned to certain parts of the system where there are unusually high needs for resources (Vanberkel et al., 2012). To obtain efficient capacity utilization a hybrid solution of both proactive and reactive tools to create short-term flexibility needs to be adapted (Fagefors, 2021). Proactive tools for creating short-term flexibility could be over-capacity, cross-trained personnel, or external staffing agencies. However, as Fagefors (2021) points out, these tools are also associated with high costs, and might not be applicable in healthcare systems where there are limited resources. Hence, it is necessary with a more cost-efficient tool, such as capacity pools. Reactive tools could be the use of overtime or queueing patients (Jack and Powers, 2009; Fagefors, 2021) when a unit experience scarce capacity. Such tools are often efficient for a short period but could in the long term be both costly and have negative effects on operations. Having proactive capacity pools could provide higher utilization of capacity and enable a better work environment (Fagfors, 2021).

Moreover, the most frequently used tools to create short-term flexibility can be divided into four categories: inventory buffers; slack capacity buffers; workforce flexibility; and subcontracting services (Fagefors et al., 2021). These are the most common tools used in more traditional manufacturing industries, however, not all of them are applicable in healthcare services. As highlighted by Jack and Powers (2009), inventories are not an option in healthcare industries due to not being able to store capacity. This is due to it not being possible to produce the whole service package and store it and hold it as inventory. Furthermore, having slack capacity buffers is not an option in healthcare because of the ability to hold capacity beyond the average level of demand due to limitations in budgets (Jack and Powers, 2009; Fagefors et al., 2021). Additionally, due to increasing costs and healthcare organizations often not being able to increase fees for services to compensate for these costs, maintaining slack capacity is not possible (Jack and Powers, 2004). Hence, only two options are left to create short-term flexibility: workforce flexibility and subcontracting.

3.3.3 Scalability

With resources having a certain capacity (Vissers and Beech, 2005) and increasing demand (Lakshmi and Iyer, 2013; Bittencourt, et al., 2018), healthcare systems need additional capacity (Fagefors, 2021). Being scalable could then support healthcare systems in balancing capacity to the experienced demand. There are a variety of definitions of what scalability is, as it is a relevant concept in traditional manufacturing, healthcare services, information technology, and others. Mazlan et al. (2020) identify scalability as the ability to manage an increased workload, while Milat et al. (2013) present scalability as the ability to expand health interventions to reach a greater part of the population, while simultaneously maintaining effectiveness. Bortonlini et al. (2018) describe scalability as the ability to modify the capacity in production by either adding or removing manufacturing resources and changing components to meet the demand fluctuations. In a humanitarian supply chain, scalability is the ability to scale up when a disaster occurs, but also scale down back to "normal" operations (Kovács and Tatham, 2009; Merminod et al., 2014). Due to a broad specter of definitions, a simple explanation of scalability can be: *The ability to scale up and down capacity to meet the experienced demand, in an effective and cost-efficient manner* (Spicer et al., 2002; Wang and Koren, 2012; Milat et al., 2013; Koren et al., 2017; Bortonlini et al., 2018; Morinière et al., 2018; Mazlan et al., 2020). Tabaklar (2017) highlights how scalability is a concept that originates from more traditional manufacturing literature, and that scalability in the healthcare sector is often referred to as "surge capacity" (Hick et al., 2004; Tabaklar, 2017). The research conducted by Hick et al. (2004) points out how surge capacity can be considered as the system's ability to go from having "normal" operations to scale up to manage an increase in demand. Hick et al. (2004) define surge capacity as:

> "The ability of the public health system to increase capacity not only for patient care but also for epidemiologic investigation, risk communication, mass prophylaxis or vaccination, mass fatality management, mental health support, laboratory services and other activities" (Hick et al., 2004, p.254)

In markets with volatile demand, much like in the healthcare sector (St. Olavs Hospital HF, 2018), scalability is an important system design characteristic (Wang and Koren, 2012). When designing a manufacturing system, a specific capacity is usually implemented to fulfill a forecasted demand (Tang et al., 2004). However, when designing such a system a dilemma occurs regarding the capacity. If the capacity is too low, there will be a loss of market share. If capacity is too high, parts of the system will be idle, resulting in higher costs due to maintaining

machines that are not operating, and loss in capital investment purchasing (Koren et al., 2017). Hence, scalability could be considered to enable operations to scale up and down when necessary, avoiding potential costs. Zamboni et al. (2019) identify how scalability can be both formative and predictive, meaning that it can refine an intervention and be used to determine how big of a scale-up is feasible. Moreover, Milat et al. (2013) highlight the key elements of scalability and lists them as: size and reach, effectiveness, and degree of control. These elements are all key to achieve scalability, enabling population-wide health improvements.

Manufacturing systems that possess the characteristics of scalability can increase their capacity rapidly, when the market needs more products, and incrementally by adding the capacity necessary to fulfill the market demand (Koren and Ulsoy, 2002). By incrementally adding capacity, it will enable the whole system capacity to expand cost-effectively, allowing the production of more products. Moreover, obtaining scalability is imperative to achieve cost-effective competition, creating greater value for the business (Koren et al., 2017). Wang and Koren (2013) identify how designing for scalability with incremental capacity steps following the demand in the market is the most economically feasible way to fulfill demand. However, as Freiheit et al. (2007) point out, attaining cost-effective scalability relies heavily on the existing system design. Therefore, when planning for scalability it should be done in parallel with the design of a new manufacturing system, as this will ensure that the material handling system can be customized for future scalability and the lifetime investment costs will be reduced (Wang and Koren, 2012; Koren et al., 2017).

Tabaklar (2017) identifies how scalability can help build resilience. In addition, scalability increases service levels by foreseeing demand fluctuations and choosing the right time to respond, enabling the supply chain to reduce the risk effects. Hence, there is a close connection between scalability and resilience, where scalability enables further resilience. Doern and Holfelder (2015) investigate the design and automation of clinical microbiology laboratories. They point out how the laboratory should be designed so that they are scalable, making their configuration flexible and enabling the laboratory to serve an increasing demand and new technologies (Doern and Holfelder, 2015). The laboratory structure can be reconsidered, and the process can be revised, to enable the development of scalability. A result of changes to the processes within the laboratory environment can be increased flexibility and capacity, which can enable the laboratory to better handle the increased demand for testing i.e., make the laboratory more scalable.

3.3.4 Prioritization and scheduling restrictions

In manufacturing, priorities are often a part of scheduling decisions, where the basis for decisions is different priority rules (e.g., earliest due date, First-In-First-Out, shortest processing time), although the final priority is made on the shop floor depending on the status of each workstation. One way of managing the demand for several products is through some sort of prioritization where one divides customers into tiers. Here, such tiers are often grouped based on the number of sales, where the first tier has the largest number of sales. In these industries, the tier with the highest number of sales will also be the tier with the highest priority. However, due to fluctuation in demand, when there is a peak in demand, the customer in the last tier might be less prioritized resulting in demand not being fulfilled (Nicholas, 2011). In the healthcare sector, prioritization is often related to patient waiting lists, where priority is affected by factors such as the severity of the disease (Déry et al., 2019; Oliveira et al., 2020). According to Fomundam and Herman (2007), the queue discipline is either first-in-first-out (FIFO) or a set of patient tiers that have different priorities.

There are several challenges related to managers creating long-term schedules. Changes in priorities and delays because of disruptions like parts shortage, machine breakdowns, or other unexpected events that occur will make the schedule obsolete and it needs to be revised. Most of the problems related to traditional push production are trying to schedule every operation for every job in advance, where decision-makers might not be involved enough with the processes to acquire the perspective necessary to make the schedules current. In contrast, pull production schedules make workers rely on a Kanban sequence board to determine job priority. Here, cards (jobs) enter the workstation and represent a priority which could typically be visualized with a color sign (green, yellow, and red). What jobs each workstation needs to prioritize is determined by the workstation downstream, and if several jobs have the same priority, it is up to the upstream operation to decide the priority of jobs. (Nicholas, 2011)

Fomundam and Hermann (2007) stated that it is possible to minimize waiting times by giving priority to clients who require shorter service times. This rule is a form of the *shortest processing time rule* that is known to minimize waiting time. In practice, especially for an MTO/ATO environment, it can be found unfair because the importance of customers is overlooked. Such rules require that it is possible to predict the processing times accurately and some customers might constantly be down-prioritized due to their longer processing times (Fomundam and Herrmann, 2007). FIFO strategy implies a prioritization strategy where the customers entering the queue first, are also the customers that will be treated first, and such a

strategy can reduce the average waiting time. Here, patients with the highest priority will experience an increase in average waiting time, while lower-priority patients will experience a decrease (Fomundam and Herrmann, 2007).

Preemptions

When working with prioritizations and scheduling dilemmas, one important part to consider is *preemption*. Some jobs may allow the so-called preemption, which refers to the possibility of interrupting another job after it has started. For preemption and non-preemption, a job with lower priority starts only if no higher priority is waiting in the same queue. The difference is when the job has been started, preemptive queue discipline allows higher priority jobs to interrupt already started jobs of lower priority, while non-preemptive jobs cannot be interrupted once the job has been initiated (Fomundam and Herrmann, 2007). According to Framinan et al. (2014), there are many situations where preemption might be needed or even interesting: (1) Arrival of new urgent job orders might require stopping jobs already being processed. (2) It might be economical or beneficial to preempt a job and/or to continue it in another machine later. (3) Sudden cancellations of clients' orders might require stopping processing a batch of products. (4) Breakdowns on machines or any other unexpected event might result in preemption.

Furthermore, there exist several types of preemptions. If a job is interrupted and the preempted operation is lost and when resumes, processing must restart from the beginning, the preemption is denoted as non-resumable. Conversely, preemption can be resumable if the interrupted job just can continue from where it was interrupted to completed. In addition, if a job can be resumed but must deal with a penalty like a cost or time, it will be referred to as semi-resumable. (Framinan et al., 2014)

Blocking

Blocking is a situation that occurs in a queuing system where there are storage limitations or restrictions in the length of the queue. Blocking might happen when there is no more capacity, and a previous machine cannot finish a job because there is no available place to put it. This can happen because of too few workers, or due to a lack of storage capacity. These situations are not only affecting the area where there is a lack of capacity, but it also affects upstream activities to hold patients longer than necessary. Such system-wide congestions can be caused by single bottlenecks at only one downstream facility. (Fomundam and Herrmann, 2007; Framinan et al., 2014)

3.3.5 Batching

According to the APICS dictionary, "process batch is the quantity or volume of output that is to be completed at a workstation before switching to a different type of work or changing an equipment setup". Traditionally, products are moved in batches from one stage to another, where each stage conducts the required operation on an entire batch before moving to the next. In situations where batch sizes and processing times vary from one stage to another, it is difficult to synchronize the material flow, and materials are waiting at each operation before they are processed. Two contradictory concepts are determining what batch sizes to use, which also separates the traditional push systems from the pull production system developed by Toyota: (1) The use of Master Requirement Planning (MRP), where the batch size is determined in advance from a central planning staff that uses lot-size rules. (2) The use of Kanban, where the batch size is determined at the floor level according to the demand for the downstream inventory buffers. (Nicholas, 2011)

There are several parameters to consider when determining what batch size one should operate with. Operating with large batch sizes can on the positive side achieve significant economies of scale but will often lead to a large inventory which also comes with a cost. A well-known conflict in inventory management is that the inventory managers will always favor policies that will meet demand with minimal inventory, while the purchasing manager wants to achieve the given economies of scale. The Economic Order Quantity (EOQ) has its main objective to identify a cost-optimum order quantity from suppliers and considers demand, purchasing - and inventory costs. (Hussain and Drake, 2011)

On the floor level, long changeover times at different processes are another cause for operating with large batch sizes, while smaller batches require rapid changeovers to be beneficial (Hussain and Drake, 2011). This can be explained with an example inspired by Anupindi et al., (2012): Let's say that there are to be produced two products: A and B, where the monthly demand for each is 1000 units. One way of meeting this demand is to produce 1000 of product A in the first half of the month and produce 1000 of product B in the second half of the month. The problem with this solution is that supply and demand are not synchronized as it is unlikely that the actual demand looks like this. Additionally, it will create an uneven workload for upstream processes, where suppliers of raw materials of both products have no orders for one-half of the months respectively. Lean production developed the terminology called level production, or Heijunka, to cope with situations like this. Level production is achieved if one can produce products A and B every other time. Furthermore, if demand for product B drops

to 500, there should be produced two of product A before one product B are to be produced, and so on, ensuring demand for both products is met, and production is leveled.

There are some obvious challenges related to changeovers to achieve a leveled production, and according to lean production, the focus should be on decreasing the changeover times. This is where the Lean tool Single Minute Exchange of Die (SMED) is central. The focus should be on reducing changeover time through improving necessary steps, eliminating unnecessary steps, and restructuring some steps to run in parallel instead of in a sequence (Nicholas, 2011). Achieving this concept will reduce the machine idle time due to changeovers, thus decreasing the changeover costs and time. It should be noted that batch size of one may not be beneficial for every process, and level production can be achieved in small batches instead of one-piece flow. In general, a batch reduction is often beneficial for larger or expensive products while less expensive products are better to handle in larger batches (Anupindi et al., 2012). Finally, batch sizes will also have an impact on the lead time and work in process (WIP). The lead time and WIP will increase as the batch size gets larger. Finally, there should be a tradeoff where both economical and productivity aspects are considered (Koo et al., 2007).

3.3.6 Line balancing and synchronization

A balanced line is a line that achieves a required output and is as efficient as possible (Nicholas, 2011). Nicholas (2011) identifies line balancing as the process of assigning tasks to workstations or operational sequences such that:

(1) The cycle time of the combined workstation sequence meets the required cycle time. This means that the output of workstations meets demand. Thus, the cycle time of the bottleneck cannot exceed the required cycle time. (2) The jobs have been allocated in the correct sequence. This point indicates that the allocation of tasks to workstations needs to meet priority requirements. When a sequence of jobs needs to be performed, there is a schedule that needs to be followed with specifications of priority for different jobs. (3) The task is completed as efficiently as feasible. When balancing a production line, the workstations need to manage the required cycle time and priority of products to enable efficiency in the production line.

Process synchronization refers to the ability of the process to meet the customer demand in terms of their quantity, time, quality, and location requirements. We can define synchronization at a level of an individual process or a supply chain. In both situations, it requires that every individual processing stages are capable, flexible, fast, and frugal. Furthermore, it requires that all stages are tightly linked together in terms of information and material flow. The result of

synchronized networks is a precisely balanced system where the outflow of each stage meets precisely and economically the inflow requirements of the downstream stage without any defects, inventory, delays, or stockouts. Finally, synchronized scenarios required precisely matching between supply and demand of several products between several processing stages. (Anupindi et al., 2012)

In a Make-to-stock (MTS) and portions of Assembly-to-order (ATO) or in production systems where products are manufactured on a repetitive basis, it should be possible to facilitate such synchronization. In pull production, the requirement to enable somewhat synchronous flow in a process, it is only necessary that the production rate and transfer of products at the upstream station roughly meet the demand rate for the downstream station. In pull production systems, the final assembly schedule (FAS) is the one that decides the rate of demand (Nicholas, 2011).

3.4 Performance Indicators

Measuring performance is an important input in decision-making processes, as it gives input and a basis for decisions to be taken. Moreover, developed performance indicators can be used to monitor trends in performance, and identify areas in a company that needs improvement. As Andersen and Fagerhaug (2002) point out, a company needs to be aware of its improvement needs, and identifying performance indicators and measuring them can form a foundation for which areas are most important to focus on. Additionally, benchmarking the performance measurement will also be important, as it will function as a reference scale. Benchmarking could provide a reference that allows comparisons and judgment of improvement, assisting in decision making and giving inputs to judge if performance is acceptable or not. However, before developing performance indicators, it is necessary to understand the whole business structure and processes. This forces the developers to think through and understand the business, its processes, and the environment in which it is operating. By reacquainting with the business and its employees, crucial input to which performance indicators are important will be identified. The performance indicators being developed should be based on the stakeholders' requirements, and as Andersen and Fagerhaug (2002) highlight, *ask the stakeholders what they want*. (Andersen and Fagerhaug, 2002)

As van der Geer et al. (2009) mention, hospital management is using performance indicators to measure performance. Furthermore, the reason for it being used is due to the increased pressure in the healthcare sector to improve its efficiency. Using performance indicators could help healthcare professionals to identify areas that need improvement, share experiences, and learn from each other (Cinaroglu and Baser, 2018). Moreover, measuring performance is fundamental in managing quality and performance. To obtain better performance in healthcare, it is important to measure it, as it will help identify the quality of the system and could lead to improved care (Cinaroglu and Baser, 2018).

One of the main goals in the healthcare sector is to improve performance, enabling better and more efficient handling of patients (Lakshmi and Iyer, 2013; Bhat et al., 2016). There exist many performance indicators influencing efficient and effective logistics. Throughout the theory and literature chapter, several important performance indicators have been identified. The following performance indicators are of interest: Throughput time, waiting time, WIP, utilization, and costs.

3.5 Summary

This chapter has provided the necessary theoretical foundation to investigate hospital laboratories from an operations management and logistics perspective. Namely, background on logistics in the healthcare sector, shared resources, layout, capacity management, scalability, prioritization, batching, process flow, and performance indicators have been presented. It has been presented that both a logistics and operations management perspective is highly relevant for hospital laboratories and hospitals in general.

Shared resources are a broad term, but are, in essence, the sharing of a resource between two or more process flows. There are advantages such as cost reductions, increased efficiency, and improved space utilization. Additionally, there are disadvantages such as increased process complexity. However, the literature on resource sharing is in more traditional industries, highlighting the need for more research in the healthcare sector and especially in hospital laboratories. The different layout types have been presented, where process and cellular layout are most relevant for hospital laboratories.

Moreover, it has been identified that it is important to balance capacity and demand to maintain good performance. To achieve this, several strategies have been presented. Furthermore, managing capacity affects costs, waiting times, customer satisfaction, idle times, and utilization. Scalability is an important feature that is necessary for the healthcare sector, as there are demand fluctuations. Scalability will then enable operations to adjust their capacity to meet fluctuating demand. Hence, scalability should be considered together with capacity management, as it provides the necessary buffer to balance capacity and demand.

It has been presented some reasons for why prioritization occurs, challenges related to this, and different prioritization rules to cope with this dilemma. Moreover, the implications different batch sizes can have on operations have been presented, where the batch size affects both costs, WIP, and throughput time. Furthermore, line balancing and synchronization have been investigated, presenting how a balanced production line is important to achieve effectiveness.

To end the literature study, performance indicators have been identified. From a healthcare perspective, the performance indicators should be based on the factors mentioned in the literature. This means that indicators such as WIP, utilization of resources, throughput times, waiting times, idle times, costs, and quality are highly relevant when wanting to improve the efficiency in a hospital laboratory.

4. Case study

This section will describe the characteristics of laboratory operations conducting genetic analyses at St. Olavs Hospital in more detail. Moreover, the process flows at the different laboratory departments will be presented, with descriptions of working methods and environment. The case study intends to highlight the relevance of the thesis topic and to give an understanding of the processes within a hospital laboratory focusing on genetic analysis. The processes are described based on the researchers' interpretation of information collected at the departments. All departments are isolating both DNA and RNA. However, for simplicity, DNA isolation is the common term used when discussing DNA/RNA isolation. More detailed information regarding the DNA isolation process at each department will be presented after introducing the three departments (section 4.4). Before introducing all the departments, it is necessary to specify that the working hours at all the departments are from 8 a.m. to 4 p.m.

4.1 Department of Medical Genetics

The Department of Medical Genetics (DMG) conducting genetic analysis consists of 20 employees and is located on the 5th floor at the laboratory center at St. Olavs Hospital. The general operations involve the assessment and guidance of patients and their families' connections with hereditary diseases, syndromes, or recent changes in the genetic material. DMG performs analysis for diagnosis and assessment of disease risk, additionally, they investigate instances where one does not know the reason for disease. DMG are very specialized and do not always know exactly what they are investigating which means that they are searching for a broad specter of potential diseases. This leads to the interpretation of answers being the most time-consuming process for this department. Demand for DMG is about 3000 samples yearly, which could be blood samples, amniotic fluid, saliva samples, and buccal smear. The department receives samples from all over Norway, as some of the services that the department offers are not available in other laboratories. Moreover, the department can experience urgent tests, but this rarely occurs.

Process flow

This section will describe the different equipment and technology used throughout the process. The complexity of different flows will be highlighted and visualized in Figure 9. The process starts with receiving samples and ends with the interpretation of analysis results. The personnel do not follow one batch from start to finish, thus, the process is divided into different personnel having different responsibilities.

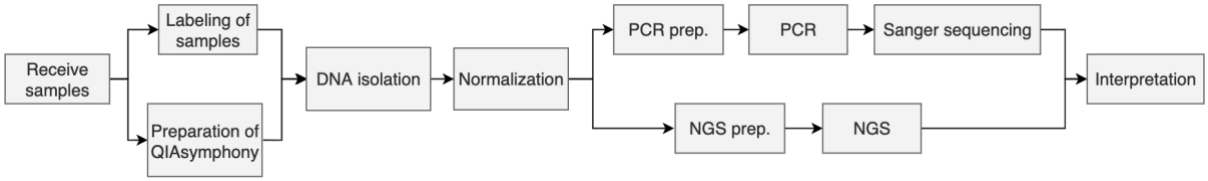

Figure 9: Process flow at Medical Genetics

DMG receives their patient samples on the fourth floor. Samples arrive either by mail or in boxes, and tests could be ordered from outside of the hospital or from internal requests. Received samples are validated by medical doctors, who order the necessary tests for the different samples. The samples are then transported to the fifth floor and delivered at the station for DNA isolation. The purpose of the isolation is to extrude the DNA from the different samples and prepare them for the next step in the process. When the isolation process is done, the DNA concentration of all samples are measured and normalized to ensure that all samples have the same concentration. Normalization usually takes 20-30 minutes. Due to machine specifications in later processes, samples are often stored to ensure that the capacity is fully utilized. Therefore, some samples are brought further in the process, while some might be stored for testing later.

After the normalization process, the isolated samples are transported to another room to prepare the DNA samples for replication. There is different preparation necessary depending on the analysis method. If the analysis is a PCR it is prepared in another location than preparation for NGS. Additionally, the different methods require different times to complete the preparation. Either way, samples are brought directly from the isolation station or from storage. Samples can be stored for up to two weeks before being used in analysis. With PCR preparation, the DNA samples are put into a Hamilton Microlab STAR machine (Figure 10). Here, the normalized isolated DNA samples are mixed with a “mastermix”. A mastermix consists of reagents being mixed with buffer, enzymes and specific probes and primers, which is further mixed with the isolated DNA. It takes 20-30 minutes to prepare one batch. After the preparation is done, the samples are transported for replication of DNA. Replication of DNA samples are done in a separate room. Preparation of NGS is a more time demanding manual process. Here, personnel use approximately two workdays to prepare a full batch of samples for NGS, before transporting the samples into a dedicated room for NGS.

Figure 10: Hamilton machine

At DMG, most analyses are usually done through an NGS. NGS has a capacity of 48 samples and takes approximately 2,5 days to run. Due to a long runtime, it is usually initiated before the weekend. Additionally, the laboratory waits for 48 samples to be available before running it, mostly due to the long runtime and costs. The NGS can mix different samples with different characteristics and does advanced sequencing. The data created through the NGS is continuously delivered to the section for interpretation. Due to it being able to analyze 120 different genes, it delivers highly detailed data.

Samples can also be run through a Sanger sequencing, which is common to do after a PCR test. The method is used to read the sequence in a patient's DNA. With sanger sequencing, a PCR machine (Figure 11) is used first to replicate DNA. The replication takes approximately 2,5 to 3,5 hours, and the machine has a capacity of 96 samples. Moreover, PCR can only analyze one gene at the time. After replicating and reading the sequence, a reference sequence is used to e.g., look for mutations in the DNA. A sanger sequencing takes an approximate of five hours from PCR is complete to data is generated and stored.

Figure 11: PCR

When conducting sanger sequencing, personnel must look over the data and find the area of interest in the DNA. When this is identified, the data related to this area is sent to the interpretation section. The main difference between this and the NGS is how the NGS delivers all possible data, enabling the interpreters to reopen the data if a patient needs another interpretation at a later point in time. If a regular sanger sequencing was the method used, and a patient need additional interpretation of the sample, it needs to be rerun through the sanger sequencing.

When the replication of DNA is done, the section for interpretation receives DNA data. The personnel in this section have specialized education relevant to what is being interpreted. Time needed to find the root-problem in DNA samples varies. As stated by the interviewee: “The department of Medical Genetics are looking for the needle in the haystack, as they do not know what they are looking for”, only that they are looking for something. Hence, time used depends on the rarity of disease, as the interpreters use international databases to search for similarities. If the disease is rare, the interpreters must use a lot of time on research to find something to compare it to. When a reliable interpretation is done, a medical doctor looks over the results. When the results are accepted, they are sent to the recipient (usually a patient’s doctor) for further discussions regarding treatment.

4.2 Department of Pathology

The department of Pathology investigates and answers biopsies and cytological samples. Additionally, they conduct autopsies for hospitals and primary health services in the region around St. Olavs Hospital. Pathology is responsible for all diagnostics based on investigations of tissues and cells, and they also perform autopsies including forensic examinations for the prosecuting authority. They receive samples both internally from the hospital, and from external health services (e.g., doctors office). As most patients are at the hospital when they are diagnosed with cancer, most of the samples received are internal orders. Due to the department analyzing samples of patients who potentially have cancer, prioritization is common in the system. Samples that are more likely to be positive for cancer have a higher priority and are marked with a color code.

The department receives tumor-tissues and blood samples. Pathology is cooperating a lot with DMG when it comes to equipment and space. This is due to DMG previously being part of the department of Pathology. A big difference between the department of Pathology and DMG is that Pathology knows that they are looking for. They receive samples from the whole human body, as their focus is cancer, the samples are taken from where the cancer is located. This can be a small lung biopsy or a whole intestine. Excess samples are stored at Dora, a location in the outskirts of Trondheim.

The department can be divided into multiple sections, where the section for molecular Pathology is one of them. Molecular Pathology is the one that are focusing on genetics analysis and will further be mentioned as Pathology. This is the section which focuses on genetic analysis and uses DNA isolation. The approximate yearly incoming volume is 2500 patient samples. Molecular Pathology has six employees (bioengineers) and receives their sample orders from the pathologists. The department have 30 dedicated pathologists who specializes in different fields. The pathologists are the ones who orders necessary analyses for samples and receives the finished end data for interpretation.

Process flow

The process flow can be divided into a *preparation-process* (Figure 12) and a *Pathology-process* (Figure 13). The preparation in this department is complex and time consuming, however, it is not part of the focus of this thesis. This is due to all samples the department of Pathology receives are going through the preparation-process, but it is not decided what sort of analysis to conduct before a pathologist have analyzed the samples. This is especially peculiar

for this department, as they receive their orders from a pathologist and are not collecting their samples directly from the section for sample receipt. Nevertheless, it is relevant to present the different steps in preparation, and what processes happen before they receive their sample orders. This is with the intention of creating a better understanding of the full process, and why they collect their orders from the pathologist.

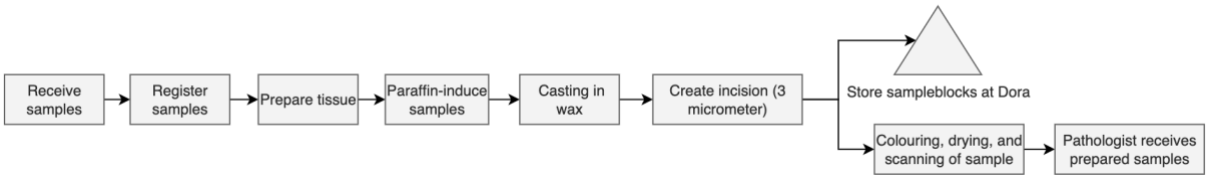

Figure 12: Preparation process

All samples the department receives goes through the preparation process. This is a comprehensive and time-consuming process, where the samples are being prepared with the necessary steps for later analysis. Each step in the preparation process has personnel with interdisciplinary knowledge, meaning that they can work at other stations in the process. The department is restricted in number of personnel available, resulting in a queue of samples at the sample registration area. All samples are received on the first and second floor in *laboratoriesenteret*. Then, they are transported up to the fourth floor where registration and all the necessary preparation takes place. After registration, the samples go through a biopsy, extracting sample cells or tissue to prepare for paraffin-induction. The department prepares as many samples for paraffin treatment as possible before the day is over and initiates the process overnight.

After the samples have been treated with paraffin, they are cast in wax to create blocks of each sample. A small incision is then made in each block, which is brought further in the process. The rest of the block is stored in an external storage at Dora. The treatment prior to this is also necessary to ensure quality of the samples, as they are stored a long time. This is also relevant for the incisions, as they are store between processes. The incisions are then treated with color to make the samples more visible. It is then necessary to dry the samples before scanning them. This is the final step before a pathologist receives the samples and can analyze them before ordering the necessary tests.

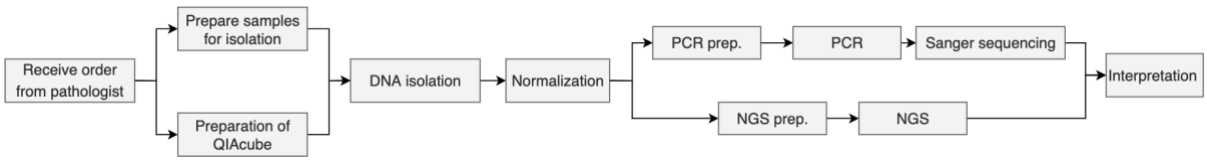

Figure 13: Pathology process

As with the other departments, the department of Pathology have multiple methods of analysis. Pathology uses a QIAcube for DNA isolation. Moreover, they conduct real-time PCR analysis (when a simple yes or no is required), NGS, and sanger sequencing. The goal is to identify mutations in the DNA, so that one can obtain information on which type of cancer it is and what sort of treatment is necessary for the patient. This means that all samples this department receives comes from patients with cancer, or from patients who wish to check if they have cancer.

The process starts with personnel checking the computer system for orders from the pathologist. If the order is for a PCR or NGS, the DNA must be isolated from the marked tumor-area. The pathologist has either sent a section from the marked area or the whole piece. When a received order requires DNA isolation, it is first necessary to prepare the tissue samples. Since they arrive either as a block or most likely in small incisions, it is necessary to extract the tissue sample. This is a reversed process where the tissue is extracted and put into a tube, where necessary supplements are added to ensure pure tissue is left for isolation. One batch of 12 samples takes half a working day to reverse, from start to finish. This happens at the fourth floor, before transporting the pure tissue in tubes up to the fifth floor for DNA isolation. The tissue samples are then inserted into a QIAcube, which is used to isolate DNA. When the isolation process is done, each sample must go through quality control, checking the concentration of each sample (normalization). The normalization takes place next to the QIAcube. However, even if the quality is not good enough, the samples are brought further in the process. This is due to samples with lower quality still being able to possibly produce some results. The samples are then transported to PCR-prep, where personnel are manually preparing each sample. Here, the isolated DNA samples are mixed with a “mastermix”. When the preparation is done, the samples are transported for PCR or real-time PCR. The specifications for the PCR machines and sanger sequencing is the same here as with DMG. When PCR is done with replication of DNA, the samples are brought further for sanger sequencing, if necessary.

If the method used is NGS, no further actions are necessary, as the data is being sent continuously as the analysis is carried out. When using NGS, the strategy is to wait and fill up samples to utilize the capacity of the machine. The NGS used at Pathology is different than at the other departments. This means that capacity and time used is different. They initiate 7 samples and one *blind* to start the NGS process. To initiate the NGS, certain kits are necessary. One batch fit eight samples, where each run needs at least seven patient samples and one *blind*.

It is costly to not fill up a kit with samples due to the kits being expensive. One kit is estimated to fit 32 samples (28 patient samples and four blinds) and are costly. Hence, they usually wait and fill up one kit to save costs. From start to finish, the process takes an approximate of 3 working days. This includes the extraction and storing of data.

After the analysis is done and the data is stored in the system, a pathologist receives the data and can start the interpretation of samples. The interpretation is done through a computer system which filters out all that is uninteresting. If the result is negative, they will still investigate the data to figure out why the answer was negative. This could be due to insufficient DNA, it being too fragmented, etc. The results are then manually inserted into a computer system where the results are sent to the requester (Usually the patient's doctor).

4.3 Department of Medical Biochemistry

The department of Medical Biochemistry (DMB) performs a wide range of different analyzes within the field of medical biochemistry, in addition to some gene and drug analyzes. DMB only receives blood samples. A big difference between DMB and the other departments is that they know exactly what they are searching for in advance to conducting the analysis. This results in less time spent on analyzing and interpreting data.

DMB can be divided into multiple sections, where special biochemistry is the section conducting genetic analysis. The section for special biochemistry is located at the fifth floor in *laboratoriesenteret*. Special biochemistry will be further mentioned as DMB. What makes DMB different from the other departments is how they have their own separate location for all processes. They receive both internal and external orders for analysis of samples and are expecting an increase in volumes. This is due to a general increasement, but also due to new methods being developed making better offers to the public. The demand for genetical analysis at DMB is approximately 2500 samples each year. The department can experience urgent tests, which is something that happens very rarely.

From interviews, it was stated that lack of cooperation between departments over time is the reason for DMB having their own room for DNA-isolation, but it could have been merged with the other departments. There are five qualified employees that have the knowledge to conduct genetic analysis for DMB, however, there are usually only three at the fifth floor, while the last two are working in other processes at the department.

Process flow

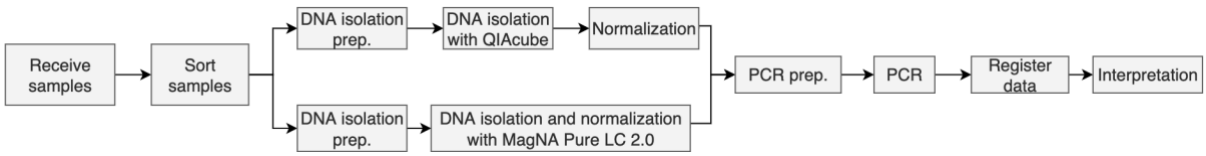

Figure 14: Medical Biochemistry Process

All samples arrive at the second or first floor, depending on if they are internal or external requests. The external samples are often received by mail. Incoming samples are picked up both in the morning and throughout the day and transported up to the fifth floor. The personnel can see in the system what samples have been registered and what sort of analysis is necessary to conduct that specific day. All samples that need to be run through the specific test is included.

When the samples are received at the DMB, they are sorted by what type of methods they are to be analyzed with. After sorting incoming samples, the ones who are going to be analyzed another day is stored in a cooling room, where the different analysis methods have their own dedicated places. The samples that are to be analyzed the same day are transported to their respected area. This means that samples that are going through the DNA isolation process are transported to DNA isolation. After transporting the samples, they are prepared for isolation, which includes to register the barcodes of each sample. Then, the DNA isolation is initiated using either a QIAcube or MagNA Pure LC 2.0.

When the DNA isolation process is done, the samples must be prepared for PCR. This includes measuring concentration and conducting normalization. After this, samples are mixed with a mastermix to enable the PCR machines to analyze the DNA and replicate it. Here, reagents are mixed to a master mix with buffers, enzymes and specific probes and primer.

After all samples have been prepared for PCR analysis, they are transported either to storage or directly into a dedicated room for analysis. Some samples are stored in refrigerators as they wait for enough samples to be available. DMB uses a PCR machine with a capacity of 96 samples, which uses approximately two hours for analysis. Time used at the PCR machine is not depending on the number of samples run in the batch.

Before initiating the PCR analysis, personnel specify what samples are placed in the machine, and where they are placed. This is a necessary preparation for each PCR analysis. However, there are also predefined templates where the personnel only need to specify the patient ID. When the replication of DNA is done (PCR), the same station is used for interpretation of results. Here, the personnel interpret the data and analyze if mutations exist in the DNA. The interpretation is manually registered into a data system where the result is sent electronically. A doctor then must confirm the results and ensure correct interpretation before communicating the results to the patient.

4.4 DNA isolation

Department of Medical Genetics:

The area where the department has its DNA-isolation machine is shared with the department of Pathology and consists of one QIAsymphony and QIAqube. However, DMG only use the QIAsymphony (Figure 15). These machines are used to isolate the DNA from different samples and are highly automatic. This means that the personnel do not need to be near the machine as it is running and can conduct other relevant tasks simultaneously. When the samples arrive at the isolation station, personnel must prepare both the patient samples and the QIAsymphony.

Figure 15: QIAsymphony and its "toolbox"

Preparation of patient samples happens at a workstation right next to the QIAsymphony. The only necessary preparation of patient samples before placing them in the QIAsymphony is labeling of barcodes, which the machine will then read to register the samples in the system. Each sample must be manually labeled and attached to a rack, which is put into the QIAsymphony. Preparation of patient samples takes an approximate of 30 - 45 minutes for a batch of 24 samples. Depending on the characteristics of the patient samples, different preparations on the QIAsymphony are needed.

When preparing the QIAsymphony, the personnel must check the “toolbox” to see if the correct kit is installed. The different parts of the toolbox need to be checked as they have a certain capacity. The QIAsymphony can check this independently and give the personnel a warning if it does not have the sufficient kit to run the isolation process. This includes being short on

articles such as those shown in Figure 16. Most of these articles are plastic consumer goods which are not recycled. Preparation of the QIAsymphony and patient samples can happen simultaneously.

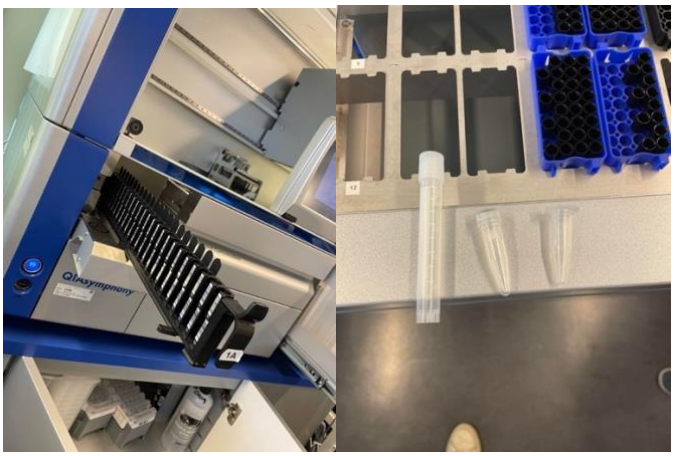

Figure 16: Rack and "toolbox" items

Before initiating the isolation process, the labeled patient samples must be suited to the rack. This means that different patient samples (e.g., blood, tissue, amniotic fluid, etc.) needs different preparation of racks, as they come in different containers. Thus, the personnel must manually change out parts of the rack to suit the samples being put on that specific rack. This implies how the QIAsymphony can isolate samples with different characteristics in the same isolation process. The QIAsymphony holds 5 racks (Figure 16), where each rack has a capacity of 24 samples. If five racks are included in the QIAsymphony, they are isolated one by one, from left to right (Figure 17). Racks can be removed and inserted while an isolation process are conducted, without interrupting the process which are running. When one rack is inserted, the QIAsymphony reads the labels and registers the samples into a system, enabling tracking of the samples.

Time is measured by racks, meaning that it will take the same time to isolate 1 as 24 samples, but if 25 samples need to be isolated it will take twice as long. Isolation of one rack takes approximately 1 hour and 15 minutes from start to finish. Each rack can hold samples with different characteristics, however, due to characteristics of later processes, the QIAsymphony allows different protocols at different racks. Different protocols are necessary to make sure the patient samples can be analyzed later in the process. Personnel puts in the protocol before starting the isolation process, this is done one a touch screen (Figure 17). After the racks are inserted and the correct protocols are prepared for the different racks, the isolation process can

start. Preparation of the machine (racks, toolbox, and protocols) takes an approximate of 20 minutes.

Figure 17: Placement of racks and touch screen

After the personnel initiates the isolation process, additional racks can be prepared and inserted into the machine. The machine isolates the DNA from the samples and extrudes them to separate tubes (Figure 18). The machine cannot run over night, as excess samples must be extracted and stored to ensure they won't be ruined for later use. Hence, the isolation process must be done before personnel can leave for the day. If a high priority test (urgent tests) enters the laboratory late in the day, it is isolated manually, as this is more efficient than running it through the QIAsymphony. The interviewee stated how a manual isolation process takes approximately 30 minutes, compared to QIASymphony using 1 hour and 15 minutes. However, there are generally few urgent tests, having on average one per month. When the isolation process is done, the isolated DNA samples are collected and brought further in the process.

Figure 18: Location of isolated DNA

Department of Pathology:

Pathology have their own QIAcube (Figure 19) which shares location with the QIAsymphony from DMG. The QIAcube is also a highly automated isolation machine, however, there are some manual labor in preparation of the isolation.

Figure 19: QIAcube

The samples are put into the QIAcube in a batch of 12 samples, which are max capacity at this machine. All samples are then registered in the QIAcube with a barcode scanner. As with the QIAsymphony, the QIAcube has kits it uses to isolate the samples. Hence, as part of the preparation, the machine must find out how many samples it can isolate with the current kit. If additional kits are necessary, the personnel manually insert extra kits. The preparation of the machine is estimated to 20 minutes.

After all the samples have been prepared, the isolation process can begin. The machine then isolates the DNA from the samples and extrudes them to separate tubes. If the running process is stopped, the samples are ruined. Due to this, some samples are isolated manually, avoiding the risk of it being ruined. The isolation process takes an approximate of one hour from start to finish. It takes one hour independent of how many samples are isolated, meaning that one sample takes as long as twelve. When the isolation is done, all samples are taken out of the QIAcube. Then, the concentration of each sample is measured (normalization).

Department of Medical Biochemistry:

The department have its own location where all the DNA-isolation is performed. In a separate room, the department have one QIAcube (Figure 19) and one MagNA Pure LC 2.0 (Figure 20). Both machines are used for isolation; however, MagNA Pure LC 2.0 requires less manual labor. Nevertheless, they are both highly automatic, however, personnel must manually ensure DNA concentration is correct after using the QIAcube.

Figure 20: MagNA Pure LC 2.0

The personnel must prepare the samples for isolation. This includes labeling the samples with bar-codes. Time used to label each sample here is the same as for the other departments. There is more preparation necessary when using the QIAcube than when using the MagNA Pure LC 2.0. The preparation for the QIAcube is the same as for the department of Pathology. Preparing the MagNA Pure LC 2.0 takes approximately 30 minutes. This includes preparing reagents and kits necessary for the machine to both isolate and normalize the DNA. Protocols for the different samples needs to be put into the machine system through the touch screen. A barcode reader reads the information on each sample and enters it into the system. When all preparation is done, the isolation process is initiated.

Today, samples are usually isolated using the MagNA Pure LC 2.0, as it relieves the personnel of manual work. The machine has a capacity of 32 samples, and the department usually waits for 32 samples being available before initiating the isolation process. It takes approximately two hours to isolate a batch of 32 samples. Time used depends on number of samples included, as it depends on number of racks. One rack fit eight samples, meaning that one rack can be isolated in 30 minutes.

If MagNA Pure LC 2.0 is busy and a certain number of samples higher than its capacity is scheduled for analysis on the same day, the QIAcube is used to isolate the remaining samples. MagNA Pure LC 2.0 is approaching the end of its service life, meaning that additional capacity investments will be necessary to replace it.

5. Case company analysis

This chapter aims to highlight key observations made at the case company. Based on these observations, research question one will be answered, and the scenarios in focus when developing the conceptual simulation model will be argued for.

5.1 Case company observations

This section intends to highlight observations made at each laboratory department. The observations will be compared between the different departments to highlight the general opportunities surrounding the DNA isolation station. As the visits were conducted, the researchers noted down general observations and obtained answers to questions regarding potential opportunities and challenges.

Restrictions

All departments have restrictions on space available, as there is little space wherever you go in the laboratory. It was further stated that space available could make it tough to locate new investments. Investing in new equipment is both a time-demanding and difficult process. Each department has its budget which needs to be followed. These budgets could vary, as others might have more critical investments needed, resulting in some departments being prioritized over others. The departments experience budgets not being sufficient.

Other potential restrictions are contamination of patient samples if cooperation is conducted at other processes (Normalization, PCR-prep). However, contamination is not a problem when it comes to sharing DNA isolation machines.

Demand

All departments expect an increase in incoming patient samples, especially the department of Pathology. Interviewees have stated that they expect an increase from 20% - 100% each year. This varies between the departments and the different samples. The reason for increased volumes is due to people living longer, people experiencing new diseases requiring new types of analyses, and new requirements to existing analyses. All departments will be affected by the general increase, while new technology is expected to shape the processes of all departments and give the public a better offer of treatment.

Prioritization and urgent tests

Department of Pathology are prioritizing their samples based on the likelihood of samples being positive for cancer or not. There have not been observed any prioritization at the other departments other than urgent tests always being prioritized above all other samples. Urgent samples can arise in all departments. Usually, the departments wait for a certain batch size of samples before initiating different processes. However, when an urgent sample enters the system, the process is sped up and the available samples are being used in a batch.

Processing strategy

When patient samples arrive at the departments, the decision on how to process the samples is often based on medical and customer-specific information, rather than being a predetermined process. Hence, most processes can be categorized as Make-To-Order. As machines are usually expensive to run, all departments wait for a certain batch size to fill up before initiating the machine. This is to utilize the capacity and save costs. Due to this, the batch size is almost always equal to the machine capacity, except when urgent tests arrive. As Duggan (2013) mentions, this results in a machine focus rather than a process focus, where the performance of the machine is maximized rather than the process. There are no other logistics-related decisions other than to fill up a batch size with different protocols at the DNA isolation.

Cooperation

The semi-structured interviews identified how the departments have been operating as independent silos, investing only for themselves. The departments have independently been investing in equipment despite several departments having similar processes, which indicates that sharing equipment should be used as an opportunity.

Furthermore, it was mentioned that DMG has previously been a part of Pathology and that they are sharing the same isolation room. They are also sharing the same room for PCR and sanger sequencing. The physical structure of both departments is reminiscent of a process layout where each process is carried out in different rooms. Both DMG and Pathology are receiving blood and tissue samples, and there are some collaborations due to tests conducted on these samples. Since there are few blood samples at Pathology and tissue samples at DMG, collaborating could also benefit throughput time for the given samples. Therefore, blood samples from Pathology are sent to DMG, and tissue samples from DMG are sent to Pathology.

DMB states how they would have good use of cooperation with other departments. They admit to not using the potential in cooperating with other departments and wish to cooperate if

possible. Their physical structure is reminiscent of a cellular layout, where all processes are conducted within the same area only dedicated to DMB activities. Moreover, the department points out how there would be of good use to centralize the DNA isolation and have dedicated personnel to isolate DNA. This is further strengthened by DMG stating how the personnel at the DNA isolation station does not need interdisciplinary expertise to isolate DNA from different departments.

Capacity and machine specifications

In contrast to what Jack and Powers (2009) and Fagefors et al. (2021) point out in the literature, it is observed in all the departments that most of the equipment available has good capacity, however, some are unused part of the time. In the literature, it was argued that slack capacity buffers should not be an option in healthcare due to restrictions on budgets. It has been observed that capacity is severely unexploited, where certain equipment is only used a couple of times a week. This is also relevant for equipment in relevance to the DNA isolation process. Both the QIAsymphony, QIAcube, and MagNA Pure LC 2.0 are partly unused in the departments.

However, certain machines have less capacity than others. Today, the department of Pathology has expressed that there is a need for additional capacity, due to the preferred strategy of maxing out capacity and using the machine once a day. DMG and DMB do not have any issues with current capacity; hence a sharing of DNA isolation machines could be a possibility, as the QIAsymphony has excess capacity. Moreover, DMB uses a MagNA Pure LC 2.0 which is soon to be replaced due to age. Hence, there are clear signs that Pathology and DMB will soon have to invest in new machines, or if possible, share machines.

Common for all departments is that the use of machines at the DNA isolation station is a better option than manual work in terms of time and quality. An overview of the existing machines for different departments is visualized in Table 6. However, it was mentioned that QIAcube is the best option for analysis of tissue samples, while QIAsymphony was best suited for analysis of blood samples, due to machine specifications. Furthermore, it is still unclear if this has a real impact on the quality or if it is negligible, and if there exists an isolation machine that could be feasible for every department and all their samples. Additionally, it has been stated that the departments will never operate with only one machine, as they are not willing to take the risk of potential downtime on such a crucial machine.

Table 6: AS-IS of machines at DNA - isolation

AS-IS overview of machines at DNA/RNA-isolation.		
Departments	**Machines used to isolate DNA/RNA**	**Specification**
Department of Medical Genetics	QIAsymphony	Capacity: 24 samples x 5 rack Time: 1 hour and 15 minutes/rack
Department of Medical Biochemistry	MagNA Pure and QIAcube	MagNA Pure: Capacity: 32 samples Time: 2 hours (4 x 30minutes) QIAcube Capacity: 12 samples Time: 1 hour
Department of Pathology	QIAcube	Capacity: 12 samples Time: 1 hour

Performance indicators

The main goal of all the departments is to deliver high-quality test results. It was pointed out by several interviewees that quality is what matters, not how fast test answers are provided. As all departments work with genetics and personalized treatment, the quality of analysis is the most important performance indicator and surpasses the other performance indicators.

However, throughput time is still highly important, as it will affect when the interpretation can start. This is important due to patients waiting for crucial information about their health and potential diseases. Both the case study and the literature highlight that delivering fast results is of high importance.

To understand the throughput time, a relevant performance indicator is to measure the queue in terms of waiting time and WIP in the system. Therefore, the WIP at the different stations will be measured as well as the WIP for the entire system. Moreover, the budget restriction indicates that it is beneficial if one can increase return on investments (ROI). The utilization of machines can indicate the need for such investments.

5.2 Alternatives for resource sharing

Interviews, meetings, visitations, knowledge, and logical thinking served as the foundation to identify the different resources that are reasonable to share. From interviews and the startup meeting, sharing machines at the DNA isolation was highlighted as the most logical. Visitations at the case company showed that some locations are already shared between departments, thus, location could be a shared resource. The motivation for sharing machines and location is to save both costs and space that today is occupied by duplication of large investments. Finally, from interviews and knowledge related to lean, sharing personnel has been recognized as an opportunity to make jobs more standardized and therefore increase efficiency and quality. Therefore, three resources that are reasonable alternatives to share in hospital laboratory processes have been identified: machines, personnel, and location (Figure 21).

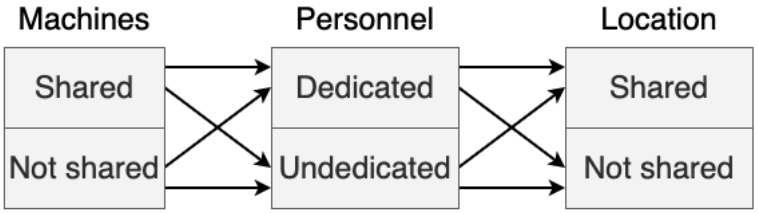

Figure 21: Resource sharing alternatives

It is interesting to investigate the effect sharing DNA isolation machines between the departments have on several performance indicators. Having shared machines implies that the departments can use the same machines to conduct their DNA isolation. In addition, sharing both personnel and location at the DNA isolation are relevant to discuss. When sharing machines, it is of interest to discuss if it could be beneficial to have dedicated personnel or to have a common location for the DNA isolation as well. Having dedicated personnel implies that there are employees solely working with DNA isolation for several departments. Location can also either be shared or not shared. Sharing location implies that one can stop having three different locations conducting DNA isolation, as it is today, resulting in one common location for DNA isolation.

Now, resource sharing alternatives have been identified. How sharing these resources affect the hospital laboratory will be further investigated. Moreover, as machines occupy space and are costly, interviewees highlighted how it would be interesting to investigate sharing machines. To further investigate the effect sharing machines have on hospital performance, a simulation model has been established. The model will be described in more detail in chapter 6. The simulation model will not reflect the best-suited location for the shared resource or

which personnel should conduct which tasks. This is due to not having sufficient information to simulate the effect sharing personnel and location will have on the laboratory performance. Therefore, this will be discussed qualitatively in section 8.1 together with the quantitative results from sharing machines. In addition, the distances in the laboratory do not appear as the main reason for the creation of queues. It is more interesting to investigate to which degree the samples are tied up to different machines. Therefore, two simulation scenarios have been developed:

(1) The three departments have the same machines as described in chapter 4. This scenario will act as a reference scenario to which the additional scenario can be compared. Here, today's situation in the three departments will be simulated.

(2) The DNA isolation station will function as a shared resource with QIAsymphonys. Here, the simulation model is used to test with input from the present operations at the hospital departments. The only change will then be to share QIAsymphonys between the three departments, investigating if sharing will affect the performance. The situation in the departments is that they do not have the necessary information to state if a given machine has the given specifications to replace another, or if there exists a machine that could satisfy the requirements for every department and all their samples. Therefore, it is assumed that the QIAsymphony can manage samples from all departments.

As the only logistics-related decision at the DNA isolation machines is the batch size, different batch sizes are relevant to investigate. In the current system, the batch size is what decides if a sample must wait or if the isolation process could be initiated. There are no other logistics-related decisions (e.g., FIFO, LIFO, shortest processing time, etc.) at the DNA isolation station.

As the hospital laboratories operate in an MTO system, they are unable to affect the volumes of incoming samples (demand), and other solutions are necessary to manage demand. The number of incoming samples depends on demand; hence, the number of available machines is what determines if demand could be fulfilled or not. Moreover, even though it seems like capacity is no problem in today's situation, it might be a problem in the future, as demand is expected to continue its increase. It is, therefore, necessary to investigate what happens with the laboratory department's operations at St. Olavs Hospital if demand increases as much as stated. Moreover, other hospital laboratories might already be in a situation where there is capacity restriction. Thus, the developed model will be used to compare two scenarios where input demand is many times larger than in today's environment.

6. Model construction

This chapter intends to describe what has been considered to develop a conceptual model that can investigate possible future events in the laboratory departments, with the implementation of shared resources and increased volumes.

According to Pidd (2004), the process of developing a simulation model can be divided into conceptual model building, computer implementation, validation, and experimentation (Figure 22). Hence, the chapter is divided into the same sections to present more detailed information on simulation model development. The chapter will present what input has been implemented and why, assumptions and decisions, descriptions of model logic, validation of the model, and discuss the technical aspects of the experiments conducted. Additionally, the simulation output will be presented.

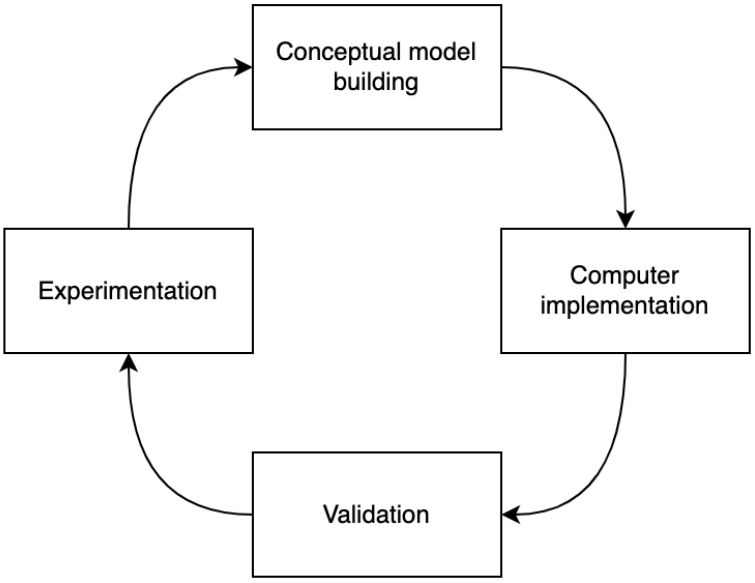

Figure 22: Simulation Modelling

Conceptual model building is where the researchers try to seize all the key features of the system that is intended to be modeled. Which key features are included in the conceptual model depends on two factors (Pidd, 2004):

- What method is used to simulate? In this thesis, discrete event simulation is the method in focus. When discrete event simulation is used, the objective is often to identify entities and understand how they interact in the system.
- The experimental frame needs to be considered. This is the set of conditions necessary to include in the model. It will help determine the level of detail in the system to be simulated.

The conceptual model building section will argue for what input was necessary to include in the model. Moreover, it will combine experience from the case study and literature study to present different characteristics of different processes and what input was necessary to include. This section will also include some assumptions and decisions that shaped the conceptual system. Computer implementation includes developing the conceptual model and developing the simulation model in FlexSim. It is here the more detailed logic and parameters are implemented (Pidd, 2004). Moreover, this section will present more detailed descriptions of the logic implemented in the system. Validation is the process where the researchers are convinced that the model is suited for use in its intended experimental frame (Pidd, 2004). This section will discuss why the developed model is valid and can produce relevant results. Experimentation refers to the use of the model. This means running the simulation as intended to produce results for analysis. Moreover, the results will not be presented here, but rather the technical aspects of designing the different scenarios in FlexSim. The simulation results are presented in chapter 7.

6.1 Conceptual model building

The creation of a simulation model might be to investigate the effects of different policies. Simulation could be a great tool to utilize when comparing different scenarios in hospital laboratories. Moreover, simulation has the advantage of simulating at different speeds, allowing the researchers to investigate a scenario of several months in just a few hours or minutes. This will assist the researchers in acquiring a bigger amount of data in a short period, creating more data for comparisons. However, to enable a simulation, the correct input of information is necessary. This section will present the necessary input implemented in the model. The input is gathered from the literature study, but mostly from the case study to make it as realistic as possible. Having a realistic model will make it more relevant to compare different scenarios, as the different scenarios could quickly become reality for many hospital laboratories. The model input is what forms the model output, through the simulation experiments (Figure 23). Moreover, some assumptions and decisions were needed to create the simulation model. As creating a simulation model could be very time-consuming, it is often necessary to simplify certain processes and introduce assumptions. This is to enable the researchers to complete the research in their given time. Hence, this section will also argue for decisions and assumptions.

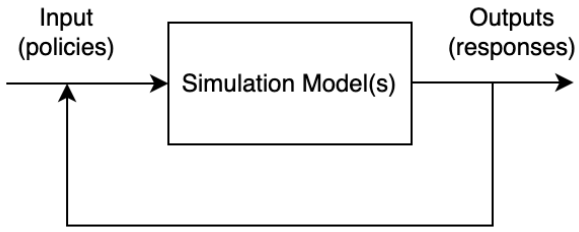

Figure 23: Experimentation and interaction (Pidd, 2004)

Before developing the model, it is important to understand the objects in the system and how they interact. A system consists of entities and resources (Pidd, 2004). When developing a discrete event simulation model, it is important to identify the different classes of entities, consider the activities they engage in, and link these activities together (Pidd, 2004). When this is done, the model can be expanded to contain more detail. Pidd (2004) refers to the "principle of parsimony", which explains how the analyst should first implement elements that are well understood before expanding the model complexity. Meaning that the less understood and more complicated elements should be added later in the model development process. The case study assisted with a general understanding of which elements are within the system, in addition to what inputs are necessary to include in the model. Moreover, as the laboratory operations are

quite complex, each department was visited separately to ensure greater understanding among the researchers.

The objects of the system (entities and resources) were identified during the visits to the different laboratory departments. Entities are individual elements in the system that are being simulated and their behavior is being tracked (Pidd, 2004). Examples of entities identified and used in the model are patient samples, personnel, and machines (PCR, QIAcube, QIAsymphony, etc.). The simulation program will track and maintain information on each entity, making it possible to identify them individually. The simulation program keeps track of the changes that occur in the individual entities as they change states throughout the simulation. The interaction of the different entities is what creates the overall state of the system.

Resources are individual elements in the system (Pidd, 2004). However, they are not modeled individually. This means that the behavior of resources is not tracked but managed as countable items. A resource in the system consists of identical items, and the system keeps count of how many resources are available. These resources were identified during the different visits, additionally, they were identified as the model development took place. An example of resources identified is the boxes that carry patient samples, which are visualized with totes in the model.

It has been observed that the laboratory operations have a stochastic behavior, hence, the model needs to implement stochastic elements. A system with stochastic elements is difficult to predict, however, one can come up with some statement on how likely certain events are to occur (Pidd, 2004). Due to the stochastic elements, simulation experiments are run for a longer period to collect a larger amount of data to compare. However, the input data with stochastic elements might change between each experiment. Pidd (2004) then suggests using pseudo-random numbers that allow the researchers to compare different policies, using approximately the same random numbers. Therefore, to ensure some randomness in the processes that require it (volume input), pseudo-random numbers were implemented after developing the model. Moreover, as different processes have certain distributions of samples going to different machines (either PCR or NGS), this was also implemented as pseudo-random numbers. The procedure for developing these numbers is further described in section 6.2.

Input decisions

The necessary decisions on input implemented in the model system can be divided into information connected to the researchers' experience at the case company, and information

based on theory, experience, and logical thinking. As the model is conceptual, certain decisions have been made to simplify the model and enable the researchers to complete the simulation before the due date of the thesis. Most of the decisions are based on real-life information from the laboratory departments, to make the system as representative as possible. The different decisions will be presented and argued for.

Decisions on inputs based on theory, experience, logical thinking, and case study

- The focus is on the DNA-isolation process, simplifying the process steps after the isolation is done. The necessary capacities and times are included in all steps, however, the detail of how the different steps is conducted is not included in the model. As DNA isolation could be a shared resource, it is the area of interest. How this shared resource affects processes downstream is of interest, but it is not necessary to implement detailed processes to analyze if the impact the shared resource have are positive or negative.
- The departments have several samples with different characteristics that they are handling every day. However, not all these samples are entering the DNA-isolation station. Hence, all samples not using the DNA-isolation station is excluded from the model.
- The time used to conduct different activities in different processes are identical to the information gathered in the semi-structured interviews. This includes machine specifications and the manual work needed by personnel before and after certain workstations.
- The working hours at the departments were included, ensuring that entities in the model were processed by operators only in the hours specified. FlexSim allows to schedule the working hours of all operators and machines in the system. This was included so operators can only process entities between 8 a.m. and 4 p.m.
- Incoming samples (demand) are decided based on statements from the interviewees. It is logical to assume that the workers involved in the process are the ones who know how many samples they analyze weekly. The demand is based on approximations provided by the interviewees rather than exact data. Additionally, the demand increase is based on expectations from the different laboratory departments. Incoming samples in today's situation are then multiplied with the expected increment gathered from the different departments and included as input in the simulation model. This creates a realistic scenario where capacity restrictions might occur with today's machines.

- Today, the number of incoming samples varies. This means that some days have fewer samples arriving while some have more. Since the information gathered on demand is either yearly or weekly, in a scenario where the number of incoming samples increases significantly, it has been decided that the samples are arriving evenly throughout the week. The volume for each day acts as the foundation for creating pseudo-random numbers, where the daily demand is used as the average value for creating variation in incoming volume. The pseudo-random numbers were generated in excel.
- Moreover, the number of incoming samples varies from department to department. Thus, the daily demand being used as the foundation for creating variation is different from department to department. This results in different incoming volumes each day at the different departments, which is a realistic demonstration of reality.
- The samples are arriving continuously throughout the day as it has been observed that there is no fixed time for the arrival of samples. Thus, it is assumed that samples are arriving randomly within the work hours (8 a.m. – 4 p.m.)
- Interviewees stated that the increase is expected to be between 20% - 100% each year. Each scenario has then been simulated with a different volume increase. It was then decided that each scenario would be simulated with a 20%, 40%, 60%, and 80% volume increase, to investigate the difference increased volume has on the two scenarios. The daily demand at each department has then been calculated for each volume increase, for the next five years. This was also done to create a situation where there are capacity restrictions. Further explanation of incoming volume can be found in section 6.2.

- Each manual station has one dedicated person managing all the manual labor. The coordination between them work so that samples never have to wait long for operators to move samples from one station to another, or to be treated at a given station. It is natural to do this due to how they are working at the laboratory departments at St. Olavs Hospital today.
  - The preparation station for DMB and DMG consists of two workers while Pathology have one when sharing QIAsymphonys. This is due to how they have

the same type of preparation while Pathology must go through a reversing of the samples to prepare them. However, the same number of workers are available in both scenarios.

- Inventory is excluded from the model. This does not include intermediate storage, as it is highly relevant to investigate with shared resources in the system. Storage of samples before and after genetic analysis at each department is not relevant due to the scope of the thesis.
    - At the initiation of the simulation, the amount of WIP and storage is zero, this means that all samples entering the system comes from the pseudo-random numbers generated in excel. Thus, all processes start from "scratch", with no intermediate storage. It is, therefore, necessary to specify that it takes some time for each department to reach its normal operations.
- Batch sizes differ from department to department and process to process. Hence, each process has been observed to acquire which batch sizes are operated with. These batch sizes have been used as input to the model.
- The different departments have unlike distributions of patient samples going to PCR and NGS, however, NGS is generally more popular for analysis. Therefore, interviewees were asked how many go to NGS and how many go to PCR after the DNA isolation. Based on these answers, a distribution is implemented after the isolation process. Moreover, the reason why some samples go to PCR, and some go to NGS is not possible to implement in the model. This is due to customer specifications, which are not shared with us because of confidentiality, and not having the necessary functions in FlexSim to implement it. Hence, a stochastic distribution is what best represents a situation where some isolated samples go to PCR preparation, and some go to NGS preparation.
    - This was implemented through pseudo-random numbers, enabling a fair comparison when comparing results. When samples are entering the system, they are tagged with information specifying if they are going to NGS or PCR. Further explanation is provided in section 6.2.
- Performance indicators were identified after the visits to the different departments. These performance indicators decide what information to collect from the model. Functions in FlexSim were used to ensure the correct information was stored throughout the simulation, creating the output for analysis.

    - Throughput time is interesting to investigate due to the importance of efficient processes. Hence, when a patient sample enters the simulation system, it is stored and measured from arrival to interpretation. Meaning that interpretation is not part of the interval in which throughput time can be measured. This enables the analysts to investigate throughput time in different scenarios and how it is affected when different input is modified.
    - The utilization of equipment is interesting to analyze. Hence, the machines used for DNA isolation are measured to investigate utilization in the different scenarios.
    - WIP is identified by queues in the system. Intermediate storage both before and after the isolation station is measured to enable an analysis of output. This is also an indicator of efficiency, as it can be analyzed how WIP is different from scenario one to scenario two.

- Distances between workstations are held approximate as the distances in the laboratory are short. Time spent walking between workstations and processes is short compared to the overall process. Hence, distances implemented in the simulation model do not have a big impact on the output and are held relatively short. Moreover, transportation is not the focus of this thesis and is implemented to make it as visually representative as possible.

- Preparation of machines is excluded. It is assumed that the machines are finished with preparation when samples are arriving, as it is logical to think that personnel at the departments start the preparation at the beginning of the day, ensuring they are ready when samples arrive. Time used for preparation of samples is longer than preparation of machines. As these activities happen side by side and are done simultaneously, one can neglect machine preparation in the model.

- There are always enough machines available after DNA isolation. It has been observed that each department has several NGS and PCR machines. It is therefore assumed that all the necessary process steps after the DNA isolation always have enough machines available. If there are any queues it is then due to the batch sizes of the machines, and not because machines are unavailable.

- Weekends and weekdays are not separated in the model. Since the focus is on DNA isolation, and DNA isolation is not conducted on weekends, the simulation period

excludes weekends. The simulation period is then set to twenty continuous workdays without weekends, simulating a month of process activities. This means that the simulation period only consists of workdays where the isolation activity happens. Furthermore, the performance indicator for throughput time does not separate between days. Thus, it will not matter if they run on weekends or weekdays.

- The simulation input is the same for both scenarios. As Pidd (2004) mentioned, this is done to enable a fair comparison. If the input is held constant and the environment of the system is held constant, it will be more relevant to discuss the impact changes to input have on the system in each scenario.

Figures 24, 25, and 26 visualize all the necessary parameters included at each process step. This is a more detailed description of each department's processes, their batch sizes, processing times, and if a machine or person is performing the process. Each figure is an elaboration of information collected in the case study, which reflects what has been included as input to the simulation model.

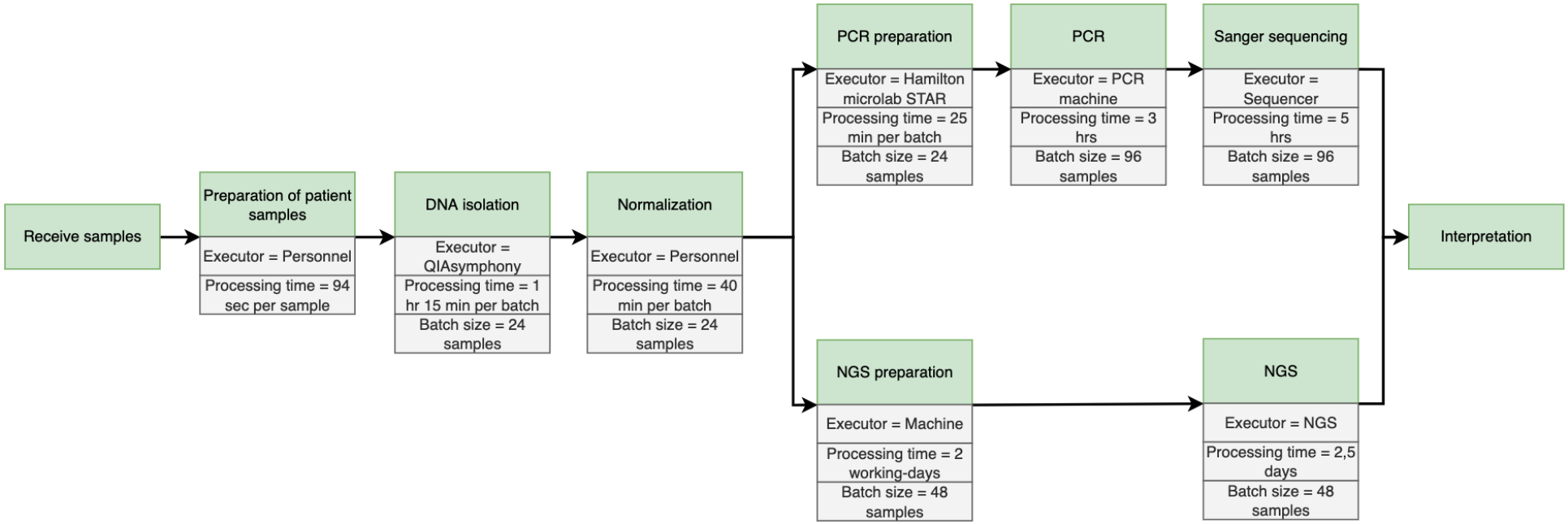

Figure 24: DMG detailed process flow

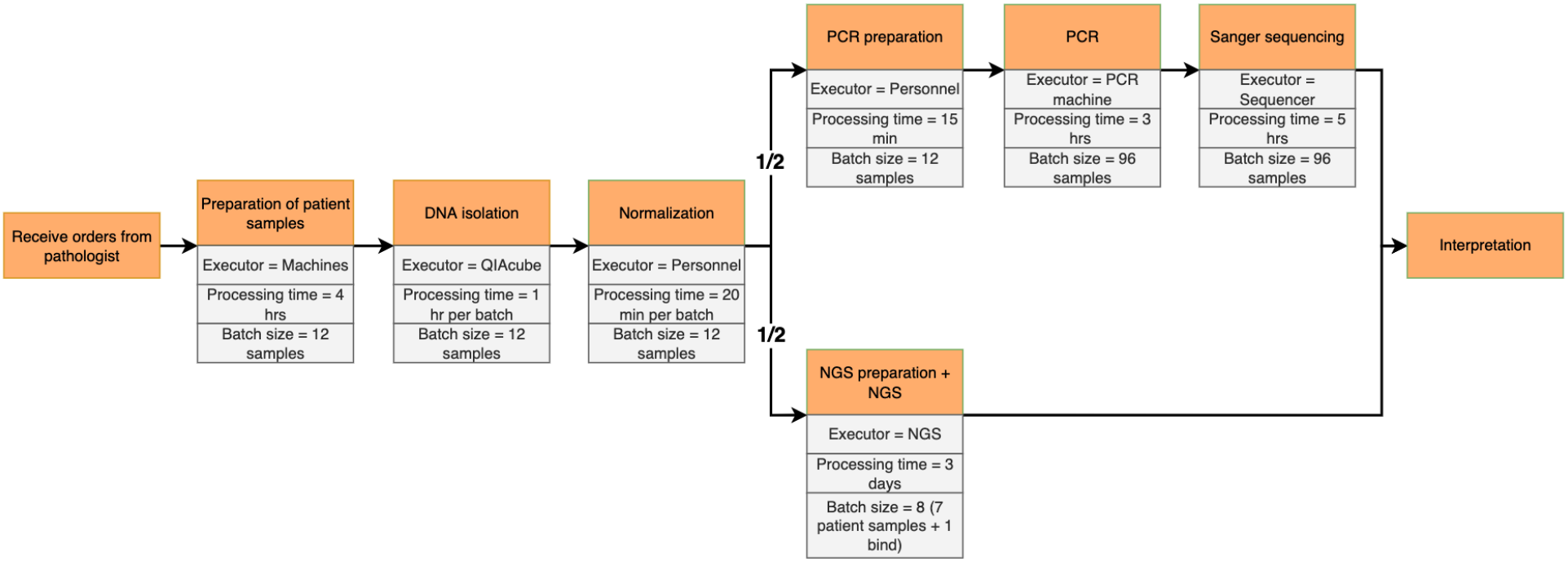

Figure 25: DP detailed process flow

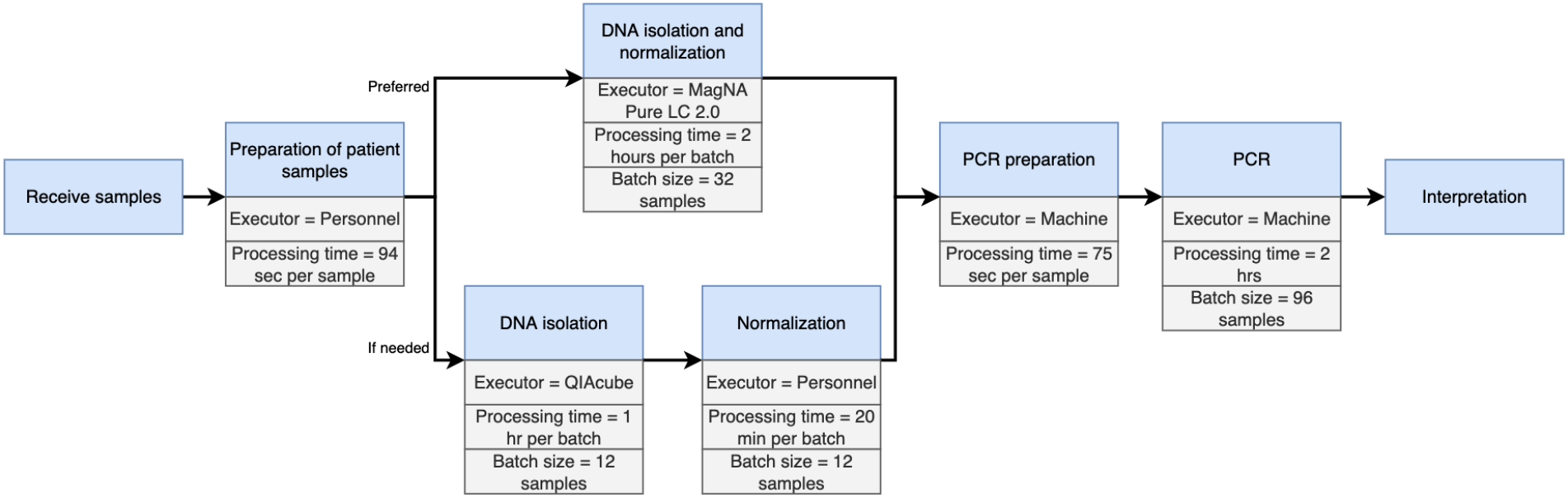

Figure 26: DMB detailed process flow

6.2 Computer implementation

After creating a clear plan of what to include in the model, all the necessary input being collected, and assumptions being made, the conceptual model could be developed. Moreover, to simplify the process of analyzing two scenarios, a model was created for each scenario. A model was first created for scenario one. As scenario two only required a few changes to implement shared resources, the model for scenario one was adapted and saved as its own model for scenario two.

The next step was then to transfer the information collected into a model development software. FlexSim was used to develop the model. This section will present a simplified description of central model logic and the technical aspects of relevant processes. This includes how samples are arriving in the system, how they are transported through the different processes, how batching is done, and how machines are implemented. Moreover, a description of how performance indicator data is calculated will be elaborated.

Arrival of samples

Arriving samples are based on information gathered from the semi-structured interviews, where all volumes were listed in incoming per week. It is therefore assumed that incoming samples are distributed evenly throughout the week. The semi-structured interviews revealed that the incoming sample volume is expected to increase between 20% and 100% each year. The increase for each department was then calculated for each year, for the next five years. The input for incoming volume is based on the weekly volume expected after five years. Incoming volume per day at each department is then calculated, and the calculation results are shown in Table 7.

Table 7: Incoming samples per department

Department	Volume increase	Volume/day after 5 years
Medical genetics	20%	24 patient samples
	40%	44 patient samples
	60%	76 patient samples
	80%	121 patient samples
Pathology	20%	20 patient samples
	40%	37 patient samples
	60%	63 patient samples
	80%	101 patient samples
Medical Biochemistry	20%	20 patient samples
	40%	37 patient samples
	60%	63 patient samples
	80%	101 patient samples

However, as there are some stochastic factors related to incoming samples, the quantity will be different from day to day. To ensure that the scenarios were compared with the same conditions, pseudo-random numbers were used.

The daily demand for each day and each volume increase acted as the average value when creating a distribution of daily demand. This ensures a distribution of how many samples are arriving each day, and the same distributed numbers are used for each scenario. This means that the distribution of incoming samples e.g., DMG with a 20% volume increase, is the same with and without shared resources.

To establish incoming patient samples to the system, with distributions, Microsoft Excel was used. FlexSim allows importing data from Excel to use as input when initiating different simulations. Hence, an Excel sheet was developed with all the necessary information on incoming patient samples. The daily demand is the same as the number of arrivals, where each arrival was distributed randomly throughout the workday. Figure 27 visualizes such a sheet, where the time of arrival and quantity of patient samples are included. Additionally, for DMG

and Pathology, the type needed to be specified. This was to ensure that incoming samples were distributed correctly between NGS and PCR after the simulation process.

Time	Name	Quantity	Type
1049		1	2
1113		1	2
1706		1	1
2321		1	1
2745		1	2
4937		1	2
5632		1	1
5919		1	2
6801		1	1

Figure 27: Arrival of patient samples

The *Time* column represents when a sample arrives in the system. This time is given in seconds after the simulation was initiated. Thus, it was necessary to calculate the number of seconds it takes from 8 a.m. to 4 p.m. each day for 20 workdays. The *Name* column is implemented as it is standard for FlexSim to include, however, no names were needed to be specified. The *Quantity* column tells the system the number of entities to be created. Since it has been specified that each *Time* is an arrival, the corresponding *Quantity* is always one. Finally, the *Type* quantity is needed for DMG and DMB to specify the correct distribution of samples going to NGS or PCR. With this information, the full schedule of arrivals to the system could be generated with the necessary information for the system to understand the schedule.

However, this input only acts as information to the system of how many entities are to be produced and when they are produced. It is, therefore, necessary to specify in FlexSim where samples will arrive, initiate the creation of the entity, and specify its visuals (color and size). Therefore, a source was implemented for the creation of samples for each department. Each source has its own excel sheet with specifications on arrival times and volumes. The system then creates the correct number of entities and ensures they are spawning when specified. Moreover, as each department have its source (Figure 28), each source is connected to the departments' specified process flow, ensuring each department acquires the correct patient samples.

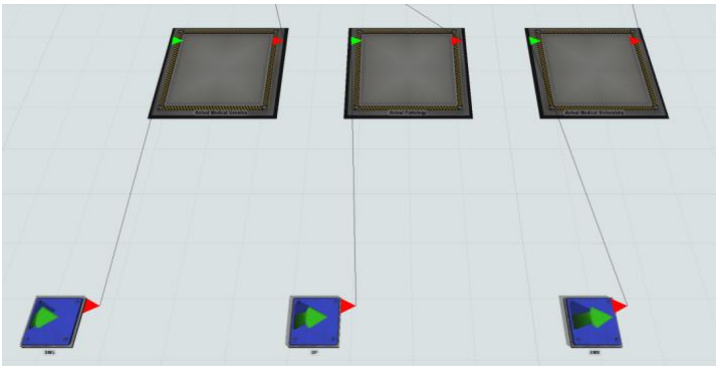

Figure 28: Source for arrivals

Transportation of samples

When implementing all the processes in FlexSim, the process flows presented in section 6.1 was used as the foundation for the flow to be implemented in FlexSim. The process flow for each department is based on information gathered at the case company, to ensure a realistic flow of patient samples. Operators are added to the system to ensure transportation manually where it is needed. Operators represent personnel in the hospital laboratory.

Operators are the ones who transport samples in the model. First, all machines for each process are added to the system, with specifications, before connecting the different processes. FlexSim has the option of easily connecting operators to machines and ensuring that they are transporting entities between stations. Each line in Figure 29 represents a connection between machines, operators, or both. When all processes are connected, the arriving patient samples follow the stream from start to finish, either being transported by an operator or processed through a machine.

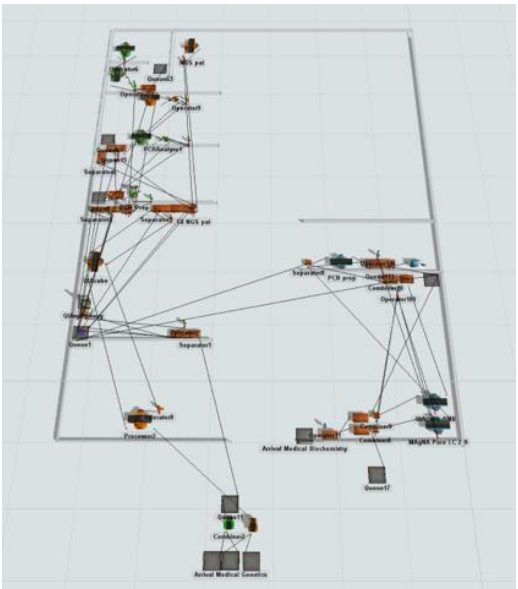

Figure 29: Process flow

At DMG, NGS is most often used as a replication method. Based on the semi-structured interviews, it is understood that approximately 1/3 of incoming samples are analyzed using PCR, while 2/3 are analyzed with NGS. To implement this logic in FlexSim, the incoming samples are split into either NGS or PCR. Figure 30 shows how the logic can be implemented at a processor, where there are two outgoing queues. Each queue represents either a PCR queue or an NGS queue. The arriving samples have different type indicators, assisting the system in understanding what entities are where. Therefore, each case in Figure 30 represents entity type. Arriving samples going to PCR are then type 1, while NGS are type 2. The processor is then able to split the flow of type 1 and type 2, ensuring that 2/3 are going to the NGS queue, and 1/3 are going to the PCR queue.

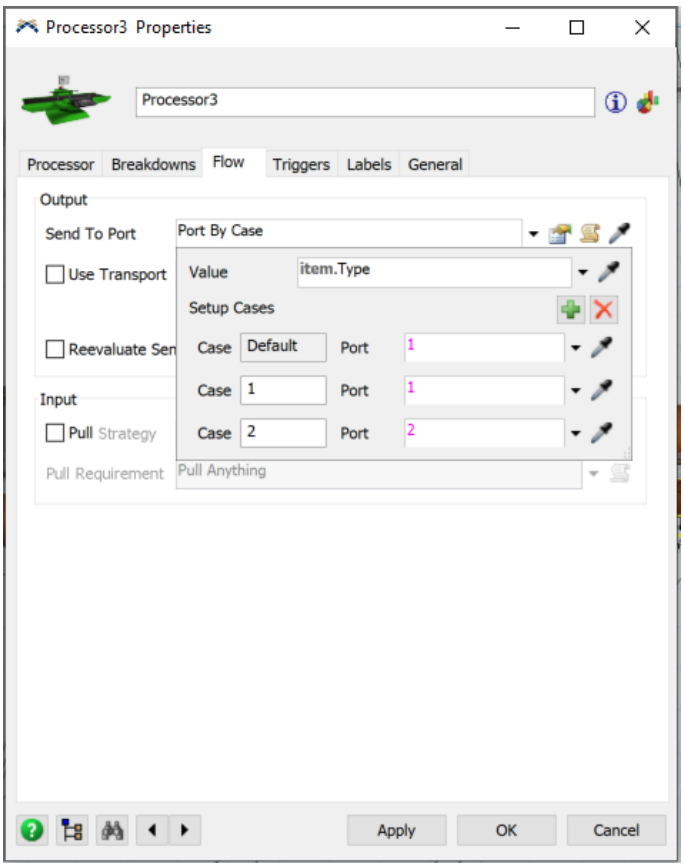

Figure 30: Splitting of samples to NGS or PCR

Furthermore, this logic is implemented to split between NGS and PCR at the department of Pathology. The same strategy is used, however, the distribution between NGS and PCR at Pathology is 50/50.

Process logic

All processes at each department have a certain logic to conduct certain operations. This logic is different from operators and machines doing the work. Figure 31 shows the DNA isolation

and Normalization process. The simulation logic here is to acquire an operator to conduct the task. The system collects tasks from a list consisting of all tasks to be completed. When a task is collected, a sub-flow is initiated. This is a flow that tells the operator how to complete the task. This could then be to travel to the correct destination for the collection of patient samples and bring them back to the correct workstation to complete the task (e.g., DNA isolation and normalization). This logic has been standardized and reused in the different departments, with different parameters, when there is manual labor. Other processes (e.g., PCR, NGS, preparation, etc.) have the same logic. What makes the logic different from the process to process and department to department is their specifications. This means that the tasks included in the list have different specifications. Such specifications can be where to collect the sample and where to deliver it.

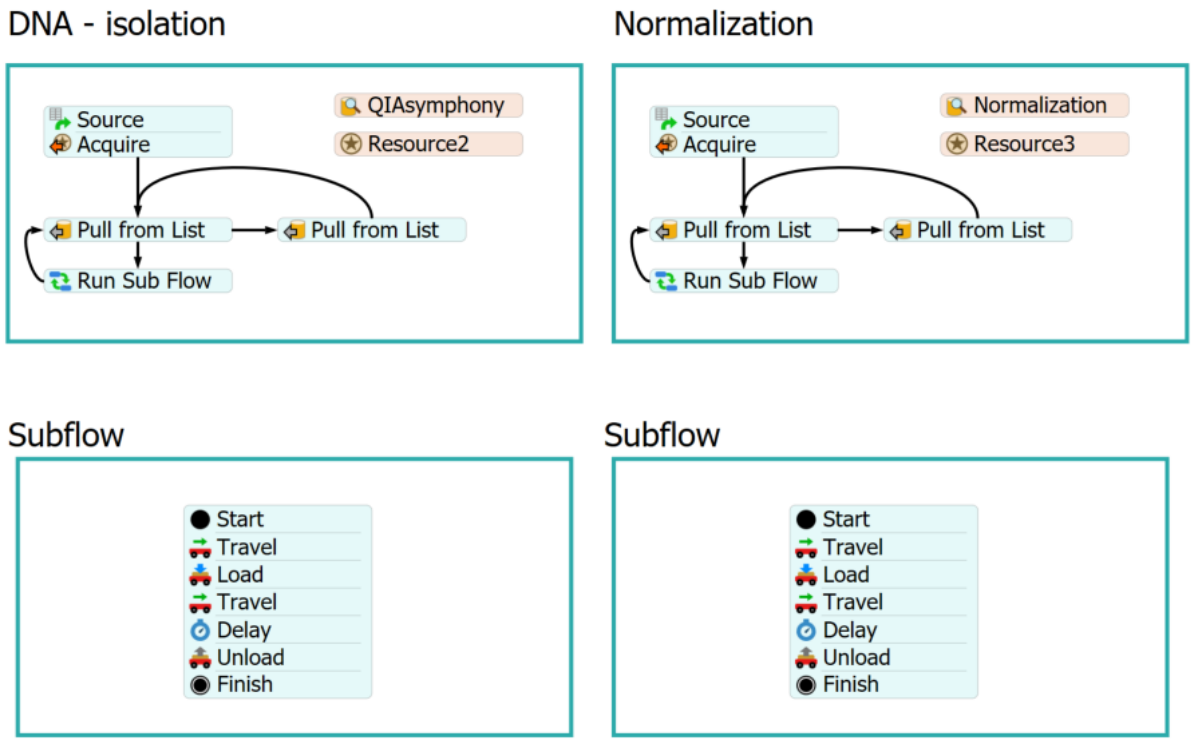

Figure 31: Process logic

Each process also often consists of machines doing the processing. The logic included in each machine is easily specified at each machine. Here, the processing times and batch sizes are implemented. The processing times are specified in seconds. Furthermore, the machines are connected to operators, ensuring that entities are delivered for processing.

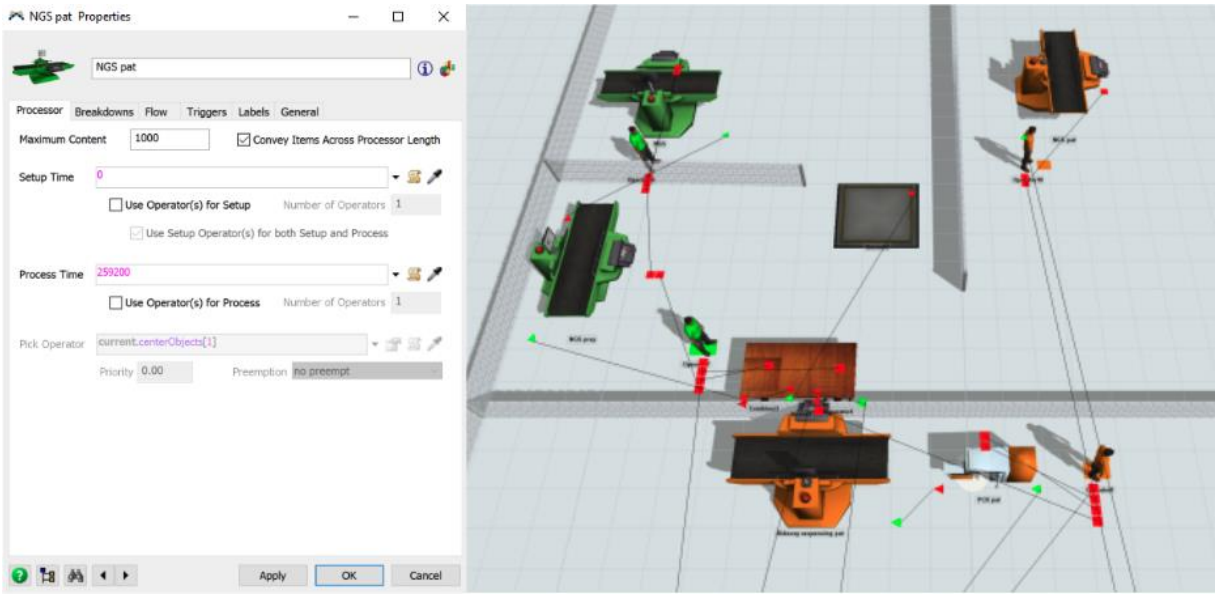

Figure 32: Machine logic

Batching

Each department has processes where there are different batch sizes, and the strategy is often to wait for a certain quantity of samples before initiating a process. Hence, a certain logic for batching entities (patient samples) has been included. To create batches, a tote is necessary, which acts as a carrier of the batch. Therefore, a logic for always having enough totes to create batches of patient samples has been implemented. This logic is the same for all departments. *Arrival: Medical Genetics* (Figure 33) shows the logic for creating totes, where they are arriving in the system whenever needed. The system waits for an event, which is when patient samples enter a certain queue. When the samples arrive at the queue, a tote is created, which can be further used in a combiner to create the batch.

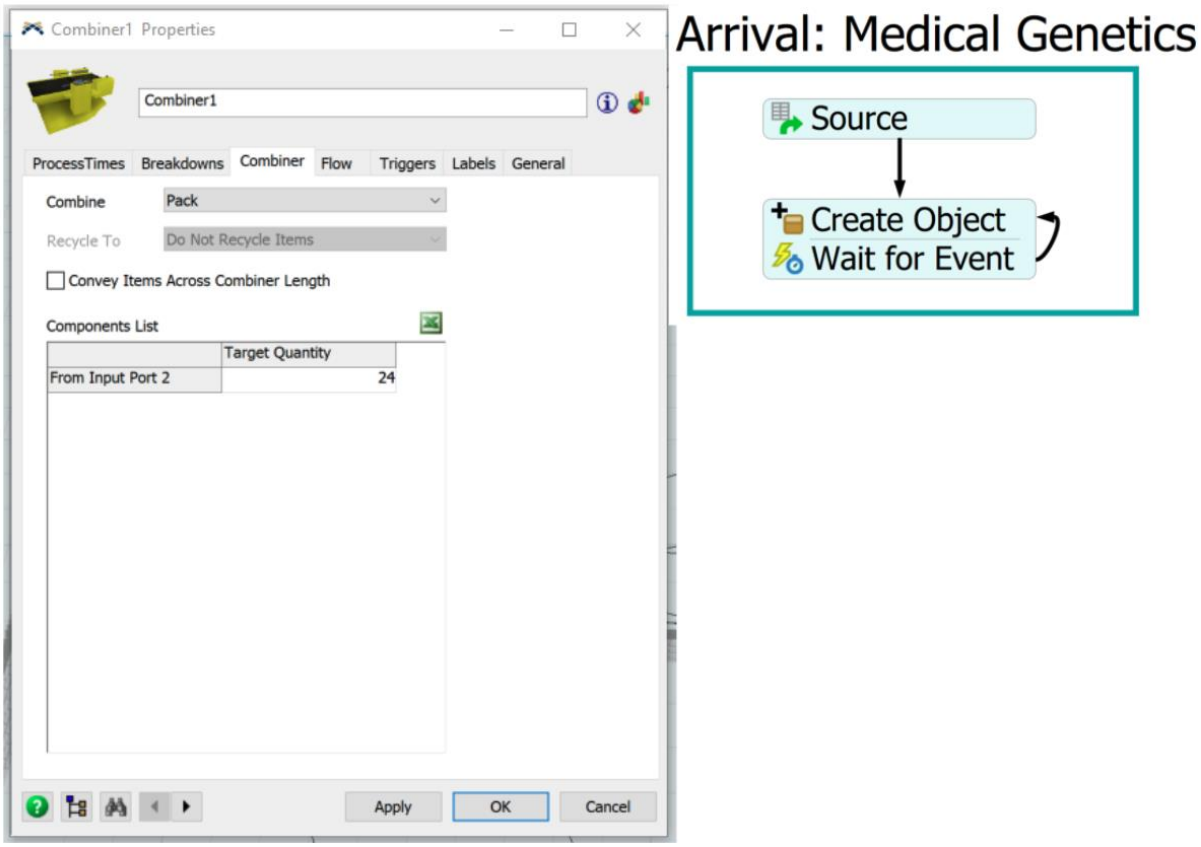

Figure 33: Batch logic

Combiners have been used to create the batching logic. The combiner can then put the necessary entities into the tote, creating a batch. Here, the batch size is specified to ensure the correct number of entities are combined with a tote. Ports are also a part of the logic here, where it is necessary to specify in which port entities are arriving, and in which port totes are arriving. The combiner then combines the incoming from each port, creating a tote with entities within, visualizing a batch of patient samples. Furthermore, logic has been implemented ensuring that if the incoming entities are not the acquired batch size but are supposed to be run anyway, it is combined into a batch of that given quantity.

6.2.1 Calculation procedure for performance indicators

For each simulation experiment, a set of performance indicators have been used to enable the comparison of results between the experiments (Table 8). FlexSim supplies a set of different options for tracking data at different steps in the simulated process and visualizing them. The indicators to be measured were throughput time, WIP, and machine utilization. The indicators were used to measure each department individually, and the DNA isolation process, both with and without shared resources. After measuring each indicator, the data were extracted to excel for further analysis.

The reason why quality has not been measured in the simulation model is due to the available data collected from the case company. Quality is often measured from a medical perspective, and it is hard to measure without a big data set that shows the correlation between failure rates and different operations. Moreover, as the sample information is protected by person confidentiality, the necessary information is not available to the researchers. Thus, quality will rather be discussed qualitatively.

Table 8: Calculation of performance indicators

Performance indicators	**Calculation procedure**
Throughput time	The throughput time for each department was measured from when entities entered the system until they exit the system. Moreover, the throughput time of the DNA isolation process was also measured. This was measured from when an entity enters the system until they are done with DNA isolation. Throughput time is measured by calculating the staytime an entity has between two specified objects. Each entity has a dedicated timer that calculates the staytime and stores the data.
WIP	WIP is measured by tracking at any given time, how many entities are located between two specified objects. The number of entities is updated every time a new entity arrives or leaves the specified objects.
Machine utilization	To calculate the utilization of machines, the total time used to process entities are measured against simulation run time. Working hours have been implemented, therefore, machine utilization is measured in the same period. Hence, utilization is the percentage of a working day a machine is processing entities.

6.3 Validation

As Pidd (2004) goes on to explain, complete validation is never possible. The reason for this is that most simulation models are developed to investigate phenomena that are not understood. A simulation model might be developed to research parts of a hospital, and it might be uncomplicated to check that the model is a valid representation of the real situation. However, in many cases, the goal is also to use the model to estimate the performance of the system under different circumstances (e.g., under different management strategies and conditions). This results in a model with uncertain characteristics, hence, complete validation of such a model is impossible. Nevertheless, this does not mean that such simulation approaches are a waste of time. The simulation model can be used to explore different solutions, analyze them, and create a brainstorming environment. Additionally, as with this thesis, one can collaborate with people who are experts in their field to help validate the results from the model.

The case study was conducted to validate the model through accurate information for input to the model, different interactions between entities, overview of processes, machine specifications, and sample specifications. Hence, the case study assisted in ensuring that the developed model was as realistic as possible, enabling a higher validity. The answers collected from each question in the semi-structured interview were double-checked with the interviewee to ensure the correct information was written down. Moreover, the information gathered from the case study was also double-checked with the supervisors in meetings after each visit. As they also gathered data, this was a way of verifying that the information collected was correct. To validate the simulation model and the different solutions developed, a workshop with personnel from St. Olavs Hospital was held. Here, feedback to validate the different characteristics and results from the model was received, in addition to discussions of possible model changes. The logistics in the system were explained, ensuring feedback from the personnel, where it was validated that the understanding of the different processes was correct.

The model deals with a description of the system. It is therefore a prerequisite that the parameters and characteristics of the system are recognizable for it to be relevant for real-life systems. Hence, different parameters and characteristics were implemented in the model to ensure high validity and relevance are presented. These were: realistic sample volumes, process steps from the three departments, working hours, and machine specifications.

These are all inputs to the model to create a realistic environment in which a shared resource can be investigated. All process steps have been implemented to the best of the researchers'

ability. Due to a thorough case study, the necessary information of all processes was gathered to create a realistic conceptual model.

Validation is also ensuring that the model is working as it should and that it performs as expected. It is important to make sure that the conceptual model developed is a valid representation of the real-life system being investigated. As the researchers followed the "principle of parsimony" presented by Pidd (2004), the model was developed in steps implementing small steps of each process at a time. The model was then tested after each step was completed, to ensure it worked as expected. This strategy was used for all processes and ensured the model was tested step by step until the process was finished (Figure 34).

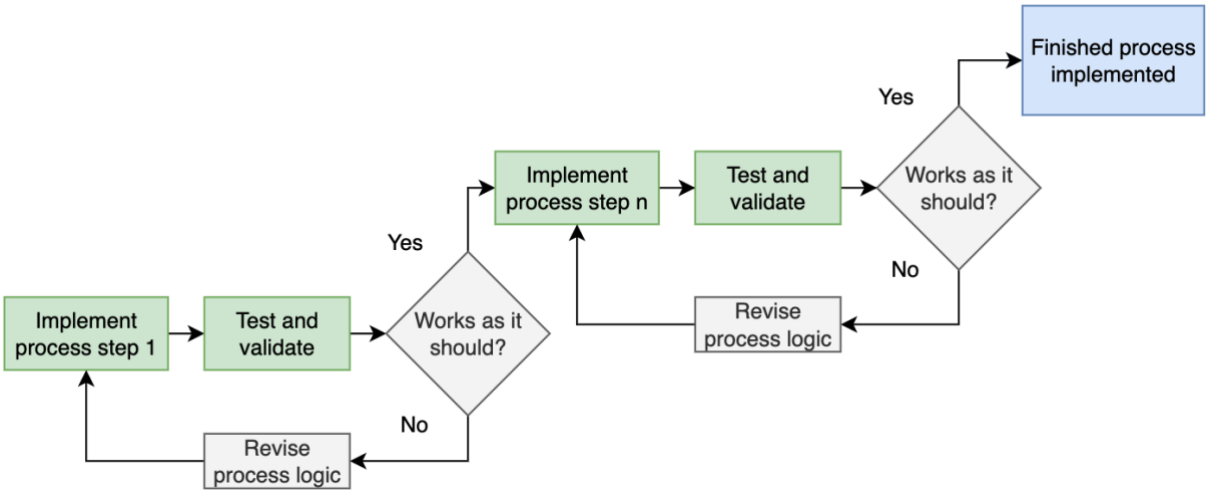

Figure 34: Implementation process

When the fundamentals of each process were implemented, the more complex logic was added. The same strategy was then used, to quality check the logic in each step before implementing the next one. Furthermore, the input collected from the case study was inserted into the developed process. Here, the process was tested to investigate if the output was valid and whether the process behavior was as expected. After implementing all necessary processes, their logic, and the input, the conceptual model was tested to ensure all entities interacted as they were supposed to.

As the input to the model is ensured to be as realistic as possible, the validity of the model is also ensured. However, as this thesis aims to investigate shared resources, a relatively unintelligible topic in hospital laboratories, it is not possible to fully validate the model. The input and model logic is what creates the model output, it is also what decides if the output is valid. The researchers have done their best to ensure that all necessary input and model logic, creating relevant output, is as realistic as possible, to ensure valid results and findings.

After validating the model, the next step was to ensure that the collection of output data was as valid as possible. Therefore, the different tools supplied by FlexSim to extract data from the simulation were investigated. Since the performance indicators were developed after the case study, the aim of investigating different data extracting tools was to identify which tools to use to collect the relevant data for each indicator. The model was then tested with different tools to extract data for performance indicators. When the preferred tools were selected, the process of conducting the different experiments was initiated.

6.4 Experimentation with scenarios

Pidd (2004) points out how discrete event simulation is a complex sampling experiment, meaning that samples are taken from different distributions throughout the simulation, and are combined to create the model behavior. Hence, the model behavior is dependent on the results of the random samples and their combination. Therefore, if the simulation is being used to compare the system under different circumstances, it is important to ensure that the different simulation experiments are analyzed under the same conditions. To ensure control of the simulation and fair comparison between the different solutions, it is essential that the randomness implemented in the model is the same for each experiment. If not, the difference in random numbers might skew the results in favor of a solution that is not optimal. As Pidd (2004) highlights, the stream of random numbers needs to be reproducible, using the same number for the different experiments. The random numbers should be produced and stored for use in all experiments, ensuring fair comparisons and a greater foundation for analysis. Hence, the excel sheet presented in section 6.2 was developed, with pseudo-random numbers.

Conducting simulation experiments means subjecting the model to different inputs at various levels, and analyzing how they affect the output (Pidd, 2004). It is common to use a simulation approach when investigating different policies and finding which ones are most optimal to improve the system. Hence, when experimenting with the developed model, it is important to separate the effect of sampling variation from the effects that result from changes to configurations or policies being analyzed. When conducting different experiments with a simulation model consisting of stochastic variables (or some sort of probability distribution), it is necessary to be aware that the results will be more difficult to interpret (Pidd, 2004).

When analyzing the output from the model, the pseudo-random numbers made it easier to analyze the changes done to input and different policies. Additionally, following the statements from Pidd (2004), a fair comparison would be ensured. Pidd (2004) mentions three principles that are important to have in mind when analyzing the output of a simulation. (1) It is important to know that simulations are complex sampling experiments, that need careful analysis. (2) The analyst needs to be careful when analyzing the output, making sure that the correct and necessary methods are used. (3) When analyzing the output of a simulation model, it is reasonable to take advantage of knowledge related to the inner characteristics of the model. These principles were all considered when conducting the different experiments and analyzing them, as they made the analysts aware of the complexity of simulation output analysis.

Furthermore, it ensured that the experiments were planned before completion. This was also done to make sure the experiments produced output relevant to the research questions.

Before conducting the different experiments, the chosen performance indicators were analyzed to ensure they were the correct ones to use. The indicators are the ones that decided what to collect from the different simulations. Furthermore, the different experiments consisted of different scenarios, where the same performance indicators were used for all the experiments. Using the same indicators are important when comparing results, especially when analyzing if a change to the system results in a negative or positive effect on the performance.

6.4.1 Simulation scenarios

This section will present the technical aspects of how the different scenarios highlighted in 5.2 were implemented in a FlexSim model. All scenarios were simulated, where the output was decided by the performance indicators. The first scenario acts as a reference scenario, where today's situation at the different hospital laboratory departments is implemented with increased volumes. The main objective of the other scenario is to investigate shared resources. The reason for implementing a reference scenario is to analyze the effects of implementing shared resources at the hospital laboratory. Furthermore, batch sizes were investigated to see what happens if a shared resource is implemented, and batch sizes are changed.

As there were two scenarios to be simulated, two different models were developed. However, to develop a model with shared resources, the model for scenario one was manipulated to operate with a common isolation station. Thus, two models were developed where both were simulated with today's batch sizes and with halved batch sizes. Both models were stored individually, to ensure an easier comparison between the performance indicators.

1. All departments have their original process structure

With this scenario, all process steps were implemented with the identified parameters. However, the processes were implemented with the decisions and assumptions presented in section 6.1. Thus, the first simulation scenario is a simulation of the original conceptual model developed, acting as a reference scenario for comparison.

To acquire the correct output from this scenario, necessary data from different processes are recorded to see how performance indicators are affected. This was recorded as explained in section 6.2.

2. The DNA isolation machines are shared, where QIAsymphony can manage all sample types

In this scenario, a change to the process flow was necessary for all departments. As DNA isolation would become one common resource, all departments were constructed to interact with QIAsymphonys. Furthermore, the model layout had to be changed where departments did not have their separate isolation machine in different locations, but rather a common area with common QIAsymphonys. As it was observed that the departments will never have only one isolation machine, thus, two QIAsymphonys were implemented in the model (Figure 35).

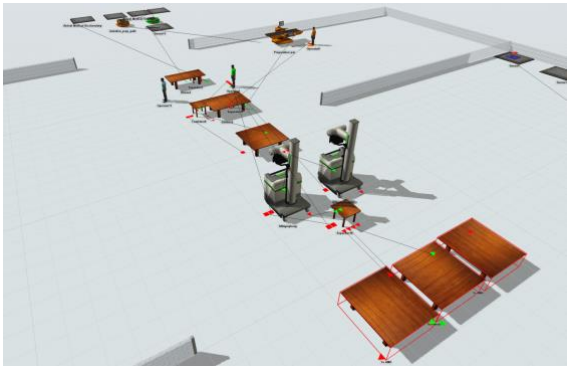

Figure 35: Sharing QIAsymphonys

The specifications of the QIAsymphony were then changed to include the flow of all three departments, enabling the isolation machine to manage samples from all departments. The receipt and preparation of samples at each department are still being done separately, meaning that the process up to the batching for isolation is conducted as in the reference scenario. It was observed that the QIAsymphony can manage samples from different departments in each rack, given they are being isolated with the same protocol. This logic has been implemented, where the batch (rack) being isolated can consist of a mix of samples from all departments. Logic has also been implemented ensuring that after the isolation, the samples are directed to their separate flows. The processes for each department after the isolation is the same as in the reference scenario. After implementing all necessary logic to create an environment where shared resources can be investigated, output from the simulation could be produced. Moreover, after simulating shared resources, different batch sizes were also simulated in the shared resource model. Additionally, how Pathology is preparing their tests have been experimented with, where one-piece-flow has been tested. Results from each scenario and experiment are presented in chapter 7.

Figure 36 visualizes the impact of a change in processes where the three departments share DNA isolation machines. This shows the process flows from every department meeting at the isolation station before splitting up and going their separate ways. Each process step has the same input parameters as presented in section 6.1.

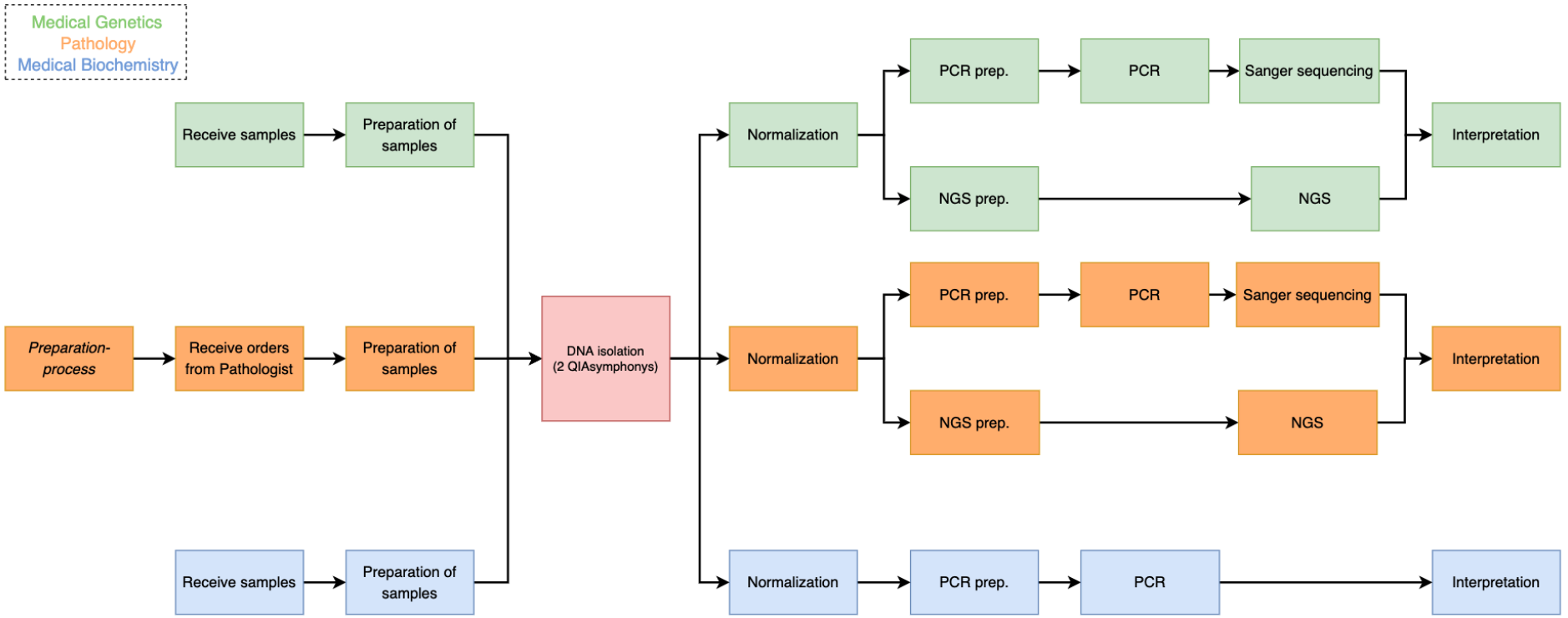

Figure 36: Shared resource process flow

7. Results

This chapter aims to present the quantitative output from the simulation experiments conducted to identify the effects of shared resources on hospital laboratory performance. Since the model was developed based on input from a case study, the model output presents results based on case-specific data. Due to the model being conceptual, the output is not directly case-specific, but more relevant for the laboratories at St. Olavs Hospital than for other Hospitals. However, the results and their significance will be discussed and generalized in chapter 8.

7.1 DNA isolation process

This section will present structured results from the simulation of the DNA isolation process. Thus, the results presented in this section are focusing on when samples enter the system until they are finished with isolation. The results will illustrate and compare the difference between the two scenarios and how they are performing.

7.1.1 Throughput for DNA isolation

First, throughput for the DNA isolation process is measured at each department and compared with and without shared resources. Here, tables for each department show the percentage distribution of when samples are finished with DNA isolation. Some samples are isolated the same day they arrive, while others use several days. Moreover, Table 12 will illustrate a summary of all departments and their average throughput time in workdays.

Table 9: Throughput DNA isolation (Pathology)

% Distribution how many days before samples are finished												
DNA Isolation	**Pathology**											
Demand \ Days	**Not Shared**						**Shared**					
	1	2	3	4	5		1	2	3	4	5	
20 %	18 %	79 %	2 %	0 %	0 %	✓	8 %	77 %	15 %	0 %	0 %	X
40 %	28 %	72 %	0 %	0 %	0 %	✓	19 %	78 %	4 %	0 %	0 %	X
60 %	30 %	70 %	0 %	0 %	0 %	✓	19 %	81 %	0 %	0 %	0 %	X
80 %	3 %	25 %	31 %	31 %	10 %	X	3 %	39 %	49 %	9 %	0 %	✓

At the department of Pathology (Table 9), the results show that not sharing performs better until the demand increase to 80%. This means that for a smaller demand level, not sharing the DNA isolation might be beneficial for this department. Once the demand increases to a certain level (between 60-80%), one can see from the Table 9 that sharing the DNA isolation is the best option in terms of throughput time.

Table 10: Throughput DNA isolation (Medical Genetics)

% Distribution how many days before samples are finished										
DNA Isolation	Medical Genetics									
Demand \ Days	Not Shared					Shared				
	1	2	3	4		1	2	3	4	
20 %	23 %	77 %	0 %	0 %	X	66 %	34 %	0 %	0 %	✓
40 %	62 %	38 %	0 %	0 %	X	77 %	23 %	0 %	0 %	✓
60 %	69 %	31 %	0 %	0 %	X	78 %	22 %	0 %	0 %	✓
80 %	75 %	25 %	0 %	0 %	✓	21 %	47 %	32 %	0 %	X

Table 11: Throughput DNA isolation (Medical Biochemistry)

% Distribution how many days before samples are finished										
DNA Isolation	Medical Biochemistry									
Demand \ Days	Not Shared					Shared				
	1	2	3	4		1	2	3	4	
20 %	23 %	59 %	17 %	1 %	X	66 %	34 %	0 %	0 %	✓
40 %	16 %	84 %	0 %	0 %	X	78 %	22 %	0 %	0 %	✓
60 %	56 %	44 %	0 %	0 %	X	79 %	21 %	0 %	0 %	✓
80 %	57 %	43 %	0 %	0 %	✓	20 %	46 %	33 %	1 %	X

At both DMG and DMB (Table 10 and Table 11), one can see that sharing resources performs better for all simulations except the one with a demand increase of 80%. Once this demand increase is included in the model, one can see a clear shift in the results, and not sharing becomes significantly better for both departments. This result contrasts with what has been observed at the department of Pathology. Therefore, sharing a DNA isolation station might be a better solution for these departments until they reach a volume increase somewhere between 60-80%.

Table 12: Throughput DNA isolation (Average workdays)

Average throughput DNA Isolation (workdays)			
Department	Volume increase	Not shared	Shared
			2 QIAsymphonys batch size 24
Pathology	20 %	1,84	2,08
	40 %	1,72	1,85
	60 %	1,70	1,81
	80 %	3,20	2,65
Medical Genetics	20 %	1,77	1,34
	40 %	1,38	1,23
	60 %	1,31	1,22
	80 %	1,25	2,12
Medical Biochemistry	20 %	1,96	1,34
	40 %	1,84	1,22
	60 %	1,44	1,21
	80 %	1,43	2,13

From these results, one can see that AMG and AMB will benefit from sharing the DNA isolation in terms of throughput time if capacity is sufficient. This result explains that these two departments will fill up batch sizes faster when their samples can be mixed with the other departments. The switch at 80% for AMG and AMB is due to the capacity restrictions at the shared resource being reached faster than it is for not shared. Thus, the common queue size before the shared resources is larger at 80% than it is when not sharing machines, which is visualized in Figure 37.

At the department of Pathology, the results are a bit different. Here, not sharing resources is performing better for both 20%, 40%, and 60% increase in volume. This is due to the low batch sizes of 12 samples at the QIAcube, where they can fill up faster than if they are operating with shared QIAsymphonys. In addition, the batch size from the DNA preparation is equal to the batch size at the QIAcube which means that the batch size is held constant throughout the DNA isolation.

While for an 80% increase at Pathology, not sharing resources is performing worse than without shared resources. This is a consequence of the capacity at the QIAcube. When the volume increases to such a degree, the available capacity at the shared resource becomes better than at the QIAcube. The shared resource has a capacity of 48 samples divided among the three departments, which gives each department on average a capacity of 16 samples. The

performance can be explained by how the queue before the QIAcube is “blocked” by the QIAcube, meaning that the number of incoming samples is larger than the outgoing samples. Thus, the shared QIAsymphonys will perform better in a way where they have a better balance of incoming and outgoing patient samples. However, this does not mean that the QIAsymphonys is performing well, only that it is performing better than the QIAcube.

7.1.2 Work in process at DNA isolation

Figure 37 shows the amount of WIP at the DNA isolation. High WIP is something that is often regarded as negative and describes the amount of samples at the DNA isolation at a given time. As demand increases, the amount of WIP increases in both scenarios. The reason for the rapid increase at the beginning is due to there not being any intermediate storage anywhere in any of the processes in the model. Hence, the first days can be neglected.

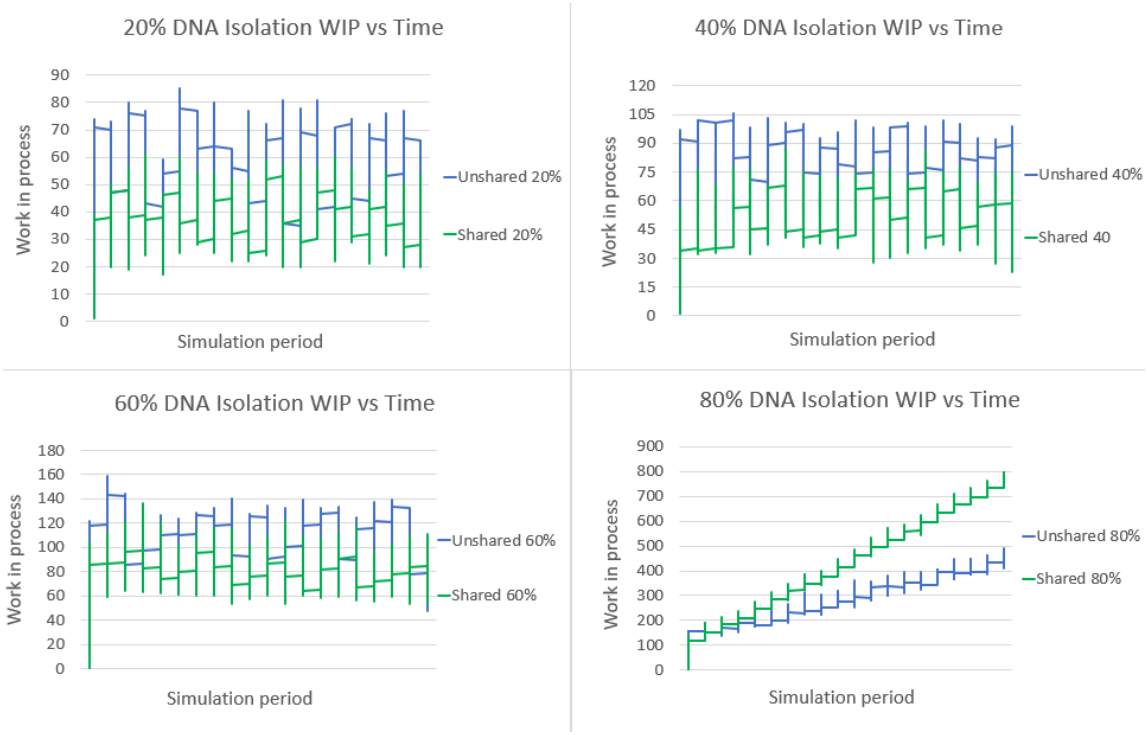

Figure 37: Work in process at DNA isolation

The results show that sharing resources is better in terms of WIP as long as the demand is manageable. This can be seen as the amount of WIP is lower at an increase of 20%, 40%, and 60%.

As shown for the throughput time, the same switch happens at an 80% increase where the demand is higher than the capacity of the machines. At an 80% volume increase, the WIP at the shared resource is increasing more rapidly. The capacity restriction can be seen as the graphs never stop increasing, which implies that the queue becomes bigger and bigger. This

happens due to all departments having a common queue before the DNA isolation, instead of each department having its separate queue. Thus, when capacity restrictions are met, blocking will have bigger consequences when sharing than when not sharing. This is due to how the shared resource needs to combine incoming volumes from all departments, while not sharing only needs to focus on their own.

7.1.3 Machine utilization at DNA isolation

Figure 38 shows how the utilization of each machine when not sharing resources increases as the volume increases. The utilization level of the machines is affected by two. Firstly, especially for 80%, the system starts with inventory level zero as visualized in the figures earlier. This might also affect the utilization level at the beginning of the simulation period. Secondly, the utilization level of these machines is affected by the implemented restriction that hinders the operators to insert racks the last hours before closing at 4 p.m. In some situations, it might be logical to work overtime to process one batch through the isolation machines. This opportunity is eliminated in the model, and their utilization level visualized below is therefore slightly lower than what would be logical in a more flexible situation. However, QIAcube 2, which is used by DMB is slowly increasing due to it only processing samples that are leftover and needed to be isolated.

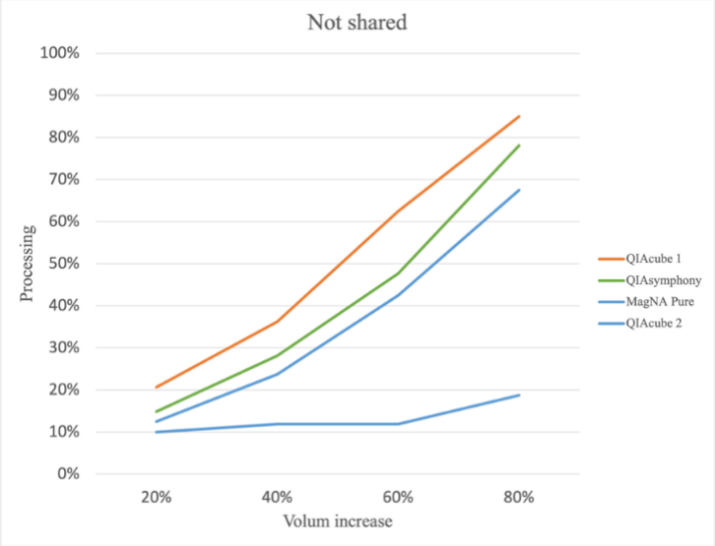

Figure 38: Utilization of machines (not shared)

Figure 39 shows how the utilization of the shared QIAsymphonys is increasing as the incoming volume is increasing. When the volume is low, only one QIAsymphony is enough to manage the incoming samples, however, as the volume increases the utilization of both machines increases quickly to almost max capacity.

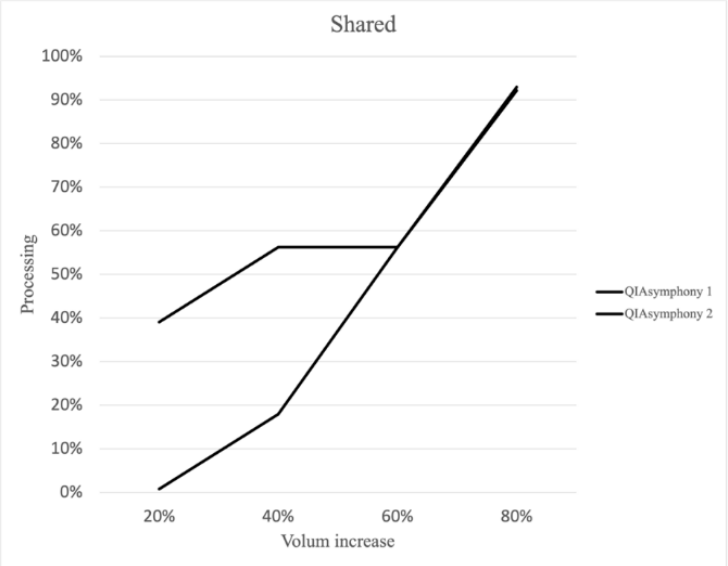

Figure 39: Utilization of machines (shared)

The same restriction was implemented here, and the results are therefore smaller than what is logical to assume. In fact, the machines were operating 100% in the last simulation period for an 80% increase over five years. The WIP increment for the 80 % increase shown earlier happens due to not having enough capacity at these machines.

7.2 Entire process

7.2.1 Throughput and WIP

Throughput and WIP at PCR is measured from when samples are entering the system until they are done with PCR and sanger sequencing. Measuring throughput and WIP at NGS is done in the same way, from the arrival of samples until they are finished with processing at the NGS.

Table 13: Throughput and WIP (PCR and NGS)

PCR	DP		DMG		DMB	
	Not shared	Shared	Not shared	Shared	Not shared	Shared
20 %	✓	X	X	✓	X	✓
40 %	✓	X	X	✓	X	✓
60 %	✓	X	X	✓	X	✓
80 %	X	✓	✓	X	✓	X

NGS	DP		DMG	
	Not shared	Shared	Not shared	Shared
20 %	✓	X	X	✓
40 %	✓	X	X	✓
60 %	✓	X	X	✓
80 %	X	✓	✓	X

The results in Table 13 show the difference in throughput performance for sharing and not sharing resources, for the whole process. The results reflect the same as shown for each department at the DNA isolation. Sharing the DNA isolation does not have any other effects on the whole process than delaying it.

When the incoming volume is low, the time it takes until a batch is filled and ready for PCR is much longer than when the volume is higher. This is due to PCR and NGS machines having much higher batch sizes than the DNA isolation machines, where samples are again waiting to fill up an even larger batch size. More detailed data which substantiates this can be seen in Appendix B. It is important to state that the differences in Table 13 vary, and appendix B visualize that these differences could be minutes to days.

Appendix B also shows WIP for the whole process of each department. However, the same situation occurs here as with throughput where the results are reflecting the same as shown for each department at the DNA isolation. Thus, Table 13 also shows which scenario is best when it comes to the amount of WIP in the system.

7.3 Additional Simulation experiments

7.3.1 Flexible batch sizes

It has been shown that introducing a shared resource will have a negative impact on the throughput time for the department of Pathology until demand reaches its capacity at an 80% increase. It is therefore relevant to investigate what happens if the batch size at the shared resource is set to be lower than their maximum. There have been simulated two additional experiments to investigate what happens if the batch size at the shared resources is set to 12 and 18, instead of 24. The cells in Table 14 that are marked with an "x" illustrate the scenarios where the capacity is lower than demand. Thus, the batch size is changed to ensure enough capacity is available.

Table 14: Throughput DNA isolation - changing batch sizes

Average throughput DNA Isolation (workdays)					
Department	Volume increase	Not shared	Shared		
			2 QIAsymphonys batch size 12	2 QIAsymphonys batch size 18	2 QIAsymphonys batch size 24
Pathology	20 %	1,84	1,76		2,08
	40 %	1,72	1,70		1,85
	60 %	1,70	x	1,69	1,81
	80 %	3,2 (x)	x	x	2,65 (x)
Medical Genetics	20 %	1,77	1,25		1,34
	40 %	1,38	1,19		1,23
	60 %	1,31	x	1,21	1,22
	80 %	1,25 (x)	x	x	2,12 (x)
Medical Biochemistry	20 %	1,96	1,26		1,34
	40 %	1,84	1,20		1,22
	60 %	1,44	x	1,19	1,21
	80 %	1,43	x	x	2,13 (x)

The table above shows that if the batch size at the shared resource is reduced, it is possible to take advantage of the flexibility excess capacity gives the shared QIAsymphonys. Here, the throughput time for the department of Pathology will be better if the batch size at the shared resource is reduced to be lower than 24. In addition, the throughput time for DMG and DMB also decreases. This show that flexible batch sizes will improve the throughput time.

7.3.2 Expanding to three shared resources

Flexible batch sizes improved the throughput time for the departments until the demand increased by 80%. With an increase of 80%, not sharing is still the best option for DMG and DMB. It is therefore relevant to investigate what happens with the throughput time when an additional QIAsymphony is added to the system.

Table 15: Additional scenario with 3 QIAsymphonys

Average throughput DNA Isolation (workdays)						
Department	Volume increase	Not shared	Shared			
			2 QIAsymphonys batch size 12	2 QIAsymphonys batch size 18	2 QIAsymphonys batch size 24	3 QIAsymphonys batch size 24
Pathology	20 %	1,84	1,76			
	40 %	1,72	1,70			
	60 %	1,70	x	1,69		
	80 %	3,20	x	x	2,65	1,72
Medical Genetics	20 %	1,77	1,25			
	40 %	1,38	1,19			
	60 %	1,31	x	1,21		
	80 %	1,25	x	x	2,12	1,18
Medical Biochemistry	20 %	1,96	1,26			
	40 %	1,84	1,20			
	60 %	1,44	x	1,19		
	80 %	1,43	x	x	2,13	1,20

As visualized in Table 15, the three shared resource situation is best suited to manage the demand increase at 80% over five years. It is relevant to point out that the not shared resource scenario, which has been a reference scenario, has in total four machines to conduct DNA isolation. Thus, the expansion to three QIAsymphonys is both realistic and affordable.

7.3.3 Additional observation at the department of Pathology

Finally, there have been observations regarding batch sizes at preparation for DNA isolation at the department of Pathology. As stated previously, the shared resource scenario is adapting the same input as the not sharing scenario. This means that the same processing times and batch sizes are used at the different process steps. However, for DMB and DMG the incoming sample flow is a one-piece flow through the preparation for isolation, while for Pathology they are preparing samples in a batch size of 12 due to their QIAcube having a capacity of 12 samples. In the sharing resource scenario, where QIAsymphonys are shared, the target batch size is different. Therefore, the effects of incoming flow being prepared similarly for all departments have been investigated. This means that samples at Pathology are also prepared one by one, rather than waiting for a batch size of 12 samples before sending them to isolation. The change in batch size at the incoming volume for the DNA isolation gives the shared resource a more

balanced inflow. The result from this change in the simulation model shows that the throughput for the shared resource improves for Pathology (Appendix B). The impact of this change on the other departments is very small, but there is also an improvement for them.

8. Discussion

This chapter aims to answer RQ2 and RQ3, based on discussions of results from the simulation model, observations made at the case company, and the literature. Moreover, the chapter aims to generalize the findings to hospital laboratories in general. Additionally, the limitations of the thesis will be discussed.

8.1 The effect of sharing resources in hospital laboratories

RQ1 identified alternatives for resource sharing in hospital laboratory processes based on a case study of the laboratory departments at St. Olavs Hospital. Machines, location, and personnel were identified as potential resources to share. This section aims to discuss these resources and how they can influence performance indicators identified in the case study and the literature. The relevant performance indicators are throughput time, utilization, WIP, quality, and costs.

Machines

The results presented in chapter 7 indicate the effect sharing machines can have on hospital laboratory operations. Moreover, it gives specific indications of effects on throughput time, WIP, and utilization. It has been observed that the three departments have large variations in available capacity. The results visualize how two of the departments are performing better with shared machines while one is performing worse. The one with the lowest capacity reaches a "blocked" situation first. For two of the departments, the shared machines reach it first, while for the last one not sharing machines reach it first. After adjusting the available batch size and adding another machine to the system, the throughput performance at the shared machines in all departments becomes better than when not sharing. Differences in throughput at the three departments when the incoming volume is increasing are decided by the capacity available at either the department or the shared machines. Thus, the performance of sharing machines depends on the available capacity, their batch sizes, and the incoming volume. Given the environment created in the simulation model, sharing machines will have the lowest throughput time until demand exceeds the available capacity.

The results show that when the incoming volume increases, the machine utilization also increases. However, with shared machines, the utilization increases at a rate that is higher than if machines were not shared. Meller et al. (2012) identify how the collaboration of resources can result in increased utilization, which is reflected in the results presented. However, higher

utilization rates imply that a shared resource will reach its maximum capacity faster, which is necessary to be aware of before implementing shared resources.

When volume is lower than the available capacity, sharing machines have less WIP. Here, several departments are collaborating to fill up batch sizes at one single machine, which results in a lower amount of samples in the queue before the DNA isolation. However, when demand exceeds capacity there is a switch where not sharing machines are performing better. If the incoming volume exceeds what the machines can manage, a "blocked" scenario will arise at the shared machines. However, this is also the case if machines are not shared. The difference is that due to the shared machines managing the flow of three departments, the amount of WIP will amass faster for the shared machines. When machines are shared, the samples are not only waiting for their departments' own samples and the machines to be available but are also waiting for samples from other departments to use the machine. Thus, there will be an additional reason for samples to wait in a queue, resulting in a larger queue before the DNA isolation. Hence, sharing machines will negatively impact the WIP more than not sharing if the incoming volume exceeds capacity.

Quality has been identified as the most important performance indicator for the hospital laboratory. To maintain high quality, the machine specifications need to manage all incoming volumes and process them with the same standard of which each department operates. The case study revealed that the departments have not investigated if there exists a multifunctional machine that can manage the flow of all departments. Wilson and Platts (2010) state how a shared resource involved in multiple production flows would need a higher requirement of mix flexibility. Thus, for a shared machine to manage the flow of all departments, it will be necessary to acquire a multifunctional machine to avoid a reduction in quality.

Sharing machines between departments might also lead to cost savings, as highlighted by Curjssen et al. (2007), Meller et al. (2012), and Muñoz-Villamizar et al. (2015). Here, one can sell machines and invest in other areas. As shown in the simulation model, sharing machines leads to higher utilization. This implies a higher return on investments (ROI), which could be crucial when having budget restrictions. Additionally, it is fair to assume that when new investments are necessary, and several departments are collaborating on the investment, a lesser amount from each department's budget is necessary to complete the investment. Thus, each department could save money from co-purchasing. Moreover, it could enable the departments to invest in more expensive equipment, if necessary, as co-purchasing results in more total capital available. This is further elaborated by Freitag (2016), identifying how shared

resources can reduce risky and capital-heavy investments. Moreover, sharing machines will enable the individual departments to cut the service costs related to the previously individually owned machine. Service costs related to the shared machines will then be divided among all three departments, providing each department with lower service costs.

Location

Today, two of the three departments are sharing a location for DNA isolation but are using different personnel and machines. There are ongoing discussions if the departments should share the location (centralizing) as well as their machines in the future. This section will discuss the pros and cons of different layout solutions that could influence such a decision. The relevant layout types are cellular (decentralized) and process (centralized).

With increasing demand and shared resources creating more complex flows, the material handling will consequently become more complex as well. And as Anderson et al. (2017) identified, when sharing resources, one needs to avoid resource conflicts as this adds to the complexity of the shared resource. Therefore, focusing on material handling could be important to hinder the negative influence on throughput time. A cellular layout is well suited to reduce the material handling inside a facility because the distances are held relatively short inside their given cell. Furthermore, Dockery et al (2014) highlighted the importance of quick access to resources. This means that shared resources should be easily accessible and located in a way such that it does not distract the flow of the other processes that are tied up to the same resources. One central benefit of process layout and sharing resources is that the facility is organized based on operations, which allows including the shared resource in the routings for all departments. This highlights the complexity in choosing a good layout and finding the trade-off in what is important for the laboratory operations, as this can vary from laboratory to laboratory. Process layout can still be a viable option despite the amount of material handling, especially if the distances are relatively short and batch sizes high, reducing the number of trips.

Furthermore, the layout solution could also have an impact on the amount of WIP. As highlighted in the literature, what benefits cellular layout from process layout is the amount of WIP. It is true that with a cellular layout the number of WIP at each cell would be lower than if the layout were a centralized station including products from all departments. On the other hand, as visualized in the results from the simulation model, the sum of WIP at all separated cells is higher with decentralized stations given that there is enough capacity to manage demand in both scenarios.

The literature shows a contrast between cellular layout and process layout when it comes to equipment utilization. The literature points out the number of duplicated machines as an indication of lower utilization, which has been further strengthened by the results in the simulation model. When duplicating machines, it is also necessary to duplicate space, hence, space is affected by decentralized layout solutions. Centralizing a given station indicates that only one dedicated area is needed to conduct a single operation, instead of multiple similar areas spread around the facility to conduct the same operation. Therefore, space utilization could be a potential benefit when centralizing departments. There is also a cost aspect when it comes to centralizing and decentralizing the location of a specific station. As mentioned, a decentralized solution might require duplication of specific costly environments (such as ventilation), machines, and space. In contrast, a centralized solution only requires such investments in one location, which can lead to freeing up both capital and space for other investments.

Location decisions could also affect the quality aspect. In hospital laboratories, contamination could potentially occur in a centralized location of a given station. Contamination could directly impact the quality of a given sample and therefore weaken the most important indicator. That said, not all stages at the case company that is included in this thesis will be affected by contamination. In processes such as DNA isolation, contamination is not an issue, and centralizing such processes could be a possibility. Anyway, when centralizing, one should always consider that the right environment is in place to conduct the operations that are needed.

Personnel

There are few manual processes in the departments, meaning that WIP is mostly depending on machine capacity, processing time, and the incoming volume. Thus, having dedicated or not dedicated personnel will have little influence on WIP. However, it could influence throughput time, cost, and quality. If a shared resource requires a high skill level, it would be logical to dedicate personnel with the correct qualifications to do this process. Then, one would utilize the existing knowledge and skill of personnel throughout the whole workday. However, if the shared resource does not require any special level of skill like it is understood with the DNA isolation process, it would be logical to not dedicate overqualified personnel to this process. One would rather use this knowledge elsewhere and utilize the existing knowledge among the employees in the best way possible.

Dedicated personnel could become experts at the DNA isolation process and reduce the throughput time due to having to specialize themself in that specific process. This is one of the

synergy effects that should be taken advantage of, as identified by Curjssen et al. (2007). When there is not-dedicated personnel, it is fair to assume that each time they are entering a process, there needs to be some sort of setup or changeover. The changeover time for switching from one job to another increases the shared resource complexity (Ferrell et al., 2020). This could be to find consumer goods such as gloves, facemasks, reagents, etc. If there are dedicated personnel, they are familiar with the process and could avoid lengthy setup or changeover times. It is therefore fair to assume that if there were dedicated personnel at the DNA isolation machines, they could affect the throughput time due to being experts in the process of preparing and running the DNA isolation process.

However, as the dedicated personnel would need to manage the flow of three different departments, there will be a learning curve at the beginning where the performance is worse before reaching the expected level of performance. Therefore, the quality of delivery could be affected as the dedicated personnel is learning to manage the flow from three departments. Moreover, as the dedicated personnel would need to manually manage a larger number of samples than they are used to at the individual level, it is fair to assume that the risk of human error will increase due to more complexity in the incoming flow. The complexity increases due to different protocols for different patient samples, and samples from different departments being mixed, hence, there are more factors for failure than if not dedicated personnel were used. By introducing more automation in the process, personnel will have to manage less of the complexity and thus decrease the risk of human error.

Freitag (2016) stated that when sharing resources, the costs related to organization and coordination of the shared resource could increase. Thus, having dedicated personnel could increase costs. However, having dedicated personnel to a given process could potentially reduce the need for workers. There could be e.g., one person managing the flow of three departments rather than three workers working independently from each other in their departments. As mentioned, experts at the shared resource could improve the throughput time and reduce changeover and setup time. Such improvement could lead to fewer work hours required, and thereby less personnel and costs to complete the same operation. Additionally, other personnel could be released to do other tasks. On the other hand, one could also argue for not dedicated personnel acquiring the same level of expertise for their specific isolation process, rather than for all three departments' isolation processes. However, a fair assumption is that dedicated personnel could have a higher potential of becoming experts, as the personnel conducts the same operation several times.

Clarification

There has been much focus on how shared resources will be affected by the increase in demand, especially when the demand is higher than the existing capacity. One thing is to have a lack of capacity in terms of the labor force, but where the machines theoretically cannot meet demand seems to be an exception. In general, companies should not end up in such a situation regardless of if they are sharing machines or not. Observations at the case company are that the available machine capacity is much larger than demand, despite that there are restricted budgets. Thus, an 80% increase over five years needs to be viewed as a worst-case scenario. For all other simulated demands, the simulation model and theory indicate that sharing the DNA isolation process is the best option in terms of throughput time, WIP, utilization, and cost. The only indicator that could potentially be negatively influenced by such a decision is quality. The researchers do not have sufficient medical knowledge to determine to which degree this will be a problem, but there have been conducted discussions of central aspects that need to be decided in advance of such a decision. Results from chapter 7.3 imply that if an extreme scenario does appear, a shared resource station could be upgraded in the same way as any other individual station and could operate with better performance than before.

Aspects such as machines, personnel, and location have been observed at the case company to be potential shared resources. These resources could also be relevant to share at other hospitals. Moreover, the identified performance indicators could be relevant for many hospitals and industries, but they might be prioritized differently. It has been observed that sharing resources could increase the performance, but also cause some complexity that needs to be considered.

8.2 The complexity of sharing resources

It has been argued that sharing resources leads to more complexity, and this section will try to highlight what is meant by this complexity. The literature study, observations at the case company, and logical thinking have been used to identify what this complexity is. In addition, this section will give some general advice on how to cope with this complexity.

As visualized in Figure 40 and argued by Freitag (2016), what makes a shared resource different from a regular resource is the dependency on more than one flow. A well-known consequence of managing a bottleneck poorly is that it will affect not only the bottleneck itself but also all downstream activities. One can say the same of a shared resource, but on a bigger scale; if not managed well, it will not only affect the shared resource but also all the downstream activities that have an upstream link to the given resource, which is further supported by Freitag (2016). Therefore, it is essential to consider scheduling, prioritization, capacity, knowledge, machine specification, and location to cope with the process flows that depend on the resource. These considerations are necessary to avoid the shared resource to become a bottleneck for the entire system. Based on the literature, case study, and logical thinking, several factors that are unique for a shared resource and are triggering the increased complexity have been identified:

1. Consider several process flows when scheduling.
2. Prioritize across several process flows.
3. Manage capacity across several ingoing process flows.
4. Employee knowledge.
5. Machine specifications.
6. Shared resource location.

All these factors are creating complexity related to shared resources in clinical laboratories. Thus, it is necessary to elaborate on how these factors triggering increased complexity of operations can be managed.

Scheduling

When having shared resources, it will be necessary to organize schedules based on demand from all process flows involved in the shared resource. Therefore, having control of demand can be beneficial to determine when to process which flow and in which volume. Moreover, when scheduling the use of the shared resource, it is necessary to ensure strategic batch sizes are used throughout the processes involved with the shared resource. Different batch sizes between the flows and the shared resource will only make scheduling more complex. Hence, it

is necessary to synchronize the shared resource with both upstream and downstream operations to create a smooth flow. Moreover, as the results in section 7.3.3 show, shared resources are operating better when all processes are using batch sizes that enable a smooth flow to the shared resource. As stated by Duggan (2013), having shared resources often leads to a wrong focus, where batch sizes are determined by the machines rather than the process. This is also confirmed by the results in the simulation model, where a batch size lower than capacity improved the performance. Additionally, the batch sizes need to be scalable, as they should be increased as the incoming volume increases. Thus, the shared resource also needs to operate with a flexible batch size to ensure scalability and enable the process to meet demand.

One important factor to consider is if the shared resource has the multifunctionality to combine several process flows simultaneously or if it needs to process them one by one. This specification is essential to determine and will be visualized and discussed below.

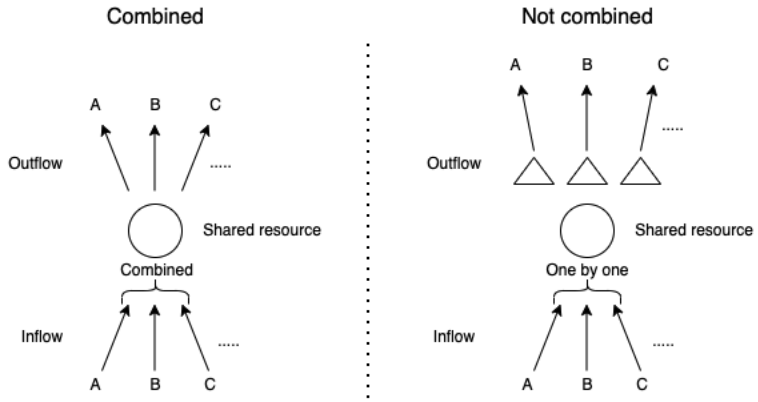

Figure 40: Managing incoming flows

Figure 40 visualizes two scenarios: one where several process flows can be combined at the same resource (left), and one where each process flow must be treated individually (right). In both systems, it is relevant to include that there could be more or fewer ingoing and outgoing flows than visualized. Moreover, it does not have to be the same amount of ingoing as outgoing flows.

When a shared resource can combine flows and process them simultaneously, the combination of flows depends on the strategy of the system. If there is a push strategy, a predetermined schedule decides the combinations of A, B, and C going into the shared resource. If pull is the strategy, the requirement of the downstream operations should decide what combination of A, B, and C is to be served by the shared resource. For both strategies, the combined batch size of A, B, and C cannot be larger than the batch size used at the shared resource.

If the resource can only process one flow at a time, to have the best possible flow, the outgoing batch size for each flow at the shared resource should be such a size that makes the downstream operation busy until their next supply arrives. Therefore, intermediate storage after the shared resource is included in Figure 40. This ensures that there is no waiting for arrivals at the downstream flows. Moreover, with a pull strategy, the downstream activities are what decide the order of flows to be processed, while with a push strategy a predetermined schedule is used. As the process flows cannot be treated simultaneously, it is relevant to mention that there should be a focus on SMED as described by Nicholas (2011), due to changeovers between different flows.

Prioritization

When sharing resources, situations where one must prioritize between several process flows may occur, this could also be referred to as a resource conflict. Such situations happen because of errors in the scheduling decisions, or as a natural part of the system where one cannot combine different process flows. Thus, it will be necessary to establish lists of priority for each flow, which needs to be obeyed when processing at the shared resource. Such a list is necessary to ensure that all involved with the shared resource acquire the same knowledge of how to manage the prioritization of different flows. Moreover, establishing such a list is necessary to avoid resource conflicts where the inflow quantity requiring the shared resource is larger than what the shared resource can manage. Essentially, the prioritization list could include the schedule of each flow and its priority, ensuring that the shared resource is not required to process more than it is capable of.

Capacity management

When sharing resources, balancing capacity and demand is especially difficult when sharing resources, as each flow could have its own demand and fluctuations. Moreover, there are fewer opportunities of affecting demand in service industries, meaning that it is more difficult to balance capacity and demand. In such situations, control of the shared resource becomes even more crucial. To manage this complexity, capacity management should aim to ensure control of demand for all incoming flows and that the capacity is sufficient to do so. When unable to combine flows, there should be enough capacity to cope with the flow that has the largest batch size. If combining flows, the capacity needs to be sufficient to manage a feasible batch size that can serve the required demand of all flows. However, as stated by Terwiesch et al. (2011), capacity management does not mean maxing out the utilization of existing resources but finding the right balance between responsiveness and efficiency. Additionally, the capacity

should be enough to be responsive in managing the fluctuation and the expected increase for all flows to maintain scalability. Thus, the schedule for the shared resource should ensure that the capacity available is used correctly and takes demand fluctuations for several flows into consideration.

The literature concludes that there are many different strategies for managing capacity to balance it with demand. However, not all are sufficient to implement in service industries. Since the customer for a hospital laboratory could be patients waiting for answers related to their health, it is important to always have enough capacity to fulfill demand. Delays in supplying test answers to patients can potentially have fatal consequences. A leading strategy would then be preferred due to the environment in which hospital laboratories are operating. Moreover, when planning how to have enough capacity to meet demand, specific approaches can have a better fit than others. Some approaches require influencing demand, the possibility to store tests and wait for periods where demand is low before conducting tests, or the opportunity to conduct tests before demand. This will not be suitable in an MTO/ATO environment. A chase approach might be applicable, as it can be used as a strategy to upscale or downscale capacity through utilization. This means that with a chase strategy, the hospital laboratory can use its underutilized resources as a tool to gain more flexibility in managing demand fluctuations. With these strategies for managing capacity, hospital laboratories can gain further control of their complexity and ensure a better balance of capacity and demand. However, the best-suited strategies vary with the characteristics of the industry in which one operates.

Employee knowledge

The developed schedules and prioritization lists should aim to ensure all involved employees acquire the necessary information to operate the shared resource. It will be necessary to create sufficient knowledge among employees to correctly use the schedule and prioritization lists, reducing the risk of human error. Thus, creating a center for generating knowledge related to operating the shared resource can ensure a better quality of the process. Moreover, as the employees are the ones who are most familiar with the process, continuous improvement is key to enable the improvement of shared resource management among employees.

Shared resources, in general, requires more knowledge among employees about how to operate them. However, Figure 40 visualizes the potential differences in the requirement of knowledge at a shared resource. It is logical to assume that a shared resource unable to combine incoming flows requires a higher level of expertise among dedicated personnel. As stated in section 8.1,

when having dedicated personnel, one should aim to only dedicate personnel with the required amount of knowledge to operate the shared resource. Furthermore, a shared resource processing one flow at a time requires more knowledge due to the different characteristics of each flow and the changeover and setup of the machine. This means that the dedicated personnel must prepare the shared resource each time a new flow is about to be processed. Moreover, a fair assumption is that combining several flows implies that it could exist one method that will be suitable for all flows, meaning that it requires a smaller range of knowledge to handle.

Thus, it will be necessary to map the level of knowledge among employees to identify if the available knowledge is sufficient to manage the increased complexity. E.g., a shared resource requiring a high level of knowledge is more difficult to share than one that is standardized. Hence, it should be a goal to standardize the shared resource as much as possible to ensure the best possible environment for employees to operate it. However, standardization heavily depends on the flows' requirements at the shared resource. Moreover, in addition to detailed schedules and prioritization lists, employees could be supported by user manuals to complete different tasks.

Machine specification

Additionally, the machines procured to be the shared resource needs to be multifunctional or flexible enough to manage all incoming flows. As highlighted by Wilson and Platts (2010), a shared resource being involved in multiple production flows would need a higher requirement of mix flexibility than a shared resource being involved in fewer flows. As discussed in section 8.1, the shared machine needs to enable operations where all requirements from ingoing flows are satisfied (quality, cycle time, batch sizes, etc.). For a shared resource to combine all incoming flows, the shared machine must be multifunctional, meaning that it could manage all incoming flows simultaneously. When each flow must be processed individually, the shared machine must be flexible enough to manage each flow separately. Thus, there would be a need for a changeover each time a new flow is about to be processed.

Shared resource location

When sharing resources, it is also necessary to ensure the shared resource has enough space available to manage all incoming flows without letting them affect each other or other external process flows. The layout of the location is what decides the flow of materials; thus, it is important to ensure the layout supports the implementation of a shared resource to operate as efficiently as possible. It is costly to change a layout, which could happen with the introduction

of a shared resource. The location needs to be designed so that it is easy to maintain control over the different flows and their needs to avoid resource conflicts and disruptions. As previously discussed in section 8.1, the characteristics of a process layout support this criterion, as it will be possible to include several flows in one shared resource. Lastly, one must ensure the layout is scalable, meaning that it should be possible to introduce additional resources to the system for extra capacity when necessary.

How to manage resource sharing complexity in hospital laboratories has been generalized to hospitals in general, however, it could also be relevant for other industries operating in similar environments. Table 16 summarizes the discussion and generalizes how to manage the complexity of sharing resources.

Table 16: How to manage resource sharing complexity

Reasons for complexity	How to manage the complexity
Consider several incoming process flows when scheduling	• Organize schedule based on the total demand for all incoming flows • Ensure control of demand • Determine strategic, flexible, and scalable batch sizes • Consider changeover and setup time
Prioritize across different process flows	• Establish lists of priority for all incoming flows • Ensure the list manages resource conflicts
Manage capacity across several ingoing process flows	• Ensure the capacity is sufficient to manage the determined batch size • Acquire an understanding of the capacity requirements for all the processes relying on the shared resource • Determine capacity management strategies (e.g., lead, lag, chase) • Enable scalability and responsiveness to fluctuations in demand
Employee knowledge	• Ensure sufficient knowledge among employees on how to operate the shared resource correctly • Ensure knowledge of how to use the schedules and prioritization lists • Simplifying the process by standardization and user-friendly tasks • Focus on continuous improvement
Machine specifications	• Ensure flexible or multifunctional machines that are able to process all incoming flows • Ensure that machines have enough capacity to process all incoming flows • Ensure that the machines used are scalable
Shared resource location	• Ensure the shared resource have enough space available to manage all incoming flows • Ensure the location supports the implementation of a shared resource • Ensure the location avoids disruptions of other external flows and operations • Create a location allowing the process to be scalable

8.3 Limitations

The most significant limitation of this thesis is how the model is conceptual. This means that the results are not 100% accurate for St. Olavs Hospital, however, it is still relevant enough to illustrate a realistic scenario. Additionally, the input data is based on approximations from laboratory personnel, and not exact data. The lack of real demand data caused approximations of how many samples are entering the system. However, approximations are presented in the thesis, and the model still provides relevant findings on shared resources in hospital laboratories.

It has been difficult to plan visitations due to time available among employees at the case company. Hence, there was limited time to ensure enough detailed data were collected for input to the model and to create a common understanding of all processes. A workshop was held to validate both the understanding of processes and the data collected. The results are conceptual and based on case-specific input, meaning that the data produced might not be relevant, but the findings and meaning of the data could be applicable. However, the discussion in sections 8.1 and 8.2 tries to generalize the results for hospital laboratories.

The thesis is limited to a single-case study. Only laboratory departments at one hospital have been analyzed and used as input to the thesis. However, multiple laboratory departments at the same hospital have been used, to solidify the real-life problem. Moreover, the observations made at the departments have also been supported by findings in the literature. Nevertheless, to further solidify the real-life problems, multiple case companies could have been acquired.

Finally, there could be bias in the thesis, due to the literature study. Here, relevant articles could have been excluded and the researchers' own subjective opinions could have affected which articles were chosen. Furthermore, there is no previous research in relevance to simulation studies of shared resources in hospital laboratories to compare the results with.

9. Conclusion

The thesis was formed as a literature and case study that supported the development of a conceptual simulation model and served as the foundation for discussions. The objective of this thesis was to investigate shared resources and their implications on hospital laboratory operations from an operations management and logistics perspective. The objective was fulfilled through three research questions.

Alternatives for resource sharing in hospital laboratory processes (RQ1) were identified through a single case study at the laboratory departments at St. Olavs Hospital. Machines, personnel, and location were identified as alternatives for potential resources to share. Sharing these resources was further investigated through a simulation model and discussions to answer what effect (RQ2) they have on the hospital laboratory performance. The effect was considered on five performance indicators: throughput time, WIP, utilization, cost, and quality. The results show that sharing resources can have a positive impact on hospital laboratory performance, despite how sharing resources often is a consequence of budget or space restrictions. Furthermore, what differentiates a system with shared resources from other systems was highlighted through six triggers creating increased complexity. Thus, there have been given general advice on how to manage this complexity (RQ3).

Results from this thesis contribute to knowledge by assisting in filling the gap in the literature related to sharing resources in hospital laboratories and how to manage them. The thesis was originally developed to focus on hospital laboratories; however, it could also be relevant for other industries that are operating in similar environments.

9.1 Further work

Sharing resources has shown itself to be a good option with the given environment and performance indicators. However, it does not mean it is the best opportunity to improve the processes. Therefore, it is important to evaluate other options such as reducing batch sizes and continuing to operate individually. A reduction of batch sizes could result in the departments exchanging machines with high capacity and possibly investing in cheaper and less complex machines. Such alternatives are important to evaluate before making any decisions. Finally, industries operating in other environments should be investigated to identify if the same effects of sharing or not sharing resources can be obtained.

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Appendices

Appendix A

Interview Guide – Part A

Introduction

Thank you for taking part in this master thesis. You possess important knowledge, and it is greatly appreciated that you take part in this interview. We will first go through a small introduction of why we are here. Then there are some general questions and formalities before we move on to more specific questions for each department.

Goal of the thesis: We will investigate shared resources in hospital laboratories and analyze how they affect the daily operations. Therefore, a hospital laboratory could be simulated to show how a shared resource behaves in a hospital context. The goal is to be able to make observations on how to manage a shared resource from a logistics and operations management perspective.

Goal of interviews and tour of laboratory: With visits and interviews, we will collect raw data that is necessary to be able to make the simulation as realistic as possible. It is you who possess the knowledge that is necessary for us so that we can carry out a good simulation. We, therefore, want to get a tour of the entire flow to increase our understanding of the work that takes place in the laboratory, and what is necessary to include as input in a simulation.

Structure: This is a semi-structured interview which means that we have some questions we must go through, but the format is freer. There will be follow-up questions if appropriate, but at the same time, we have a sheet we rely on so that we get the necessary information.

Agenda: We want to start with some formalities, and some general questions about the department. Then we want a review of their department at the same time as we ask more specific questions for each station.

Interview guide – Part B

Formalities:

This is to document who we have talked to and to ensure that we process the information we receive from this interview correctly.

Questions	Answers	Comments
Department		
Name		
Working position		
E-mail		
Are you comfortable with us recording or transcribing this interview for our own sake?		
Is it okay if we take pictures when needed?		
Can we send a follow-up email afterwards if we have missed essential information?		
Is the information we receive confidential?		
Is there any other important information you want to add?		

Interview guide - Part C

General questions for each department:

This is being done to ensure that we have the overall information about your department. The information we receive will help us gain a general understanding of how you work and the scope of the department

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Questions	Answers	Comments
How is the workday at this station? • When does the workday start and when does it end? • How many employees are at work simultaneously? • Are employees dedicated to specific work tasks? • Are the employees doing "everything", meaning that they are following one batch from start to finish.		
How do you get the information necessary to know what to do each day? • Is there any use of an ERP system?		
What volumes are this department operating with? • Yearly, monthly, weekly, daily? • Are there seasonal variations to demand?		
Does this department process several different samples, or is it just one type of sample? • What samples are this department processing? E.g., Blood, urine.		
If possible, what happens if a test fails?		
What do you consider to be important KPIs (performance indicators) for this department? (E.g., Throughput time, waiting time ...)		
How are urgent tests managed?		
Can we create a quick flow chart that shows which stations the tests go through at this station before we start the tour?		

Interview guide - Part D

Questions to understand the DNA isolation:

Part D is asked to understand the challenges that are associated with sharing the specific station «DNA Isolation». The answers we get here will be useful to enable discussions of the advantages and disadvantages of coordinating the individual station across the departments.

Questions	Answers	Comments
Are there more departments using this station as a step in their testing? If so, is there cooperation at this station? If not, what challenges will it bring if you choose not to do so? • Do different departments have conflicting requirements for implementation		
Is the same knowledge required to manage products from all departments through this station? • Would it have been possible to have dedicated employees for this station?		
If it must be shared, do some of the departments need higher priority than others?		
If it can be shared, can one get rid of some machines and free up capital and space for other investments?		
Does it require more cooperation beyond the mentioned station to bring about such a division of a single station? • Communication • Planning		

Interview guide - Part E

Questions for each station in the departmental process:

Part E is conducted to ensure that we have detailed information about each step in the processes. The information we receive will contribute to a more detailed understanding of each station.

Question	Answer	Comment
Is this station manual or with the use of machines?		
What is the name of this station, and can you easily explain what is happening here? • What is the name of the machines?		
Does this station work with batch sizes? • If yes, what batch sizes are used?		
How long do you spend processing a batch size at this station? If there are several machines at the station • What are the processing times of the machines? • Are the processing time depending on the batch sizes?		
What are the changeover times at the different machines? • Are there any costs related to the changeover?		
Depending on previous answers: How are urgent tests managed?		

Interview guide - Part F

Concluding questions:

- Are there any more you wish to add that we have not discussed?
- Validation of questions and answers:
    - Go through the information that could be confusing to make it clearer, ensuring that the information received is correct
- Thank you for taking part in this interview!

Appendix B
Department of Medical genetics

Throughput for PCR

Table 17: Throughput PCR (Medical Genetics)

% Distribution how many days before samples are finished				
PCR	Medical Genetics			
Throughput time / Demand	Not Shared		Shared	
20 %	Up to 13 days	X	Up to 13 days	✓
40 %	Up to 9 days	X	Up to 8 days	✓
60 %	Up to 6 days	X	Up to 6 days	✓
80 %	Up to 4 days	✓	Up to 6 days	X

Throughput for NGS

Table 18: Throughput NGS (Medical Genetics)

% Distribution how many days before samples are finished				
NGS	Medical Genetics			
Throughput time / Demand	Not Shared		Shared	
20 %	Up to 10 days	X	Up to 8 days	✓
40 %	Up to 8 days	X	Up to 7 days	✓
60 %	Up to 7 days	X	Up to 7 days	✓
80 %	Up to 6 days	✓	Up to 7 days	X

Work in process

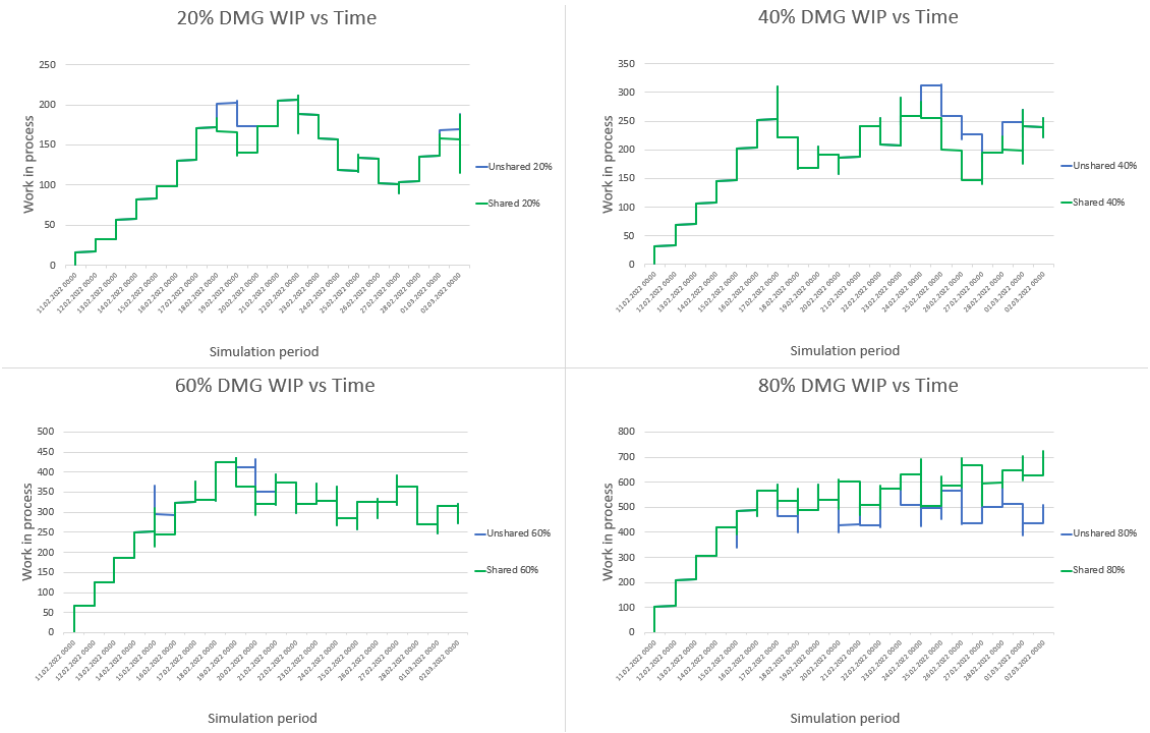

Figure 41: Work in process (Medical Genetics)

Department of Pathology

Throughput for PCR

Table 19: Throughput PCR (Pathology)

% Distribution how many days before samples are finished				
PCR	Pathology			
Throughput time / Demand	Not Shared		Shared	
20 %	Up to 11 days	✓	Up to 12 days	X
40 %	Up to 7 days	✓	Up to 7 days	X
60 %	Up to 6 days	✓	Up to 6 days	X
80 %	Up to 7 days	X	Up to 6 days	✓

Throughput for NGS

Table 20: Throughput NGS (Pathology)

% Distribution how many days before samples are finished				
NGS	Pathology			
Throughput time / Demand	Not Shared		Shared	
20 %	Up to 6 days	✓	Up to 6 days	X
40 %	Up to 6 days	✓	Up to 6 days	X
60 %	Up to 6 days	✓	Up to 6 days	X
80 %	Up to 8 days	X	Up to 7 days	✓

Work in process

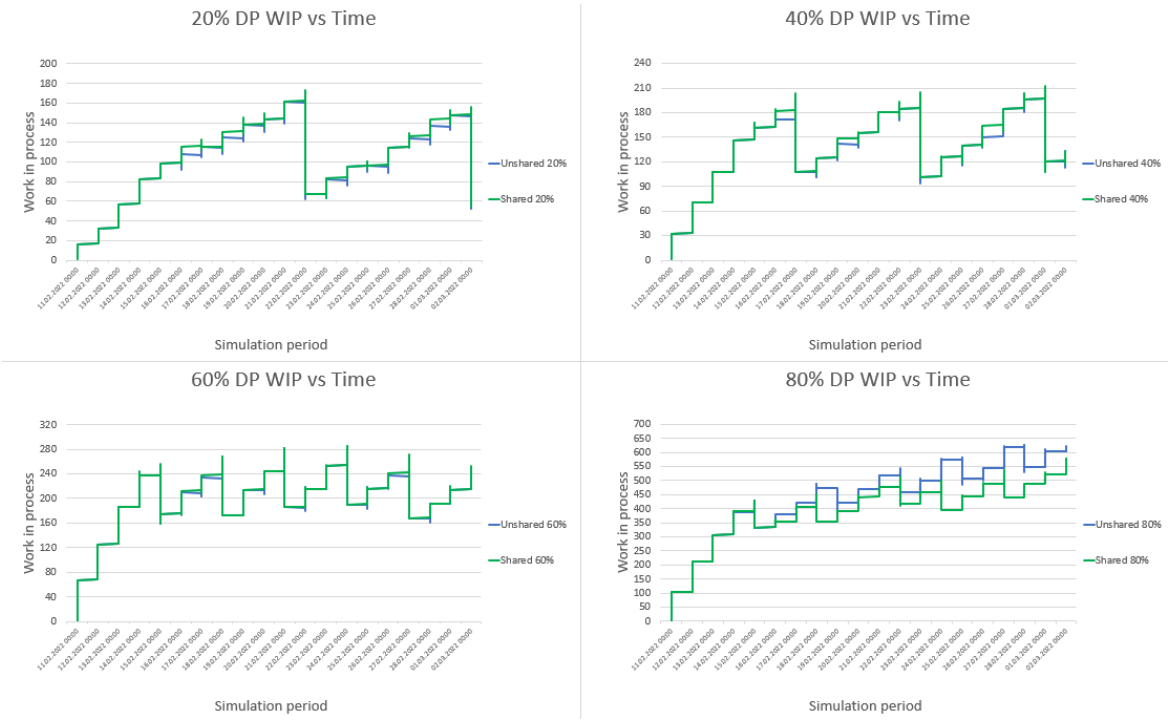

Figure 42: Work in process (Pathology)

Department of Medical Biochemistry

Throughput for PCR

Table 21: Throughput PCR (Medical Biochemistry)

% Distribution how many days before samples are finished				
PCR	Medical Biochemistry			
Throughput time / Demand	Not Shared		Shared	
20 %	1-9 days	X	1-6 days	✓
40 %	1-5 days	X	1-4 days	✓
60 %	1-3 days	X	1-2 days	✓
80 %	1-3 days	✓	1-4 days	X

Work in process

Figure 43: Work in process (Medical Biochemistry)

Pathology – One piece flow

Table 22: Throughput for Pathology when changing DNA preparation

% Distribution how many days before samples are finished												
DNA Isolation	Pathology											
Demand \ Days	Shared						Shared - One piece flow					
	1	2	3	4	5		1	2	3	4	5	
20 %	8 %	77 %	15 %	0 %	0 %	X	15 %	84 %	1 %	0 %	0 %	✓
40 %	19 %	78 %	4 %	0 %	0 %	X	27 %	73 %	0 %	0 %	0 %	✓
60 %	19 %	81 %	0 %	0 %	0 %	X	28 %	72 %	0 %	0 %	0 %	✓
80 %	3 %	39 %	49 %	9 %	0 %	✓	3 %	39 %	45 %	13 %	0 %	X