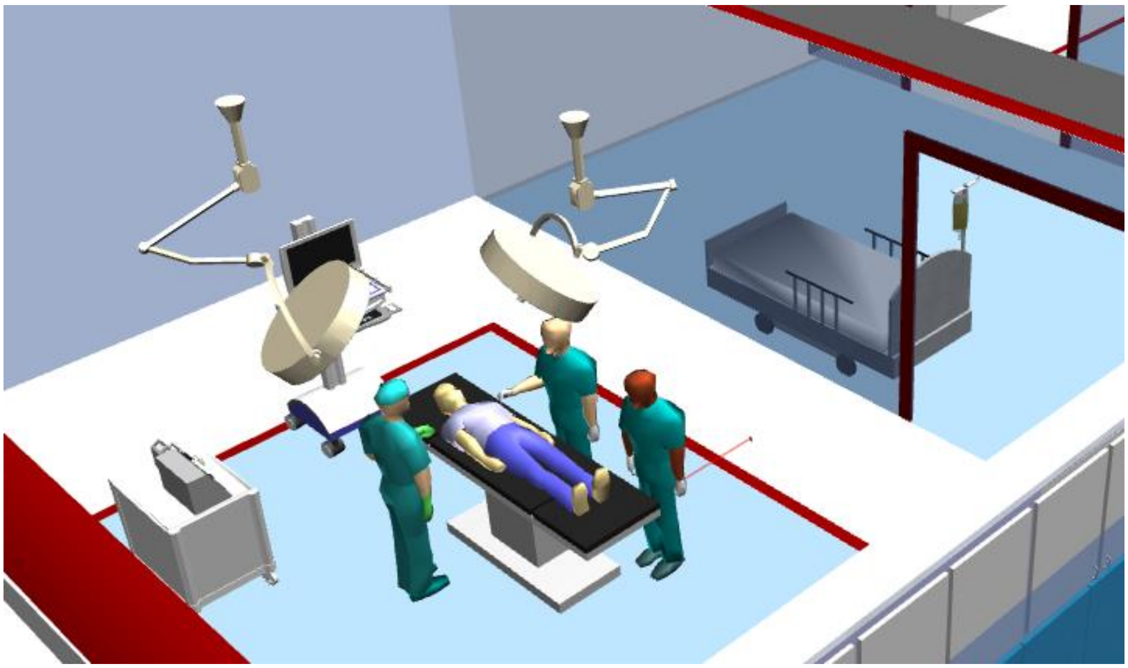
MASTER THESIS

OR OPTIMIZATION AT DR. HORACIO E. ODUBER HOSPITAAL



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Management Summary

Motivation & research goal

A couple of years ago, Dr. Horacio E. Oduber Hospitaal (HOH) at Aruba started project 'Hunto Miho', which means 'better together'. With this project HOH wants to realize their ambition to become one of the best hospitals in the region. A data analysis, which is part of this project, shows an operating room (OR) utilization rate of 69% (anesthesia time included, changeovers excluded), which OR management thinks is too low. Besides that, the analysis shows much overtime and many early ends. OR management thinks it is possible to increase the OR performance and wants to reconsider the current way of scheduling. Therefore, we analyze the current OR scheduling process, measure the current OR performance and design an alternative scheduling strategy.

We compose the following research goal:

> *Evaluate the current surgical scheduling process and design a scheduling strategy to improve the OR performance.*

Research method & results

First, we perform a context analysis to measure the performance of the current situation and define the KPIs, which we use for measuring the different scheduling strategies. Table 1 shows HOH's current performance. There is no data available to measure the current service degree of emergencies and access time of electives.

Table 1: Current performance of the KPIs

KPI	CURRENT PERFORMANCE
UTILIZATION	69%
OVERTIME	33,603 minutes
CANCELLATIONS	251
SERVICE DEGREE EMERGENCIES	N/A
ACCES TIME ELECTIVES	N/A

Then, we study the literature to find suitable interventions for the scheduling strategy. Besides two intervention possibilities based on the literature, we suggest two other suitable interventions. The following interventions are selected:

- Switching from a hybrid policy to a flexible policy: stop reserving capacity for emergency surgeries by using the emergency OR (Emergency OR).
- Using the request list consequently (Request List).
- Minimum booking rate for OR sessions (MBR).
- Implementing slack (Slack).

We create a simulation model and compose 140 experiments with different settings of the selected interventions. Table 2 shows the baseline setting of the simulation model.

Table 2: Setting of the baseline experiment

Setting	**Value**
Emergency OR	True
Request List	False
MBR	0%
Slack	0%

To measure the experiments and compare them with the baseline experiment, we assign weights to the KPIs in Table 3.

Table 3: Weights per KPI

KPI	**Weight**
Utilization	0.5
Overtime	0.1
Cancellations	0.2
Service Degree Emergency (SDE)	0.1
Average Access Time (AAT)	0.1

An analysis of the results of the experiments shows that the best performing experiments have the following characteristics:

- No emergency OR
- Request list
- A high minimum booking rate (50%)
- Some slack (5%-10%)

If HOH decides to keep the emergency OR, the request list and a high minimum booking rate still have a positive effect on the OR performance. Slack also has a positive effect. However, less slack is needed, i.e., 2.5%-5% instead of 5%-10%.

Table 4 shows the mutation on the KPIs of the best performing experiment opposed to the baseline experiment. The direction of the arrow indicates an increase or decrease of the KPI. The color indicates an improvement or deterioration of the KPI, i.e., green means improvement and red means deterioration.

Table 4: Mutation of KPIs best performing experiment opposed to the baseline experiment

KPI	**Decrease/increase**
Utilization	6.5%↑
Overtime	0.8%↑
Cancellations	19.7%↓
SDE	1↑
AAT	33.3%↓

Table 5 shows the individual effect of the input variables on the KPIs. We relate the effects on the KPIs to the booking rate. If the booking rate increases, the performance on utilization and AAT increase, and the performance on overtime, cancellations and SDE decrease.

Table 5: Input – output relations

Input/KPI	Utilization	Overtime	Cancellations	SDE	AAT
Emergency OR	--	++	+	++	--
Request List	+	-	0	0	++
MBR	++	-	-	-	++
Slack	--	++	++	+	--

According to results of the simulation study, HOH should close the emergency OR and implement slack in the OR schedule. Specialists should be convinced that their OR session time increases when the emergency OR closes and slack is implemented. A drawback of implementing slack is that OR employees could think they have more time for the same amount of surgeries. So, they need to be convinced that this extra time is meant for operating emergency patients.

HOH uses the request list not consequently, but should do this according to the results. We suggest that the task of rescheduling the patients via the request list is performed by the OR planner. For implementing minimal booking rate, we suggest an online application in which specialists can hand in their OR program. If specialists do not succeed in meeting the minimal booking rate or handing in their program in time, their session becomes available for other specialists to claim it. For implementing the request list and minimum booking rate, we propose to run pilots.

To realize the interventions, we suggested a step-by-step plan that contains the following main steps:

1. Create a roadmap together with the OR committee.
2. Involve specialists and OR personnel.
3. Develop the online application (MBR).
4. Evaluate the changes.

Further Research

Besides the simulation of scheduling interventions, we simulate perfect starts, fast changeovers and increased booking accuracy to see what the effect of these experiments is on the overall OR performance. The results show that these experiments have a significant positive impact on the OR performance. Therefore, we suggest HOH should perform further research on how to realize these experiments.

Furthermore, we show that the session roster is suboptimal and the booked time for changeovers are underestimated. We believe that further research in these areas could also help to improve HOH's OR performance.

Managementsamenvatting (Dutch)

Aanleiding & onderzoeksdoel

Een aantal jaar geleden begon Dr. Horacio E. Oduber Hospitaal (HOH) op Aruba met het project 'Hunto Miho', wat 'samen beter' betekent. Met dit project wil HOH de ambitie om een van de beste ziekenhuizen in de regio te worden, waarmaken. Een data-analyse, die onderdeel uitmaakt van dit project, laat zien dat de operatiekamer (OK) benutting 69% (inclusief anestesietijd, exclusief wissels) is, waarvan het OK management vindt dat dit te laag is. Daarnaast laat de data-analyse zien dat er veel overwerk en vroege eindes zijn. Het OK management denkt dat het mogelijk is om de OK prestatie te verbeteren en is daarom bereid een andere planningsstrategie te overwegen. Daarom analyseren wij in dit onderzoek het huidige planningsproces, meten we de huidige OK prestatie en ontwerpen een alternatieve planningsstrategie.

Het onderzoeksdoel:

Evalueren van de huidige OK-planningsproces en ontwerpen van een planningsstrategie om de OK-prestaties te verbeteren.

Onderzoeksmethode & resultaten

Als eerste doen we een analyse van de huidige situatie om de prestaties te meten met behulp van prestatie-indicatoren (KPI's). Deze KPI's zullen we later weer gebruiken om de verschillende planningstrategiën te beoordelen. Tabel 1 laat HOH's huidige prestaties zien. Er is geen data beschikbaar om de servicegraad van spoedpatienten en toegangstijd electieve patiënten te meten.

Tabel 1: Huidige prestaties van de KPI's

KPI	HUIDIGE PRESTATIE
BENUTTING	69%
OVERWERK	33.603 minuten
ANNULERINGEN	251
SERVICEGRAAD SPOEDPATIËNTEN	N/A
TOEGANGSTIJD ELECTIEVE PATIËNTEN	N/A

Daarna voeren we een literatuurstudie uit om geschikte interventiemogelijkheden voor de planningsstrategie te identificeren. Naast twee interventiemogelijkheden uit de literatuur, stellen we nog twee andere geschikte interventies voor. De volgende interventies zijn geselecteerd:

- Sluiten van de spoed OK (Spoed OK).
- Consequent gebruik maken van de aanvragenlijst (Aanvragenlijst).
- Minimale boekingsgraad voor OK sessies (MBG).
- Implementeren van slack (Slack).

We bouwen een simulatiemodel en stellen 140 experimenten op met verschillende zettings van de geselecteerde interventies. Tabel 2 laat de zettings van het basisexperiment zien.

Tabel 2: Zettings van het basisexperiment

Zetting	**Waarde**
Spoed OK	WAAR
Aanvragenlijst	ONWAAR
MBG	0%
Slack	0%

Om de experimenten te kunnen meten en vergelijken met het basisexperiment, geven we gewichten aan de KPI's in Tabel 3.

Tabel 3: Gewichten per KPI

KPI	**Gewicht**
Benutting	0,5
Overwerk	0,1
Annuleringen	0,2
Servicegraad spoedpatiënten (SGS)	0,1
Gemiddelde toegangstijd (GTT)	0,1

Na een analyse van de resultaten concluderen we dat de best presterende experimenten de volgende karakteristieken per interventiemogelijkheid tonen:

- Geen spoed OK
- Aanvragenlijst
- Een hoge mimimale boekingsgraad (50%)
- Een beetje slack (5%-10%)

Mocht HOH besluiten om de spoed OK te houden, hebben de aanvragenlijst en minimale boekingsgraad nog steeds een positief effect op de OK prestaties. Slack heeft ook een positief effect op de OK prestaties, maar minder slack is nodig, dat wil zeggen 2,5%-5% in plaats van 5%-10%.

Tabel 4 laat de mutaties van de KPIs van het best presterende experiment ten opzichte van het basisexperiment zien. De richting van de pijl geeft aan of het gaat om een toename of afname. De kleur geeft aan of het gaat om een verbetering (groen) of verslechtering (rood).

Tabel 4: Mutaties van de KPIs van het best presterende experiment t.o.v. het basisexperiment

KPI	**Toename/afname**
Benutting	6,5%↑
Overwerk	0,8%↑
Annuleringen	19,7%↓
SGS	1↑
GTT	33,3%↓

Tabel 5 laat het individuele effect van de input variabelen op de KPI's zien. De effecten op de KPI's zijn te herleiden naar de boekingsgraad. Als de boekingsgraad toeneemt, verbetert de benutting en GTT en verslechtert overwerk, annuleringen en SGS.

Tabel 5: Input – KPI relaties

Input/KPI	Benutting	Overwerk	Annuleringen	SGS	GTT
Spoed OK	--	++	+	++	--
Aanvragenlijst	+	-	0	0	++
MBG	++	-	-	-	++
Slack	--	++	++	+	--

Volgens de resultaten van de simulatiestudie moet HOH de spoed OK sluiten en slack implementeren in de OK-planning. Specialisten moeten worden overtuigd dat hiermee hun OK-sessietijd toeneemt. Een nadeel van het implementeren van slack kan zijn dat het OK-personeel denkt meer tijd te krijgen voor hun werkzaamheden. Dus moet aan hen worden uitgelegd dat deze tijd bedoeld is om spoedpatiënten te opereren.

HOH gebruikt al de aanvragenlijst, maar niet consequent en zou dit wel moeten doen volgens de resultaten. We stellen voor dat de OK-planner de taak van het herplannen van de patienten via de aanvragenlijst erbij krijgt. Voor het implementeren van de minimale boekingsgraad stellen we een online applicatie voor waarin specialisten hun OK-programma's kunnen indienen. Als specialisten niet de minimale boekingsgraad halen of niet op tijd hun programma indienen, komt hun sessie beschikbaar voor andere specialisten om te claimen. Voor het implementeren van de aanvragenlijst en minimale boekingsgraad stellen we voor om pilots te starten.

Om de interventies te realizeren, stellen we een stappenplan voor met de volgende hoofdstappen:

1. Roadmap maken met de OK-commissie.
2. Specialisten en OK-personeel betrekken.
3. Online applicatie ontwikkelen (MBG).
4. Veranderingen evalueren.

Vervolgonderzoek

Naast de simulatie van de interventiemogelijkheden voor de planningsstrategie, simuleren we perfecte starts, snellere wissels en verbeterde boekingsaccuratesse om te zien wat het gevolg hiervan op de OK-prestaties is. De resultaten laten zien dat al deze experimenten een positief effect op de OK-prestaties hebben. Daarom stellen we voor dat HOH hier verder onderzoek naar doet.

Daarnaast laten we zien dat het sessierooster suboptimaal is en dat de geboekte tijd voor de wissels onderschat wordt. We denken dat verder onderzoek naar deze twee gebieden HOH kan helpen bij het verbeteren van de OK-prestaties.

Preface

In front of you lies the result of my master thesis project at HOH. By finalizing this report, I conclude a chapter of my life. Almost seven years I have studied in Enschede at Universiteit Twente. A great period in which I have learned a lot, met a lot of great people and enjoyed great moments.

I want to thank HOH for giving me the opportunity to do my master thesis project at Aruba and providing me with an inside look in the hospital. A special thanks goes out to Stefan Lucas, Mark Veenendaal and Indra Paulina. Thanks to them, I learned a lot about what is going on behind the scenes of a hospital. Previously, an unfamiliar sector for me, but very interesting. Furthermore, a shout-out to Stefan Groenveld, my Aruba buddy. He arranged a lot of thinks for me at Aruba and showed me the country. Partly thanks to him, I have had a great time at Aruba.

I also thank my examination committee, Gréanne Leeftink and Erwin Hans, for their supervision and support. I have always experienced our meetings as pleasant. I would like to thank Jasper Buil for his feedback from Rhythm.

And last, but not least, I want to thank my parents for their unconditional mental and financial support.

Robert Andringa
Enschede, May 2018

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List of Abbreviations

AZV	Algemene Ziektekosten Verzekering
BIM	Break-In Moment
CSSD	Central Sterile Supply Department
ENT	Ear, Nose and Throat
FCFS	First Come First Serve
HOH	Dr. Horacio E. Oduber Hospitaal
ICU	Intensive Care Unit
KPI	Key Performance Indicator
LEPST	Longest Expected Processing with Setup Time
LEPT	Longest Expected Processing Time
MSE	Mean Square Error
MRSA	Methicillin-Resistant Staphylococcus Aureus, a bacterium
OR	Operating Room
PACU	Post Anesthesia Care Unit
SA	Simulated Annealing
SEPT	Shortest Expected Processing Time

Chapter One - Introduction

This chapter gives an introduction to this research. First, we give a short introduction about the hospital in Section 1.1. Section 1.2 gives the motivation for the research. After that, we compose the research goal and research question in Section 1.3. Finally, Section 1.4 formulates the scope of this research.

1.1. Research context: Dr. Horacio E. Oduber Hospitaal

Dr. Horacio E. Oduber Hospitaal (HOH) was founded in 1977 and is the only hospital on Aruba. The hospital has a capacity of six operating rooms (ORs), 288 beds and treats more than 10,000 inpatients annually. HOH offers all major medical specialties such as Gynecology, Urology, Internal medicine, General Surgery, and Cardiology (HOH, 2017).

1.2. Motivation for this research

A couple of years ago, HOH started project 'Hunto Miho', which means 'better together'. With this project HOH wants to realize their ambition to become one of the best hospitals in the region. Subsequently, Rhythm, a consultancy company for optimization in healthcare, performed a data analysis on the OR data of HOH. One of the problems that arose from this data analysis, is the low utilization of the ORs. The current utilization is between 71% and 75% (including anesthesia, excluding changeovers) for the clinical ORs and 49% for the outpatient OR. HOH's OR management finds this too low. Besides that, the analysis shows much overtime and many early ends. OR management thinks it is possible to increase the OR performance and wants to start a discussion within the hospital about the current way of scheduling. To help OR management in this discussion and provide some guidance, this research evaluates the current situation, measures its performance and designs an alternative scheduling strategy for elective surgeries.

1.3. Research goal & research questions

In response to the motivation in Section 1.2, we define the following research goal.

Research goal:

> *Evaluate the current surgical scheduling process and design a scheduling strategy to improve the OR performance.*

To accomplish this goal the following research questions need to be answered. We shortly elaborate on the path that should be taken to get an answer on each question and discuss the chapter in which the question is answered.

1. *What is the current OR planning process for elective and emergency surgeries, and what resources are used?*

To understand the current scheduling strategy for elective surgeries, we map the whole planning process. We do this for both elective and emergency surgeries. Much information about the planning process is already gathered by Groenveld (2018). Employees of several departments who are involved in the planning process are questioned, e.g., the OR planner, the OR manager, and employees of the Admissions Department. Missing information is gathered by questioning the involved parties again. Furthermore, we map the resources used for performing surgeries. We give information about the performing specialties, ORs, OR capacity, etc. This question is answered in Chapter 2.

2. *What is the OR performance of the current scheduling strategy?*

Before any recommendations are done to improve the OR performance, we need to define and measure the performance of the current situation. In Chapter 2, we measure the performance with the help of the available data, which are stored in Excel files. Amongst others, these files contain: type of surgery, duration, specialism, day, begin and end time per performed surgery over the period January 2016 up to and including June 2017. The dataset together with the data analysis performed by Rhythm is the basis of the measurement of the current OR performance.

3. *What are suitable scheduling strategies for elective and emergency surgeries for HOH?*

Much literature exists about scheduling surgeries and many papers propose a scheduling algorithm to increase OR performance. However, not all papers and algorithms are suitable for HOH, since every hospital has its own particular characteristics, size and case mix of surgeries. We gather the necessary literature by using the snowball effect. The literature research starts with reading three review papers. Then, we use backward and forward search on citations to explore other useful papers. Furthermore, we use Google Scholar and Scopus to expand the selection. We use keywords such as ‘operating room’, ‘scheduling’, ‘planning’, ‘elective surgeries’, ‘scheduling algorithms’ or a combination of these. Chapter 3 answers this question.

4. *What is the effect on OR performance for the suggested scheduling strategies?*

In Chapter 4, we create a simulation model with the help of Siemens Tecnomatix Plant Simulation. Since the environment of an OR is very complex, it is very hard to develop mathematical models to calculate the performance of a scheduling strategy. Furthermore, simulation is a powerful tool to make the problem and its possible solutions visual, which can be helpful to convince people. First, the current situation is simulated. With help of the historical data, we calculate the arrival intensity and surgery duration of each surgery. Then, we validate the simulation results of the model of the current situation. The results from the simulation need to match the current performance, derived from the second research question. Next, we implement the scheduling strategies that are identified in the third research question in the simulation model. Finally, we perform experiments to measure the effect of the suggested strategies. We analyze the results of the experiments in Chapter 5.

5. How should HOH apply the best performing scheduling strategies in practice?

For HOH it is very important that this research results in a feasible solution. So, implementation of the best performing scheduling strategy is as important as finding a scheduling strategy which improves OR performance. Therefore, recommendations together with an implementation plan are formulated in Chapter 6.

1.4. Scope

1.4.1. Operating rooms and specialties

The scope of this research includes elective and emergency surgeries that take place on all six ORs. The research focuses on surgeries of the following specialties: general surgery, ophthalmology, orthopedics, urology, neurosurgery, ENT, pain treatment, gynecology, plastic surgery and cardiology. The dataset also contains surgeries from the specialties anesthesiology, pulmonology, internal medicine, radiology and oral surgery. However, the number of surgeries of these specialties is less than twenty per specialty in one and a half year and therefore excluded.

1.4.2. Materials, personnel, ward beds, pre-operative screening

Excluded from the scope of this research are operating materials, personnel, ward beds, and pre-operative screening (POS). We assume that these are not a limitation for operating a patient and are therefore not included in the simulation model. In reality surgeries could be canceled due to a shortage of one of the above mentioned. We include these shortages explicitly in the cancellation rate, but not as a specific parameter in the model.

1.4.3. Cancellations

Within the cancellations we identify two sub groups: cancellations with a planning cause and without a planning cause. Within the first group there are cancellations that depend on the scheduling strategy. Some examples of these are: ‘overrun program’, ‘program change’, and ‘intervention emergency surgery’. The second group are external factors, and do not depend on the scheduling strategy. Some examples of this group are: ‘patient did not attend’, ‘operating materials not in stock’, and ‘hurricane’. We include this group as parameter in the simulation model.

Chapter Two – Context Analysis

This chapter describes the current situation with regard to the OR planning process within HOH. First, we show in Section 2.1 a theoretical framework of different managerial levels within healthcare. With the help of this framework, we answer the first research question on the different managerial levels: strategic, tactical, offline operational and online operational in Section 2.2, Section 2.3, Section 2.4 and Section 2.5 respectively. Section 2.6 gives the data and definitions which we need for measuring the OR performance. Section 2.7 discusses HOH's demand for and supply of care. In Section 2.8 we define the KPIs, before we measure the current OR performance in Section 2.9, which therefore gives an answer to the second research question. Finally, we summarize this chapter in Section 2.10.

Let us recapitulate the first and second research questions:

1. *What is the current OR planning process for elective and emergency surgeries, and what resources are used?*
2. *What is the OR performance of the current scheduling strategy?*

In this chapter we make use of 'Optimalisatie OK-planning' (Groenveld, 2018) and 'Situatieanalyse OK-planning' (Karis & Huizingh, 2015) for answering the first research question.

2.1. Healthcare planning & control framework

This section discusses the healthcare planning and control framework of Hans, Van Houdenhoven & Hulshof (2012) (see Figure 2.1). We use this framework as a tool to map the planning and control decisions regarding the OR planning within HOH.

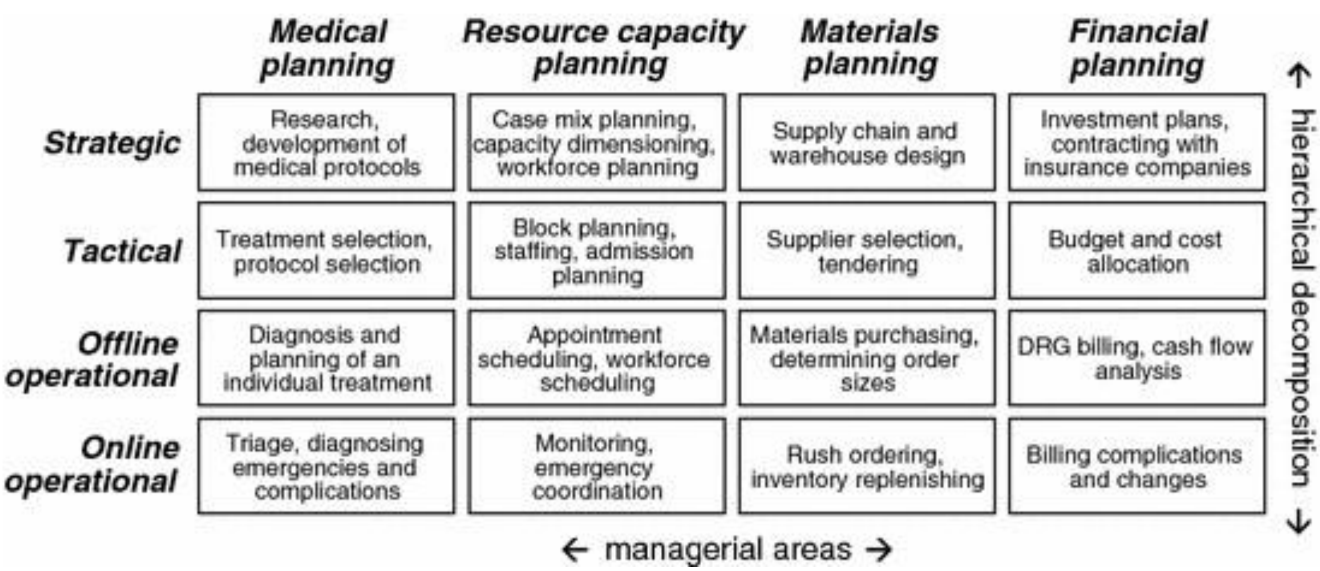


Figure 2.1: Healthcare planning & control framework (Hans et al., 2012)

The healthcare planning and control framework consists of four different hierarchical levels, which we explain shortly.

- **Strategic decisions** are long term, structural decisions. Applied on OR planning, a strategic decision can be renovating the OR complex to increase capacity. The planning horizon for this type of decisions is usually years.
- **Tactical decisions** are medium-long term decisions. Regarding OR planning a decision of this hierarchical level is the allocation of the OR capacity to specialisms. The planning horizon for this type of decisions is usually months.
- **Offline operational decisions** are short term decisions. For example, scheduling elective patients. The planning horizon for this type of decisions is usually days or weeks.
- **Online operational decisions** are decisions that are made to monitor the process. An example of such a decision is intervening the elective OR program when an emergency patient needs to undergo surgery. There is no planning horizon for this type of decisions, because the moment when an online operational decision is needed, is unknown.

Besides the hierarchical levels, the framework has four managerial areas.

- **Medical planning decisions** are decisions about medical protocols, treatments and diagnoses.
- **Resource capacity planning decisions** are decisions about planning, scheduling and monitoring resources like ORs, personnel and ward beds.
- **Materials planning decisions** are decisions about storing and distributing materials.
- **Financial planning decisions** are decisions about budgeting and controlling financial flows.

We discuss resource capacity planning on different hierarchical levels in the upcoming four sections. The other three managerial areas are not discussed, since these are not within the scope of this research.

2.2. Strategic level

This section describes the planning and control decisions concerning the strategic level. We discuss the case mix profile, production agreements, OR capacity, specialties, OR personnel, the OR committee and capacity of downstream resources.

2.2.1. Case mix profile

Since HOH is the only hospital on Aruba, it has to treat (almost) all patients on the island. Data from 2013 shows that HOH treats around 11,000 patients on a yearly basis. The proportion elective/emergency is 75.6%/24.4% (obstetric and pediatrics care excluded) and 37.3% of these patients need to undergo surgery (Kamphorst, Kortbeek, Lucas & Van der Sloot, 2015). In Section 2.7 we discuss HOH's case mix profile with help of the available data in more detail.

2.2.2. Production agreements

Algemene Ziektekosten Verzekering (AZV) makes agreements with HOH and the independent medical specialists individually about their budget and yearly amount of treatments. Every performed treatment needs to be declared at AZV by HOH or independent specialist until the budget is reached. After the budget is reached, HOH and specialists are not paid for the performed treatments. Currently, there is no coordination between demand, budget agreements and OR capacity allocation.

2.2.3. ORs and OR capacity

HOH has six ORs (see Figure 2.2 for a plan view of the OR complex). OR3 is the only OR with a cleanout drain and therefore urology surgeons prefer to operate in this OR. OR5 is the most advanced OR, because it has a high quality laminar air flow, and therefore most orthopedic surgeries take place in this OR. OR6 is an outpatient OR, thus most small elective surgeries take place in this OR.

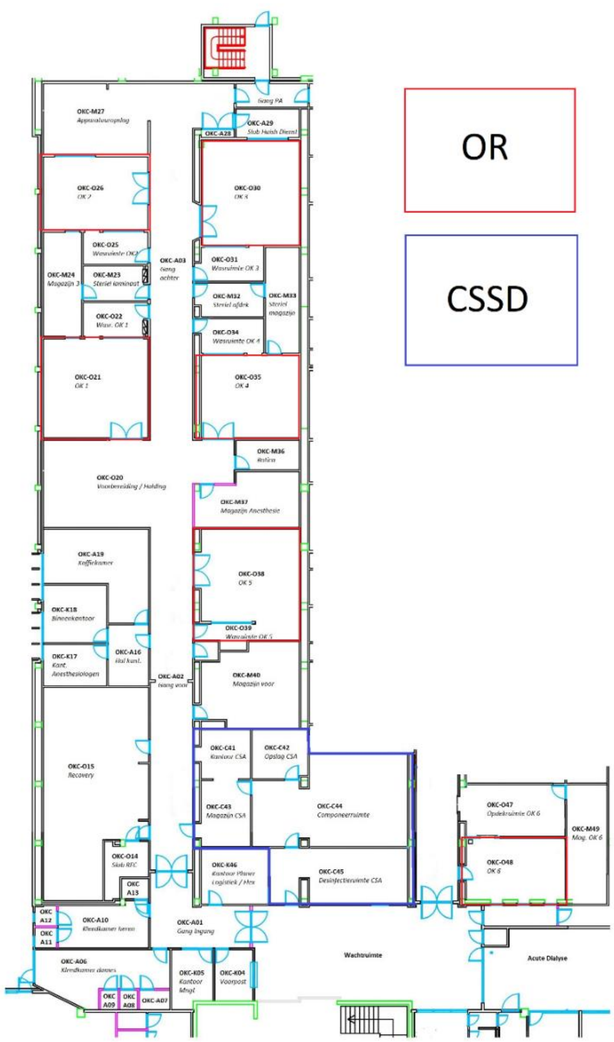


Figure 2.2: OR complex HOH

During an OR day, personnel and performing specialists need to be present at 7:00, so that the first surgery can start at 7:30, which is the beginning of the OR session. The OR session ends at 14:30, so the last surgery should be finished before that. A working day for the personnel (OR day) ends at 15:00, so they have time to finish some activities and change clothes. Between the surgeries personnel has the right to have two lunchbreaks of 15 minutes. The OR team decides when these lunchbreaks takes place. Sometimes there are two sessions on one OR day. Then, the OR day is split up between a morning and an afternoon session. The morning session ends at 11:00 and the afternoon session starts at 11:00, so that both sessions have 210 minutes. Concluding, an OR day has a capacity of 420 minutes minus the lunchbreak, so 390 minutes. Table 2.1 shows a summary.

Table 2.1: OR capacity

Period	***From***	***To***	***Total (minutes)***
OR day	7:00	15:00	480
OR session	7:30	14:30	420
Morning session	7:30	11:00	210
Lunchbreak	Between surgeries		30
Afternoon session	11:00	14:30	210
OR capacity			**420-30 = 390**

2.2.4. Specialties and specialists

The specialties below make use of the OR capacity. Per specialty the number of specialists is indicated between the brackets. Most specialists are independent, four gynecologists and two urologists are in pay of HOH.

- General surgery (6)
- Neurosurgery (1)
- Cardiology (2)
- Gynecology (5)
- Plastic surgery (2)
- ENT (2)
- Orthopedics (4)
- Urology (3)
- Ophthalmology (3)
- Pain treatment (performed by a neurologist, see OR personnel)

2.2.5. OR personnel

Below a summary of the OR personnel is shown, all in pay of HOH. Per job the number of employees is indicated between the brackets.

- Surgery assistants (33)
- Anesthetists (5)
- Anesthesia assistants (11)
- Secretariat (4)

- Central Sterile Supply Department (CSSD) (9)
- Recovery (4)
- OR management (2)

2.2.6. OR Committee

HOH has an OR committee to make decisions of different hierarchical levels concerning the OR complex. The OR committee represents all stakeholders of the OR. The goal of this committee is to treasure the quality and quantity of the services within the OR complex. An example of a decision taken by the OR committee can be changing the starting and ending time of the OR day. The committee organizes an assembly every month and has the following members:

- Cluster Manager
- OR Manager
- OR Manager Assistant
- Orthopedic Surgeon
- General Surgeon
- Plastic Surgeon
- Anesthetist
- Anesthesia Assistant

2.2.7. Capacity ward beds

HOH has a total of 288 ward beds, divided over amongst others: three surgical departments, three non-surgical departments, pediatrics department, obstetrics department and psychiatric department. There are eight beds in the recovery department and ten in the intensive care unit (ICU). HOH does not have a post anesthesia care unit (PACU).

2.3. Tactical level

This section discusses the tactical decisions with respect to the OR planning. First, we discuss the OR session roster and how OR capacity is allocated to the specialties. Then, we explain how HOH deals with emergency surgeries inside and outside the OR day. Finally, we elaborate on how OR personnel are staffed.

2.3.1. OR session roster

Every year the foundation of the OR session roster is made, which is based on the session roster of the previous year. Every specialist has one fixed session per week, with a few exceptions, such as the Neurosurgical surgeon who has one extra session every two weeks. Furthermore, there are some 'flex' sessions in the roster. These sessions are not dedicated to a specialist, which means multiple specialists can make use of the same session. When a specialist wants to operate a patient outside his/her regular OR session, he/she can send a request to the OR planner to operate in a flex session. When a specialist is absent during his/her session, e.g., because he/she is attending a congress, the specialists' session becomes a flex session. Sometimes a flex session is assigned to a specialist, when the number of patients of this specialist on the request list is long enough to fill an entire OR session. The request list is also used for rescheduling cancelled patients in sessions of other specialists, which we discuss in Section 2.5. Figure 2.3 shows an example of the OR session roster.

OKTOBER 2017							
Week 40		OK 1	OK 2	OK 3	OK 4	OK 5	OK 6
Maandag	7:30-11:00	PONA	HOKF	CUBJ	TROR	KUIKD	MOSV
2/10/2017	11:00-14:30	SPOED	HOKF	CUBJ	TROR	KUIKD	MOSV
Dinsdag	7:30-11:00	PETT	CABS	PETJ	RILA	WINF	LACS
3/10/2017	11:00-14:30	SPOED	CABS	PETJ	RILA	WINF	LACS
Woensdag	7:30-11:00	LACG	GYN HOH	URO HOH	CASY	HAIP	JACB
4/10/2017	11:00-14:30	SPOED	GYN HOH	URO HOH	CASY	HAIP	JACB
Donderdag	7:30-11:00	GYN HOH	KNO	CUBJ	NIEH	SORL	SLAG
5/10/2017	11:00-14:30	SPOED	KNO	CUBJ	NIEH	SORL	SLAG
Vrijdag	7:30-11:00	flex	GYN HOH	PIJN	WILY	LACG	RILA
6/10/2017	11:00-14:30	SPOED	GYN HOH	PIJN	WILY	LACG	PONA
OKTOBER 2017							
Week 41		OK 1	OK 2	OK 3	OK 4	OK 5	OK 6
Maandag	7:30-11:00	PONA	HOKF	CUBJ	TROR	KUIKD	MOSV
9/10/2017	11:00-14:30	PONA	SPOED	CUBJ	TROR	KUIKD	MOSV
Dinsdag	7:30-11:00	PETT	CABS	PETJ	RILA	WINF	LACS
10/10/2017	11:00-14:30	PETT	SPOED	PETJ	RILA	WINF	LACS
Woensdag	7:30-11:00	LACG	GYN HOH	URO HOH	CASY	HAIP	JACB
11/10/2017	11:00-14:30	LACG	SPOED	URO HOH	CASY	HAIP	JACB
Donderdag	7:30-11:00	GYN HOH	RAVR	DARD	NIEH	CARDIO	SLAG
12/10/2017	11:00-14:30	GYN HOH	SPOED	DARD	NIEH	CARDIO	SLAG
Vrijdag	7:30-11:00	flex	GYN HOH	PIJN	flex	SORL	PETT
13/10/2017	11:00-14:30	flex	SPOED	PIJN	flex	SORL	CASY
OKTOBER 2017							
Week 42		OK 1	OK 2	OK 3	OK 4	OK 5	OK 6
Maandag	7:30-11:00	PONA	HOKF	CUBJ	TROR	KUIKD	MOSV
16/10/2017	11:00-14:30	PONA	HOKF	SPOED	TROR	KUIKD	MOSV
Dinsdag	7:30-11:00	PETT	CABS	PETJ	RILA	WINF	LACS
17/10/2017	11:00-14:30	PETT	CABS	SPOED	RILA	WINF	LACS
Woensdag	7:30-11:00	LACG	GYN HOH	URO HOH	CASY	HAIP	JACB
18/10/2017	11:00-14:30	LACG	GYN HOH	SPOED	CASY	HAIP	JACB
Donderdag	7:30-11:00	GYN HOH	KNO: CI	DARD	NIEH	SORL	SLAG
19/10/2017	11:00-14:30	GYN HOH	KNO: CI	SPOED	NIEH	SORL	SLAG
Vrijdag	7:30-11:00	LACG	GYN HOH	PIJN	CASY	WINF	RILA
20/10/2017	11:00-14:30	LACG	GYN HOH	SPOED	CASY	WINF	PONA

Figure 2.3: OR session roster

2.3.2. Capacity for emergency surgeries

Until June 2016, there was no OR capacity reserved for emergency surgeries. When an emergency patient arrived, he elective program needed to be intervened, if the emergency surgery was very urgent, or the surgery took place after the OR day, if the surgery was less urgent. On the 4th of July 2016, HOH introduced the emergency OR. Every afternoon, between 11:00 and 14:30, there are no elective surgeries planned on one of the clinical ORs, so that this capacity can be used for emergency surgeries. This OR is the emergency OR for the whole week, after which another OR becomes the emergency OR for the following week (see Figure 2.3). When the emergency OR is not available before 11:00 or the emergency OR is occupied, the elective program still needs to be intervened for very urgent emergency surgeries.

2.3.3. Personnel staffing

A standard OR team consists of the following people:

- Surgeon (1)
- Anesthetist (1)
- Surgery assistant (3)
- Anesthesia assistant (1)

The anesthetist is only present in the OR when anesthesia is performed and can have multiple ORs under his control. Exceptions for a standard OR team are: neurosurgery, which has two surgery assistants instead of three, outpatient surgeries (OR6), which also have two surgery assistants and no anesthetist, and orthopedics, which has four surgery assistants instead of three.

After 15:00 there is a team, with the same composition as a standard OR team, for finishing the elective surgeries that overrun and for taking care of all emergency surgeries after 15:00. This team can go home when the last surgery is finished. However, the team needs to be available until 7:00 for emergency surgeries after it went home. Besides this team, that is 'on call', there is a backup team for handling peak moments between 15:00 and 7:00.

2.4. Offline operational level

In this section, we describe the offline planning process of the elective surgeries. This process starts when a specialist decides that a patient should undergo surgery and ends when the specialist performs the surgery. Figure 2.4 shows a schematic view of this process. There are some differences between the planning rules formulated by the OR committee and practice, which are indicated in the flowchart with asterisks. After we describe the planning process, we elaborate on these differences.

2.4.1. Three months up to 72 hours before OR day

The planning process for elective surgeries starts when the specialist decides that a patient needs to undergo surgery after a visit in the outpatient clinic. The patient gets an indication for the date of surgery and is send to the department POS. All elective patients need to be screened before they can get surgery. The screening is normally three months valid, so the patient needs to make an appointment with POS for a screening at most three months before the day of surgery. During the screening, POS checks if the patient is healthy enough for anesthesia.

If the screening is okay, POS sends the patient to department Admissions where an FIN number is created and the patient is registered in Chipsoft. Chipsoft is the software program that HOH uses for scheduling surgeries. An FIN number is linked with an MRN (patient) number and unique for every hospitalization. So, a patient has one MRN number, but can have multiple FIN numbers if he/she has been hospitalized multiple times for multiple surgeries. If the screening is not okay, POS consults the specialist to see what needs to be done, so that the surgery can go on.

2.4.2. 72 up to 24 hours before OR day

The specialist needs to hand in a list of patients he/she wants to operate three working days (72 hours) before the day of surgery (OR day) at the OR planner. So, if the OR day is on Thursday, the specialist needs to hand in his/her patient list before Monday 7:00. In practice, not all specialists hand in their patient list in time. The OR planner requests the patient list at the specialist if he/she did not send it. When the OR planner received all lists, she picks up the patient cards at Admissions, checks them for completeness and adds missing information. Also, the OR planner checks if enough surgery instruments are available to perform the surgeries. If FIN numbers from the patients are missing, these are requested by the OR planner at department Admissions.

When all information is gathered, the OR planner calculates the length of the OR program with help of Chipsoft. The expected duration of a surgery is calculated by taking the average of the last 25 surgery of the same surgery type of the performing surgeon, outliers excluded. Every surgery has its own code in Chipsoft. The length of the program, including changeover times, should not exceed 390 minutes to prevent overtime. The planned changeover time is 9 minutes per changeover for all surgeries, except for the surgeries that take place on OR6 and surgeries that are performed by one ENT specialist. The booked time for these changeovers are 6 minutes. If the program is too long, the OR planner asks the specialist which patient(s) should be removed from the schedule and operated on another day. If there is some space left in the program for more surgeries, the OR planner asks the specialist what to do with this capacity. There are no constraints for the minimum length of the program, e.g., if there is one short surgery in the program, the session is not cancelled.

When the length of the program is okay, the OR planner sends the tentative program to all specialists in question and department Admissions. The deadline for sending the tentative program is 12:00 two working days before the OR day. So, if the OR day is on Thursday, the tentative program should be send before Tuesday, 12:00. However, in practice this deadline is not always met.

For the sequence of the OR program the OR planner reckons with the following guidelines. The following surgeries are scheduled first, in order of priority: child patients, pregnant patients, patients with a metabolic disorder and surgeries with the longest expected duration. Last surgeries to schedule are MRSA patients and patients under local anesthesia.

2.4.3. 24 hours before OR day (hospitalization day)

On the day preceding the OR day, hospitalization day, at 9:15, bed consultation takes place at the nursing department with the care managers of the nursing departments, the Hospitalization & Discharge Coordinator and an employee of Admissions. During this consultation, the attendees discuss which patients are discharged, so they know which beds are released. The employee of department Admissions informs which patients are going to be hospitalized. So, they check if there are enough beds available to hospitalize all patients on the OR program. If this is not the case, feedback is given to the OR planner, who informs the specialists. The specialists see if there are any patients that can be discharged. All specialties have a number of ward beds in the nursing departments and the Hospitalization & Discharge Coordinator ensures that patients lie on beds of the corresponding specialty. Emergency patients are an exception, they are put on a bed of another specialty if there are no beds available of the corresponding specialty. If there are still too few beds available after the specialist has checked if there are patients that can be discharged, the specialist informs the OR planner which patient should be removed from the OR program. These patients are called by department Admissions that their surgery is canceled.

After that, Admissions calls the clinical patients to inform them about their hospitalization, which takes place between 9:30 and 10:00. Admission strives to call these patients before 10:00 since these patients need to be hospitalized at 12:00. Then, the patients for day surgery are called. According to the OR regulations, the patients for day surgery need to be called at 14:00, two working days before the OR day. However, this is not possible when the tentative OR program is available only 24 hours before the OR day. If patients cancel their surgery, Admissions reports this to the OR planner, so she can inform the specialists. The specialist and OR planner try to schedule other patients instead of the canceled patients if they receive the cancellations in time. After the schedule is adjusted, the OR planner sends the final program to the specialists, Admissions and nursing department at 12:00 the day before the OR day.

2.4.4. OR day

During the OR day, the specialists perform surgery on the patients that are scheduled on the OR program. Information about the surgery such as timestamps of patient entering and leaving the OR and surgery duration are stored in Chipsoft.

2.4.5. Differences OR regulations and practice

The asterisks in the flowchart indicate there is a difference between the OR regulations and practice. There are four differences identified, which are explained below.

* The deadline for specialists to hand in their patient lists to the OR planner, three working days before the OR day, is not always met.

** It is the specialists' responsibility to hand in their patient lists in time. When they do not do this, the specialists are not allowed to perform surgery on the OR day according to planning rules formulated by OR management. The reason for this rule is to make sure that specialists hand in their patient list in time. However, the OR planners are good-hearted towards the specialists and request the patient lists at the specialists if they did not send their patient lists. The OR planners are not supposed to do this, but it happens much in practice. Also, specialists communicate changes in their patient lists often after the deadline.

*** The deadline for sending the tentative program is 12:00, two working days (43 hours) before the OR day. This deadline is not always met.

**** Patients for day surgery should be called after the tentative program is known, 14:00, two working days (41 hours) before the OR day. In practice, the tentative program is often available one day before the OR day, through which these patients can be called after the clinical patients are called, since clinical patients get priority.

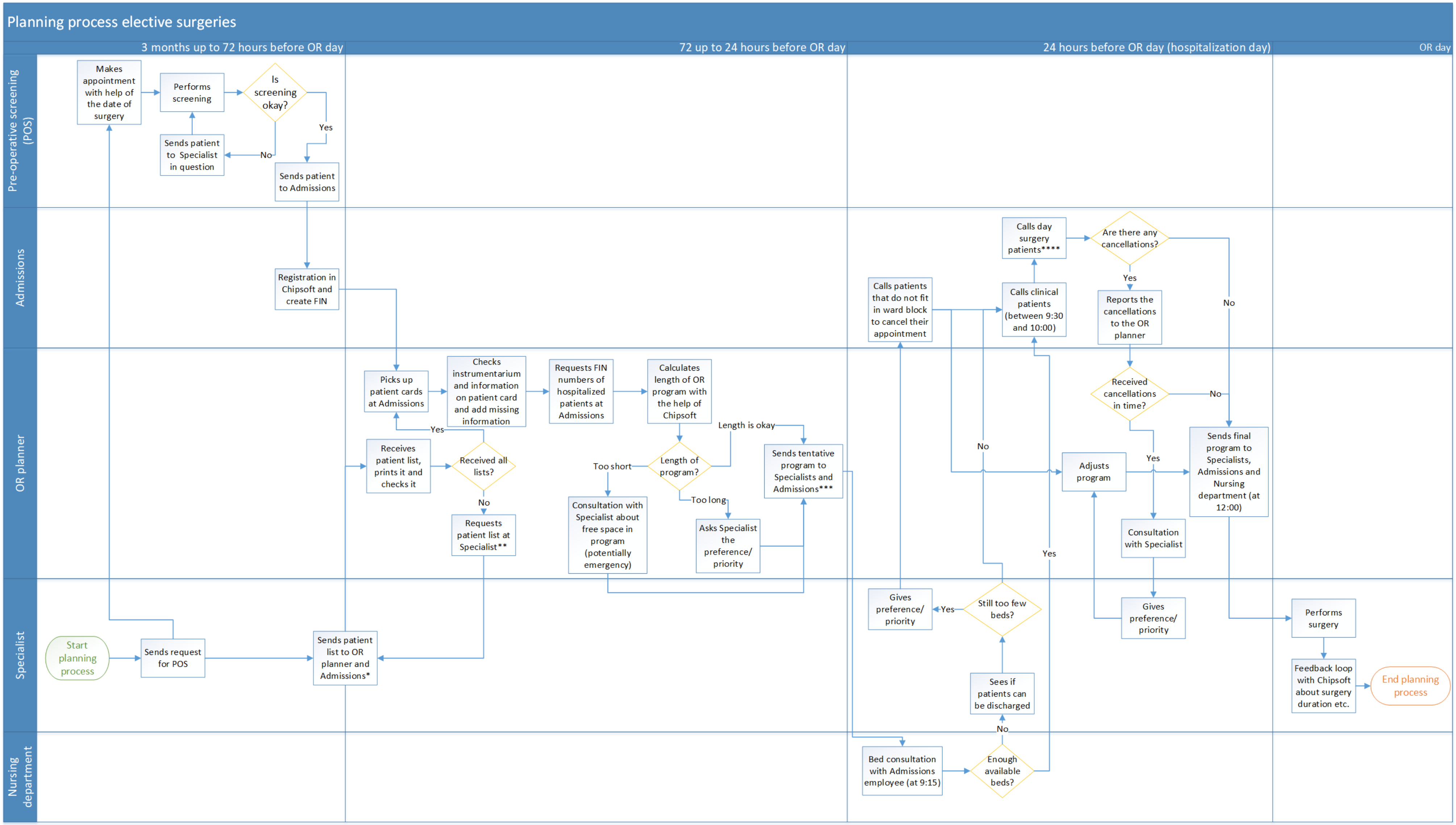


Figure 2.4: Flowchart planning process

2.5. Online operational level

Online operational decisions are decisions for monitoring the process and reacting to unforeseen events (Hans et al., 2012). HOH makes these decisions when a certain event occurs. For example, an emergency surgery can be scheduled at the moment the specialist makes the decision an emergency patient needs to undergo surgery. Before that moment, HOH did not know an emergency patient needed to be scheduled. Therefore, we discuss emergency surgeries in this section. Furthermore, cancellations are events that require online operational decisions, so we elaborate on these as well.

2.5.1. Emergency surgeries

HOH makes two subgroups in types of emergency. The first group consists of all emergency cases that are performed inside the OR day, so between 7:00 and 15:00 and are called 'emergency in OR day' ('spoed'). The second group contain all emergency cases that are performed outside the OR day, weekend days and holidays included. These group of emergency cases are called 'emergency in shift' ('spoed in dienst'). Most of the 'emergency in shift' cases take place on OR1 and OR5 since these ORs are the largest and close to the entrance, so easy to enter.

HOH has four different priorities concerning emergency surgeries:

- Urgency A: life-threatening – surgery should start right away, with a maximum waiting time of two hours.
- Urgency B: threatening irreversible condition – surgery should start within two to six hours.
- Urgency C: condition for which delaying the surgery can cause function damage – surgery should start within 24 hours.
- Urgency D: surgery should start within 72 hours.

Emergencies during the OR day lead to interventions in the elective program, which can cause delay, cancellations of elective surgeries or overtime. Since July HOH has an emergency OR during the afternoon session (see Section 2.3) to prevent interventions in the elective program.

2.5.2. Cancellations

In Section 2.4, we already mentioned the cancellations that appear when Admissions calls the patient. These cancellations are known before the program is definitive. But, there are also cancellations that occur during the OR day. For instance, when a patient does not show up for hospitalization, or a patient is not sober. In that case, there is OR capacity reserved for the surgery, but cannot be used for that surgery. Maybe a surgery that was initially scheduled after the cancelled surgery could be performed earlier, so that the OR session finishes early that day. But if this cannot be arranged, there is a gap in the schedule. A surgery could also be cancelled when the program overran and the start of the surgery would be after 14:30. In that case, the specialist can put the patient on the request list and the OR planner tries to find an empty spot in another specialist's session to operate the patient. However, the usage of the request list is not mandatory, it is up to the specialist if he/she wants to use this possibility. We give an overview of the causes for cancellations in Section 2.9.

2.6. OR data and definitions

In this section, we give the definitions, composed by Rhythm, we use to measure the OR performance in Section 2.9. Also, we elaborate on the used data and adjustments we make in this data.

2.6.1. Definitions

OR day: from 7:00 to 15:00 on working days.

OR session: from 7:30 to 14:30 on working days.

Morning session: 7:30 to 11:00 on working days.

Afternoon session: 11:00 to 14:30 on working days.

Session time: 420 minutes.

OR capacity: 390 minutes.

Surgery duration: time between a patient enters and leaves the OR, i.e., the time needed to operate a patient, including anesthesia time.

Changeover time: time between two surgeries in an OR session.

Utilization: total surgery duration during OR session / session time. Note that utilization includes anesthesia time, but changeover time is excluded.

Emergency in OR day: emergency surgery that starts inside the OR day (between 7:00 and 15:00).

Emergency in shift: emergency surgery that starts outside the OR day.

First surgery of the OR session: the first elective surgery or 'emergency in OR day' during an OR session.

Last surgery of the OR session: the last elective surgery or 'emergency in OR day' during an OR session.

Very early start: start of the first surgery of the OR session before 6:30 (one hour before the start of the OR session).

Modestly early start: start of the first surgery of the OR session between 6:30 and 7:15 (between one hour and a quarter before the start of the OR session).

Start in time: start of the first surgery of the OR session between 7:15 and 7:45 (between a quarter before and after the start of the OR session).

Modestly late start: start of the first surgery of the OR session between 7:45 and 8:30 (between a quarter and one hour after the start of the OR session).

Very late start: start of the first surgery of the OR session after 8:30 (one hour after the start of the OR session).

Very early end: end of the last surgery of the OR session before 13:30 (one hour before the start of the OR session).

Modestly early end: end of the last surgery of the OR session between 13:30 and 14:15 (between one hour and a quarter before the end of the OR session).

End in time: end of the last surgery of the OR session between 14:15 and 14:45 (between a quarter before and after the end of the OR session).

Modestly late end: end of the last surgery of the OR session between 14:45 and 15:30 (between a quarter and one hour after the end of the OR session).

Very late end: end of the last surgery of the OR session after 15:30 (one hour after the end of the OR session).

2.6.2. Data

To measure the current OR performance, we use HOH's OR data from the 1st of January, 2016 until the 30th of June, 2017. This dataset contains 15,604 data entries about performed surgeries, of which 13,481 took place in an OR. 21 entries are missing data about the start and end time of the surgery and therefore removed from the dataset. Some data entries have overlapping regarding the surgery times, i.e., the start time of a surgery is before the end time of the preceding surgery in the same OR. We only take a look at the overlapping surgeries that take place between 7:00 and 15:00, since these are of influence on the utilization inside an OR day. Table 2.2 shows the overlapping surgeries per OR. Most of the overlapping entries are solved by changing the end time of the first surgery into the start time of the second surgery. In this way, every adjustment solves two entries. However, by applying this method, we assume that there is no changeover time between the two surgeries. Two entries are moved to a different OR, because the performing specialist was performing more surgeries in the same session in that OR. Three entries are removed from the dataset since the total overlap of these entries is equal to the total surgery duration, i.e., the second surgery starts later than the first surgery, but ends first. We do not adjust the overlapping entries of OR6, since this OR has much more overlapping entries than the other ORs and the surgery duration of most of these surgeries are a few minutes. We accept that the data of OR6 is not fully clean. Table 2.2 shows a summary of all adjustments of the overlapping entries. Furthermore, there is an elective surgery that was performed in the middle of the night and an elective surgery that was performed in the weekend. We change the type of these two surgeries from 'elective' to 'other'. From the original dataset 13,457 entries remain.

Table 2.2: Data adjustments overlapping entries (n=13,457, OR system HOH, 2016-2017)

OR	Overlap surgery times	Adjustments
OR1	26 surgeries	Adjusted end times of 13 surgeries
OR2	33 surgeries	Adjusted end times of 15 surgeries Remove 1 surgery
OR3	45 surgeries	Adjusted end times of 20 surgeries Removed 1 surgery Moved 1 surgery to OR5
OR4	40 surgeries	Adjusted end times of 19 surgeries Moved 1 surgery to OR6
OR5	14 surgeries	Adjusted end times of 5 surgeries Removed 2 surgeries
OR6	217 surgeries	No adjustments

Besides the data about the performed surgeries, there are 1085 cancellations in the same period. 1014 of these cancellations were planned in an OR. 78 cancellations are wrongly registered in Chipsoft. So, these cancellations are not real cancellations. 936 cancellations remain for the data analysis.

2.7. Demand for and supply of care

In this section, we give HOH's profile. We elaborate on the number of OR sessions in Subsection 2.7.1. Then, we discuss the total production in Subsection 2.7.2, i.e., the number of elective surgeries and emergency surgeries per OR, weekday and specialty. After that, we discuss the case mix based on the data in Subsection 2.7.3. Finally, we give an overview about the emergency surgeries in Subsection 2.7.4.

2.7.1. Sessions

For the analysis we use OR data from the 1st of January, 2016 until the 30th of June, 2017, which are 547 days of data. Excluding the holidays, 17 in total, and weekend days, 156 in total, 374 workable days remain for OR sessions. Since HOH has six ORs, there are 2244 workable OR days. If there is at least one elective surgery or 'emergency in OR day' on a workable OR day, we assume there is an OR session on that workable OR day. We count 2155 OR days with a session and 89 without a session. OR days without a session can be clarified by the recesses during the summer months, for six week one OR is closed, and in the last week of December most ORs are closed for elective surgeries. Another reason for workable OR days without a session can be that a specialist is ill and it is not possible to give the OR session to another specialist. We do not distinct morning or afternoon sessions from OR sessions. Table 2.3 shows a summary of the above-mentioned information.

Table 2.3: Sessions summary (OR system HOH, 2016-2017)

First day data	1-1-2016
Last day data	30-6-2017
Number of days	547
Holidays	17
Weekend days	156
Workable days	374
Workable OR days	2244
OR days with session	2155
OR days without session	89

2.7.2. Production

Figure 2.5 gives an overview of the total number of elective surgeries, 'emergency in OR day' and 'emergency in shift'. In total 78% are elective surgeries and 22% are emergency surgeries. OR6 has most elective surgeries and least emergency surgeries. That makes sense, since OR6 is an outpatient OR and most of these surgeries are small and have a short surgery duration. As said before, most 'emergency in shift' are performed in OR1 and OR5. This is confirmed by the data.

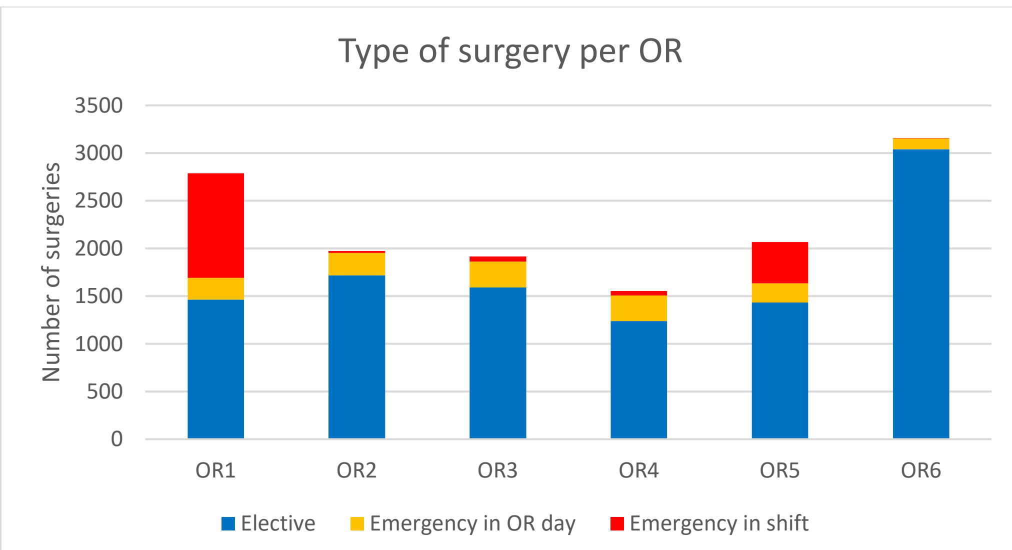


Figure 2.5: Elective surgeries, 'emergency in OR day' and 'emergency in shift' per OR (n=13,457, OR system HOH, 2016-2017)

2.7.3. Case mix

Table 2.4 shows a summary of the number of elective and emergency surgeries per specialty. General Surgery is the specialty with most elective and emergency surgeries. The gynecologists perform relatively many emergency surgeries. Ophthalmology has few emergency cases in comparison to the amount of elective surgeries. Since the specialties Internal Medicine, Anesthesiology, Oral Surgery, Pulmonology, and Radiology each have less than twenty surgeries in one and a half years, we exclude these specialties from the simulation model in Chapter 4.

Table 2.4: Surgeries per specialty (n=13,457, OR system HOH, 2016-2017)

Executing specialty	Surgeries	Elective	Emergency
General Surgery	4085	2701	1384
Ophthalmology	2372	2276	96
Gynecology	2044	1249	795
Orthopedics	1583	1284	299
Plastic surgery	781	708	73
ENT	762	701	61
Urology	744	626	118
Neurosurgery	460	402	58
Pain Treatment	449	417	32
Cardiology	129	99	30
Internal Medicine	18	9	9
Anesthesiology	15	2	13
Oral Surgery	11	11	0
Pulmonology	3	2	1
Radiology	1	0	1
Total	13457	10487	2970

We use the case mix classification method developed by Leeftink & Hans (2017) to visualize HOH's case mix. From the dataset, we identify 1317 unique surgeries (surgery types), based on their surgery code. Per surgery type, we determine a 3-parameter lognormal distribution, which is considered the best fitting distribution for surgery durations (May, Strum & Vargas, 2000; Stepaniak, Heij, Mannaerts, Quelerij & Vries, 2009). We add data from the period 2013 up and until 2015 to the dataset to increase the number of surgeries per surgery type. 281 surgery types have 20 or more performed surgeries and are responsible for 87% of the total OR production. Four surgeries are excluded because the mean square error (MSE) between the data and distribution of the surgeries are too big. We use an upper boundary of 0.004 for the MSE. For the remaining 277 surgeries, we calculate the mean (m) and standard deviation (s) per surgery type to plot the case mix in the case mix classification figure of Leeftink & Hans (2017).

Figure 2.6 visualizes HOH's case mix. On the x-axis, the duration of the surgeries in relation to the OR session capacity (c), which is 390 minutes, is shown: m/c. The y-axis represents the coefficient of variation (s/m). From this figure we conclude that HOH has many small surgeries compared to the OR session capacity. Moreover, most surgeries have a small coefficient of variation, but some of them are very big. Since we excluded the surgery types that have less than 20 performed surgeries, 87% of all surgeries is taken into account. These surgeries have a mean of 53 minutes. The missing 13%, consisting of 1036 surgery types, have a longer mean duration, 81 minutes, and therefore would have been plotted more to the right side in the figure, compared to the surgery types that are now plotted.

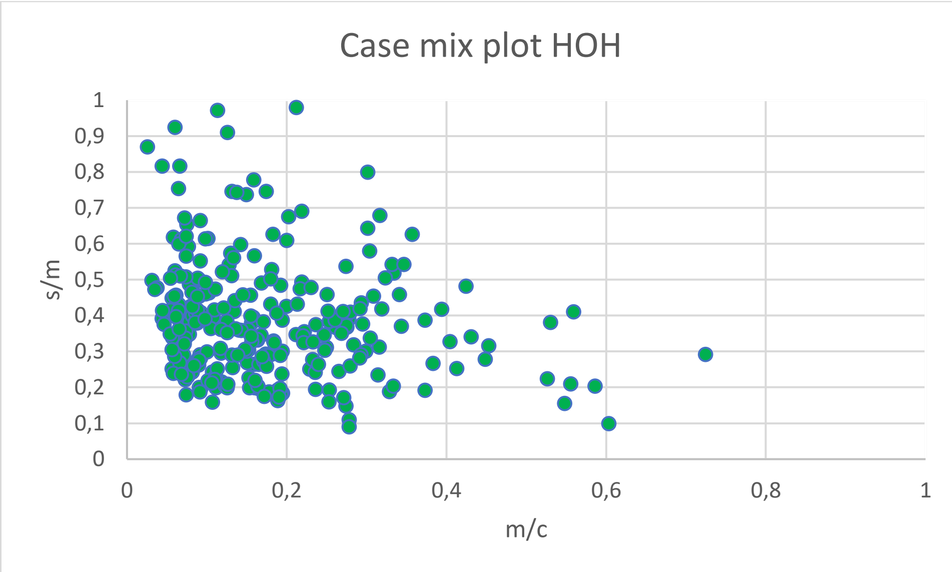


Figure 2.6: Case mix plot of the identified surgery types (n=277, OR system HOH, 2016-2017)

2.7.4. Emergency surgeries

Figure 2.7 shows the number of emergency cases per priority per weekday (see Section 2.5 for an explanation of the priorities). Urgency B and C are the priorities that occur most. On Friday most emergency surgeries are performed. Weekend days have relatively few emergency cases compared to the other days.

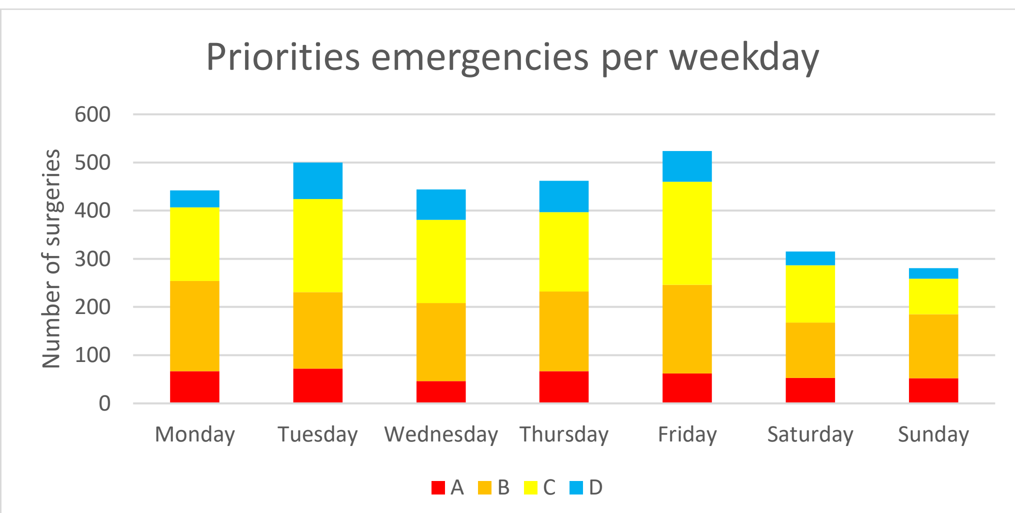


Figure 2.7: Priority of emergency surgeries per weekday (n=2970, OR system HOH, 2016-2017)

2.8. KPI selection

Before we measure the current OR performance, we define the KPIs. In Chapter 5, we use the same KPIs to measure the results of the experiments of the simulation study. First, we select utilization since this performance indicator is the most important factor for performing this research.

The second KPI is overtime. Overtime is not desirable since it costs HOH extra money to let OR personnel work in overtime. If the same work is executed within the OR session, HOH does not have to pay these extra personnel costs. Besides that, OR personnel is not satisfied with much overwork.

Cancellations is the third KPI. For this KPI we only consider cancellations that were cancelled due to planning causes. Since HOH and most specialist get paid per surgery, they want to cancel as least as possible. Also from the patient's point of view, cancellations are not desirable, e.g., the patient needs to be sober for a second time.

Since the scheduling strategy should be able to help emergency patients in time and meet the service requirements, service degree emergencies is our fourth KPI.

The last KPI is access time electives, which is the time between the arrival of the patient in the outpatient clinic of the specialist and the date of the surgery. Because we assume that the patient wants to be helped as soon as possible, we believe this is an important factor when developing a scheduling strategy.

We believe that with these KPIs represent the most important stakeholders, i.e., HOH, patients, specialists and OR personnel. In the next section, Section 2.9, we measure the current OR performance of the selected KPIs. It is only possible to measure the current performance of utilization, overtime and cancellations, since there is no data available to measure the service degree of emergencies and access time of electives. In Chapter 4, we elaborate on how we measure the KPIs in the simulation model. In Chapter 5, we assign weights to the KPIs and give the scoring method for comparing the experiments. A summary of the KPIs:

- Utilization
- Overtime
- Cancellations
- Service degree emergencies
- Access time electives

2.9. OR performance

In this section, we measure the current OR performance. We first consider the OR utilization in Subsection 2.9.1. Then, we discuss the overtime in Subsection 2.9.2. Subsection 2.9.3 elaborates on the cancellations.

2.9.1. Utilization

Figure 2.8 shows how the OR session time, 420 minutes, is utilized. We take the following into account: late start, surgery duration, changeover time and early end. We only look at how time inside an OR session is utilized, so early starts, late ends, and 'emergency in shift' are not taken into account. Late start is the number of minutes between the beginning of the OR session, 7:30, and the start of the first surgery of the OR session. Surgery duration is the time that a patient is in an OR. Changeover time is the time between two surgeries. The changeover times seem very high, between 18% and 20%, however these times include lunchbreaks. There is no data available about the lunchbreak times, therefore it is good to keep in mind that this is, in theory, 7% of an OR session. OR employees have the right to have two 15-minute lunchbreaks, however they do not always take a break. Early end is the number of minutes between the last surgery of the OR day and the end of the OR session, 14:30. See Section 2.6 for a summary of the definitions. Figure 2.8 shows, besides the categories mentioned above, 'late start emergency' as well. This category is the number of minutes an OR session started after 7:30 because an 'emergency in shift' (started before 7:00) ended in the OR session. The percentage of this category is very small and therefore negligible.

HOH has an average OR utilization of 69%. The average utilization of the clinical ORs is between 70% and 75%, and 73% on average. OR6 has a remarkable low utilization of 49%, and high percentages of late start and early end compared to the other ORs.

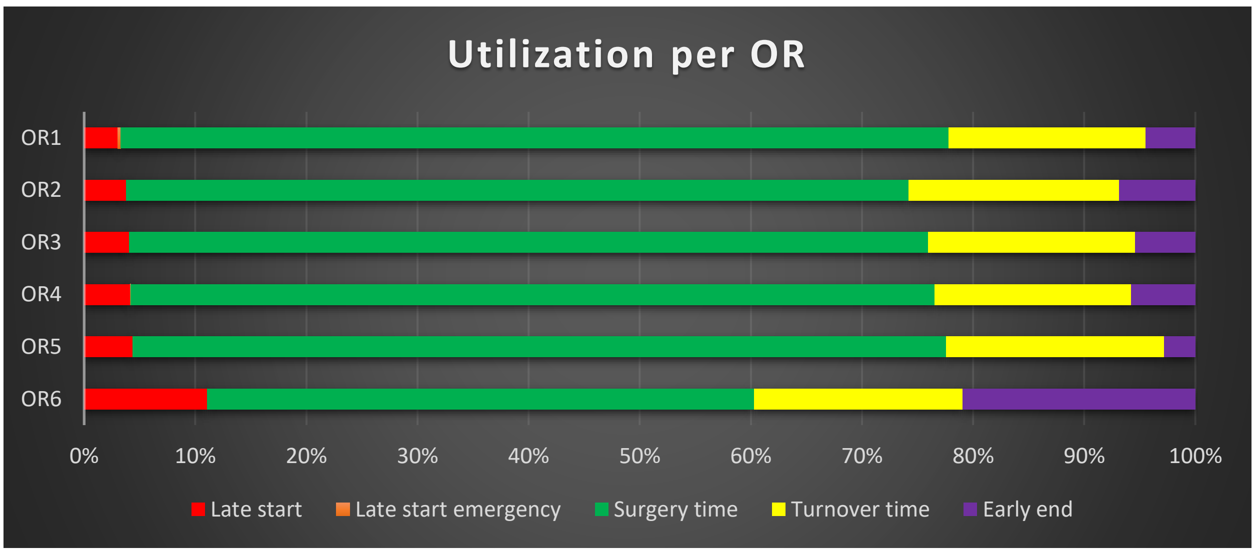


Figure 2.8: Utilization per OR (n=2155, OR system HOH, 2016-2017)

According to Van Houdenhoven, Hans, Klein, Wullink & Kazemier (2007) a 100% utilization is an unattainable utopia. They state that the maximum utilization that can be realized, depends on the average case standard deviation, assuming a normal distribution, and the accepted risk of overtime. They propose that since Ophthalmology and General Surgery have a small standard deviation, these specialties should have a relative high norm utilization: 91% and 90%, respectively, with an accepted risk of overtime of 31%. On the other hand, ENT has a large standard deviation and therefore should have a relative low norm utilization: 75%, with an accepted risk of overtime of 31% (Van Houdenhoven et al., 2007). At this moment, HOH does not have a norm utilization that they aim for, for any specialty. Also, they do not consider an accepted risk of overtime and therefore it is hard to state what a good norm utilization would be.

2.9.2. Overtime

This section analyzes the percentage of the performed surgery duration that is inside and outside the OR session. For this calculation, we do not consider 'emergency in shift'. Figure 2.9 shows that the amount of surgery time performed before the beginning of the OR session, 7:30, is very small, 0% - 1%. For overtime, the amount of surgery time performed after the end of the OR session, 14:30, we make a distinction between 'overtime elective' and 'overtime emergency'. 'Overtime elective' concerns late ends of elective surgeries, 'overtime emergency' concerns 'emergency in OR day', started before 15:00, that end after 14:30. Especially, the category 'overtime elective' is interesting for this research. The overtime of elective surgeries in the clinical ORs is between 4% and 6% of the total performed surgery duration.

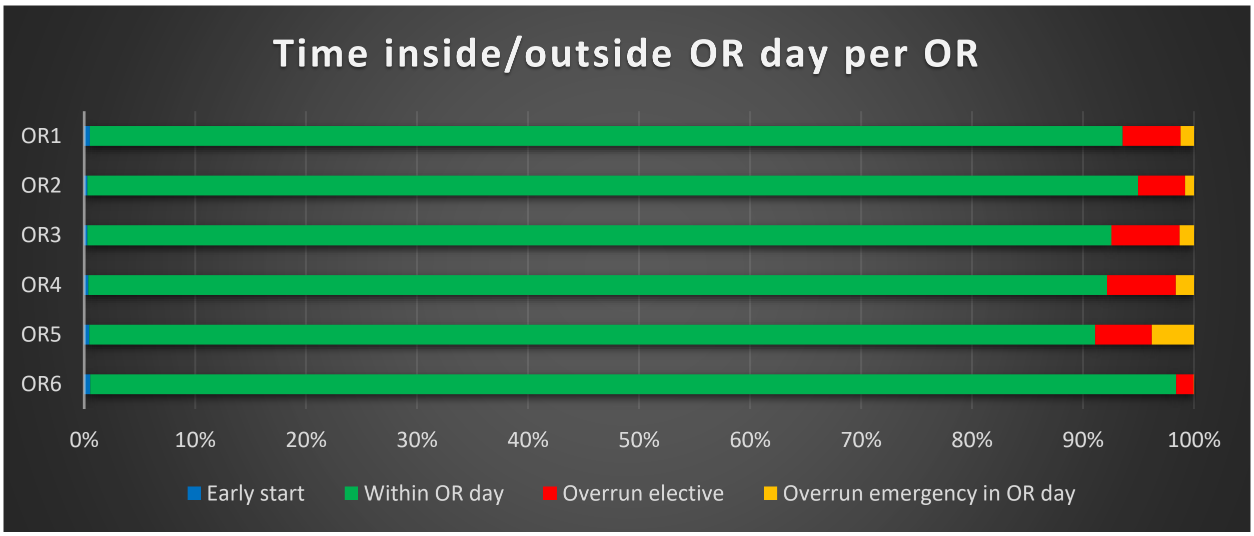


Figure 2.9: Surgery time performed inside and outside OR day (n=2155, OR system HOH, 2016-2017)

Table 2.5 shows the total overtime of elective surgeries in relation to the total OR capacity of the performed OR sessions per OR, which is on average 15 minutes per OR session. We calculate the total OR capacity by multiplying the number of sessions times the OR capacity per session, 390 minutes. The total amount of overtime of the elective surgeries is between 3.4% and 5.3% for the clinical ORs.

Table 2.5: Overtime in relation to capacity, in minutes (n=2155, OR system HOH, 2016-2017)

OR	Overtime elective	Sessions	Capacity	% overtime of capacity
OR1	6533	371	144,690	4.5%
OR2	4713	355	138,450	3.4%
OR3	7462	371	144,690	5.2%
OR4	7331	357	139,230	5.3%
OR5	6471	373	145,470	4.4%
OR6	1093	328	127,920	0.9%
Total	**33,603**	**2155**	**840,450**	**4.0%**

In Figure 2.10, we count the number of sessions that ended too early or too late. For 'too early' and 'too late', we make the distinction between more than a quarter ('modestly') and more than an hour ('very'). Every end of a session between a quarter too early and a quarter too late, we define as 'end in time'. See Section 2.6 for the exact definitions.

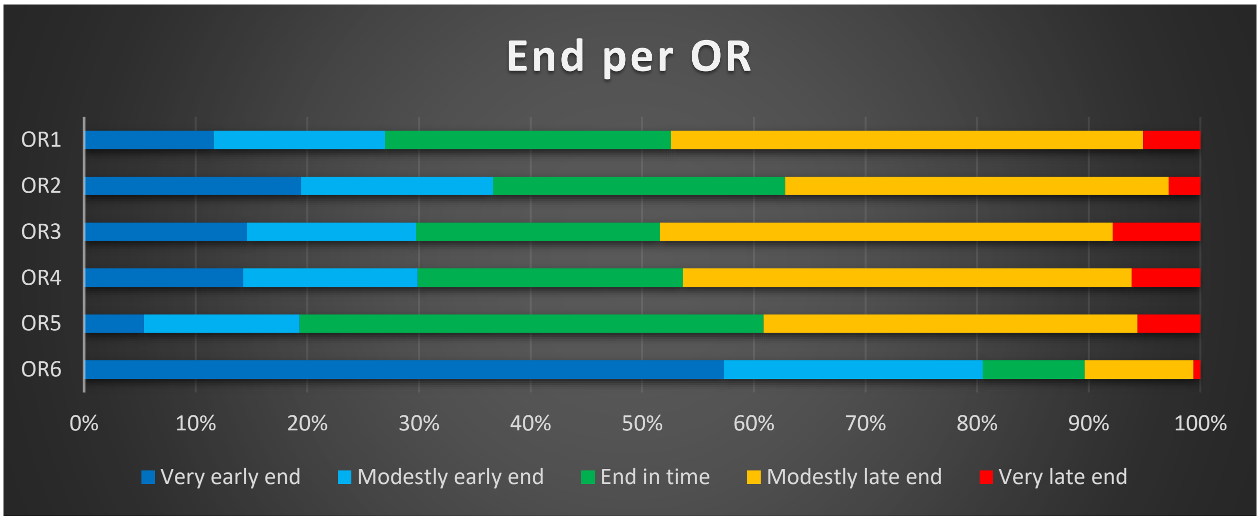


Figure 2.10: Early and late ends per OR (n=2155, OR system HOH, 2016-2017)

A reason for overtime can be late starts. As Figure 2.8 shows, between 3% and 11% of the OR session time is lost due to late starts. Figure 2.11 compares the number of sessions that started too late, too early and in time per OR. For the clinical ORs, between 23% and 40% of all OR sessions start after 7:45. For OR6 this is 61%.

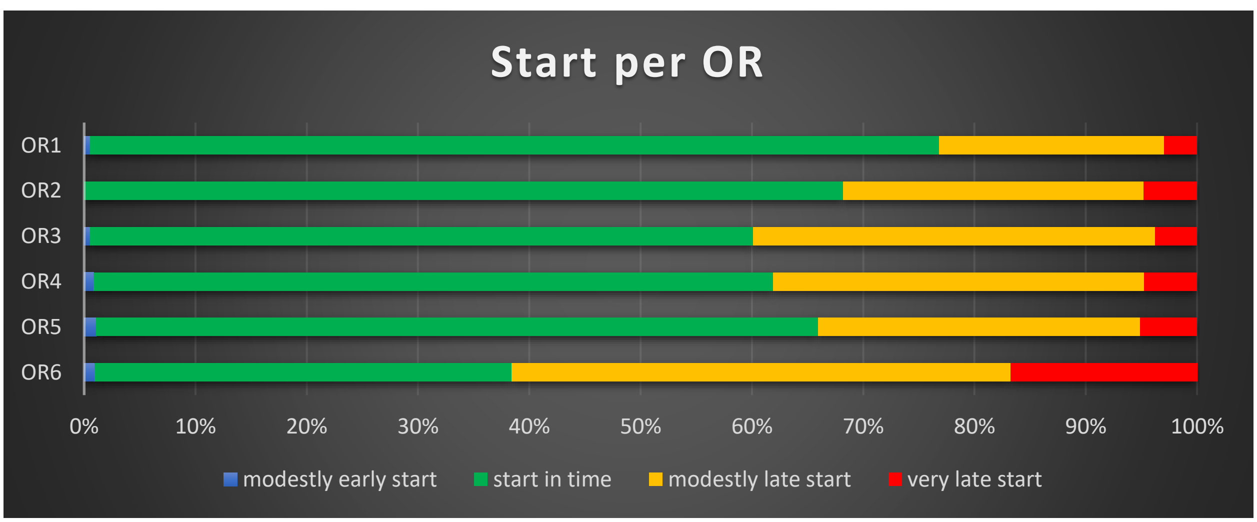


Figure 2.11: Early and late starts per OR (n=2155, OR system HOH, 2016-2017)

Table 2.6 relates Figure 2.10 and Figure 2.11 and shows how many times a late start results in a late end. We give the number of sessions that started after 7:45 and show the percentage of these sessions that ended before and after 14:45. Furthermore, we calculate the possible savings of overtime in minutes.

When a session starts later than 7:30 and ends after 14:30 it could be possible to save overtime. These possible savings are calculated by taking the minimum of time that a session started too late and the overtime of that session. For example, if a session starts at 7:50 and ends at 14:40, 10 minutes of overtime could be saved if the session started in time. However, it could be that a late start is not always the reason for a late end.

Table 2.6: Late ends, ends in time and possible savings after a late start (n=9927, OR system HOH, 2016-2017)

OR	Start after 7:45	End before 14:45	End after 14:45	Possible savings of overtime (min)
OR1	81	51%	49%	1579
OR2	105	64%	36%	1629
OR3	130	55%	45%	2301
OR4	122	57%	43%	2205
OR5	113	68%	32%	1526
OR6	197	89%	11%	687
Total	**748**	**67%**	**33%**	**9927**

A big influence on utilization and overtime is how the sessions are booked. HOH's booking policy is to book no more than 390 minutes for the elective surgeries including changeovers and excluding lunchbreak (see Section 2.4). Table 2.7 shows that many sessions are overbooked, i.e., an OR session schedule is longer than 420 minutes, including changeovers and lunchbreak. Note that emergency surgeries are not taken into account in the booking policy, but are included in Table 2.7. When an emergency patient arrives at the hospital and needs to undergo surgery, 61 minutes are booked for the surgery, regardless the type of surgery. The booked duration of 61 minutes is unfounded. Low utilization and early ends of OR6 (see Figure 2.8 and Figure 2.10) can be clarified by its low bookings rate. Especially the number of sessions for which less than 300 minutes are booked, is very high, 109 out of 328 sessions in total.

Table 2.7: OR session booking, including 30 minutes lunchbreak (n=2155, OR system HOH, 2016-2017)

OR	< 300	300 to 330	330 to 360	360 to 390	390 to 420	420 to 450	> 450	Total	% booked > 420
OR1	34	18	26	54	54	77	108	371	50%
OR2	42	23	34	48	63	62	83	355	41%
OR3	39	29	37	61	69	51	85	371	37%
OR4	61	32	40	53	61	45	65	357	31%
OR5	41	16	34	50	60	84	88	373	46%
OR6	109	27	37	18	44	33	60	328	28%
Total	**326**	**145**	**208**	**284**	**351**	**352**	**489**	**2155**	**51%**

Figure 2.12 shows the bookings accuracy of the elective surgeries. We take the difference between the booked duration and realization as a percentage of the booked duration. A negative booking accuracy means that the surgery took shorter time than expected, which we call underrun. A positive booking accuracy indicates that a surgery took longer than expected, which we call overrun. The figure shows that

most surgeries, 54%, have a negative booking accuracy and thus are overestimated. We consider this as good because most this means most surgeries do not overrun.

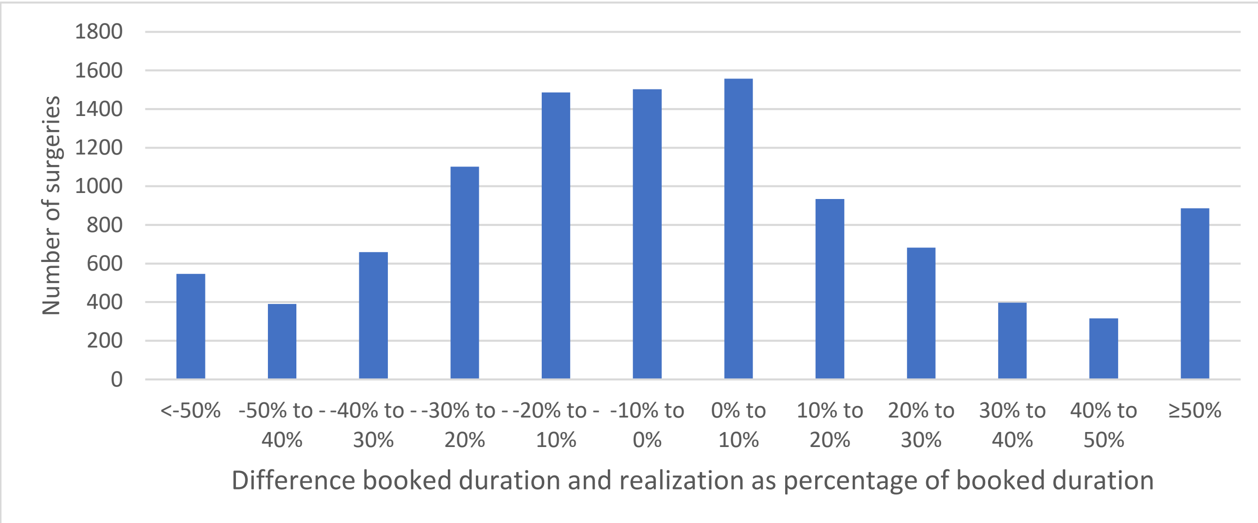


Figure 2.12: Booking accuracy of elective surgeries (n=10463, OR system HOH, 2016-2017)

Figure 2.13 shows the difference between the booked duration and the realization of the OR sessions. Although Figure 2.12 shows that the elective surgeries are booked quite accurately, i.e., 52% of the surgeries have a deviation of maximum 20%, most booked OR sessions deviate much from the realized durations. An explanation for this could be the unfounded booking of 61 minutes for emergencies. Another reason could be that the changeover times or lunchbreaks diverge from the booked times, which we show later on in Figure 2.14. From Table 2.7, we already concluded that most of the time OR6 is not fully booked. Besides that, most sessions in OR6 take less time than expected.

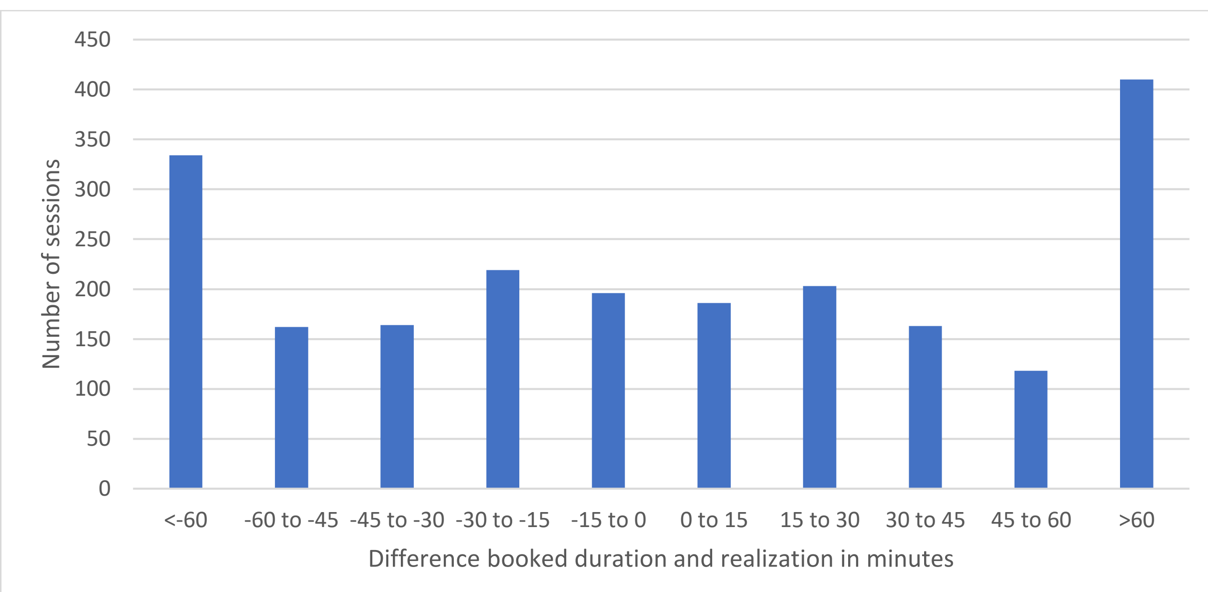


Figure 2.13: Booking accuracy of OR sessions (n=2155, OR system HOH, 2016-2017)

Table 2.8 shows the percentage of late starts and starts in time when a session is relative fully booked, i.e., more than 390 minutes (less than 30 minutes of slack). Compared to Figure 2.13 there is a slight difference: less sessions start after 7:45. A reason for this could be that personnel are aware of the fully booked program and are therefore more eager to start in time.

Table 2.8: Percentages late starts and starts in time of 'fully' booked OR sessions (n=1192, OR system HOH, 2016-2017)

OR	Booked > 390	Start before 7:45	Start after 7:45
OR1	239	85%	15%
OR2	208	76%	24%
OR3	205	73%	27%
OR4	171	75%	25%
OR5	232	79%	21%
OR6	137	55%	45%

Maybe personnel are also more eager to work faster so that they end in time when an OR session is relatively fully booked. Table 2.9 shows that most of these sessions have a realization which is shorter than the booked durations. Another explanation could be that changeover times or lunchbreaks are shorter.

Table 2.9: Percentages under- and overrun of 'fully' booked OR sessions (n=1192, OR system HOH, 2016-2017)

OR	Booked > 390	Realization < booked	Realization > booked
OR1	239	62%	38%
OR2	208	70%	30%
OR3	205	60%	40%
OR4	171	56%	44%
OR5	232	50%	50%
OR6	137	94%	6%

When considering sessions with less than 360 minutes booked in Table 2.10, i.e., having more than one and a half hour of slack, the realized durations are often longer than the booked durations. Once again, OR6 is an exception: most OR session in OR6 are underrun.

Table 2.10: Percentages under- and overrun of 'empty' OR sessions (n=679, OR system HOH, 2016-2017)

OR	Booked < 360	Realization < booked	Realization > booked
OR1	78	29%	71%
OR2	99	34%	66%
OR3	105	26%	74%
OR4	133	18%	82%
OR5	91	15%	85%
OR6	173	66%	34%

Changeover times can also have great influence on overtime, i.e., longer changeover times than expected increase the probability of overtime. In Figure 2.14, we show boxplots of the changeover times, including lunchbreaks, per OR. The cross in the middle of the boxplot represents the mean of the changeover times. The figure also shows the mean as a number next to the cross. The booked changeover times are 9 minutes for the inpatient ORs and 6 minutes for OR6 (see Section 2.4). Although lunchbreaks are not included in the booked changeover times, we conclude that there is a great gap between the booked changeover times and realized changeover times. We exclude changeovers between the last elective surgery of the day and emergency surgeries, because the arrival of the emergency patient could be much later than the end of the last elective surgery. The inpatient ORs show changeover times of 0 and OR6 shows negative changeover times due to inconsistencies in the data (see Section 2.6).

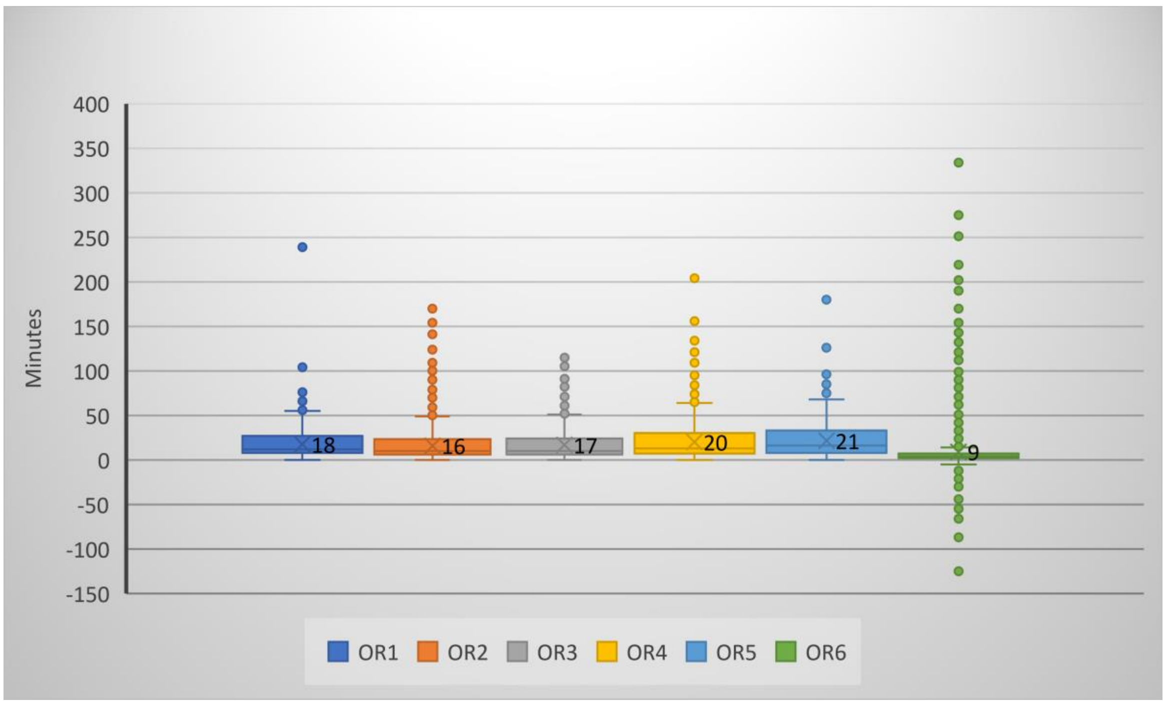


Figure 2.14: Changeover times per OR (n=6571, OR system HOH, 2016-2017)

2.9.3. Cancellations

When a surgery is cancelled, the reason for cancellation is registered in Chipsoft. Table 2.11 shows the reasons and corresponding frequency of the cancellations. We classify every cancellation in one of the following sub categories: patient, OR planning, materials, specialist, ward beds, POS, Admissions, personnel and other. The sub category indicates where the cause for the cancellations are. For example, OR planning is the sub category for ‘intervention emergency surgery’, because maybe a different scheduling strategy could prevent these cancellations. For some cancellations it is hard to identify a cause, e.g., ‘specialist cancelled’, since this reason says nothing about the underlying cause. Nevertheless, because the specialist makes this decision, we categorize this cancellation as ‘specialist’. Note that the cancellations in Table 2.11 only consider cancellations registered in Chipsoft, cancellations that occur before the definitive OR program is known (see Section 2.4), are not registered.

Table 2.11: Reasons of cancellation and corresponding frequency (n=936, OR system HOH, 2016-2017)

Reason of cancellation	**Frequency (% of total)**	**Category**
Patient cancelled	197 (21%)	Patient
Program overrun	109 (12%)	OR planning
Material not in stock	93 (10%)	Materials
No show patient	89 (10%)	Patient
Program change	62 (7%)	OR planning
Program too long	60 (6%)	OR planning
Patient too ill for surgery	58 (6%)	Patient
Specialist cancelled	57 (6%)	Specialist
Patient ill	34 (4%)	Patient
Specialist ill	33 (4%)	Specialist
No ward bed available	26 (3%)	Ward beds
Patient not sober	22 (2%)	Patient
Intervention emergency surgery	20 (2%)	OR planning
Calamity	17 (2%)	Other
Surgery not necessary	12 (1%)	Other
Material/equipment broken	10 (1%)	Materials
Caesarean section patient	9 (<1%)	Patient
Power failure	7 (<1%)	Other
Screening patient insufficient	5 (<1%)	POS
Admissions did not call patient	4 (<1%)	Admissions
Insufficient number of personnel Gen. Surg.	4 (<1%)	Personnel
Anesthetist cancelled	2 (<1%)	Specialist
Patient unreachable	2 (<1%)	Patient
Insufficient number of personnel anesthesiology	2 (<1%)	Personnel
No ICU bed available	2 (<1%)	Ward beds
Total	**936**	

We distinct the sub categories in two main categories, namely organizational and non-organizational. The organizational category contains cancellations on which HOH could have influence. For example, a cancellation due to 'material not in stock' possibly could be prevented if HOH maintains a different stock policy. We assume that HOH cannot have influence on non-organizational categories, these cancellations occur anyway. Table 2.12 categorizes the cancellations.

Table 2.12: Number of cancellations per category (n=936, OR system HOH, 2016-2017)

Organizational category	**Frequency (% of total)**
OR planning	251 (27%)
Materials	103 (11%)
Ward beds	28 (3%)
Personnel	6 (<1%)
POS	5 (<1%)
Admissions	4 (<1%)
Total	**397 (42%)**
Non-organizational category	
Patient	411 (44%)
Specialist	92 (10%)
Other	36 (4%)
Total	**539 (58%)**

251 cancellations are due to the OR planning, which is 2.4% of the total number of elective surgeries (10,487). The remaining number of cancellations, 6.8% of the total number of elective surgeries, are considered as cancellations on which the OR planning has no influence and therefore as a parameter added to the simulation model in Chapter 4.

2.10. Conclusion

In this chapter, we discussed the first and second research questions:

1. *What is the current OR planning process for elective and emergency surgeries, and what resources are used?*
2. *What is the OR performance of the current scheduling strategy?*

With the help of the healthcare framework (Hans et al., 2012) we identified HOH's resource capacity planning on different hierarchical levels. We summarize HOH's healthcare framework in Figure 2.15. Also, a flowchart is given, with which we described the planning process for elective surgeries and we explained how emergency surgeries are handled. Furthermore, we used the case mix classification figure of Leeftink & Hans (2017) to visualize HOH's case mix.

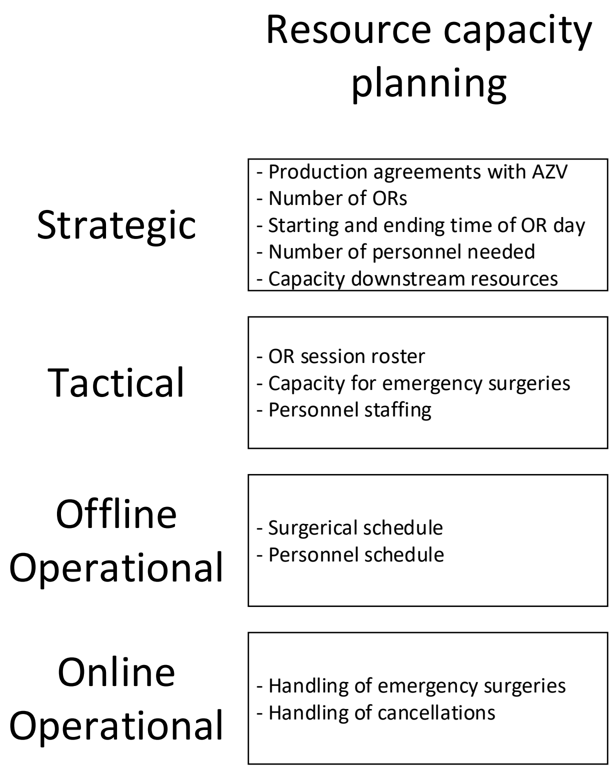


Figure 2.15: Resource capacity planning of HOH

The average utilization is 69%, with an average utilization of the clinical ORs of 73% and 49% for OR6. The low utilization of OR6 can be explained by the low booking rate and underrun of many sessions in OR6. The total overtime is 33,603 minutes, which is on average 15 minutes per session and 4% of the OR session capacity. In total 2.4% of all elective surgeries were cancelled due to the OR planning. We use these three performance indicators as KPIs for measuring the intervention possibilities. Besides these three KPIs, we defined access time electives and service degree emergencies as KPI. Unfortunately, there is no data to measure the current performance on these KPIs. In the next chapter, Chapter 3, we define the intervention possibilities for experimenting. After creating the simulation model in Chapter 4, we use the KPIs to measure the experiments in Chapter 5. Table 2.13 summarizes the current performance of the KPIs.

Table 2.13: Current OR performance summarized

KPI	CURRENT PERFORMANCE
UTILIZATION	69%
OVERTIME	33,603 minutes
CANCELLATIONS	251
SERVICE DEGREE EMERGENCIES	N/A
ACCES TIME ELECTIVES	N/A

Chapter Three – Intervention Possibilities

In this chapter, we answer the third research question: *What are suitable scheduling strategies for elective and emergency surgeries for HOH?* To answer this question, Section 3.1 discusses the literature about OR planning and scheduling, puts that in perspective of the HOH's situation and describes the most interesting scheduling strategies. Then, in Section 3.2, we discuss the intervention possibilities for the simulation study we perform in Chapter 4. The most relevant scheduling strategies, identified in Section 3.1, and some other interesting strategies that follow from the identified processes in Chapter 2, are put into experiments for the simulation model. In Section 3.3, we discuss the added value of our research to literature. Finally, Section 3.4 summarizes the content discussed in this chapter.

3.1. Literature study approach

Since the ORs are considered as the most expensive resources, but also the biggest revenue generators within a hospital (Health Care Financial Management Association, 2005; Macario, Vitez, Dunn & McDonald, 1995) it is important to manage these resources as efficiently as possible. Therefore, there is much literature about OR planning and scheduling. We use the following three literature reviews to find relevant articles about OR planning and scheduling applicable on the situation of HOH: *"Operating room planning and scheduling: A literature review"* (Cardoen, Demeulemeester & Beliën, 2010), *"Trade-offs in operating room planning for electives and emergencies: A review"* (Van Riet & Demeulemeester, 2015) and *"Operational research in the management of the operating theatre: a survey"* (Guerriero & Guido, 2011). In the remainder of this section, we discuss four different areas of scheduling strategies: OR policy, scheduling system, advance scheduling and allocation scheduling. OR policy and scheduling system concern the tactical level of the healthcare framework of Hans et al. (2012) (see Chapter 2). The two scheduling steps, i.e., advance scheduling and allocation scheduling, cover the offline operational level of the healthcare framework.

3.1.1. OR policy

In literature the distinction between elective and non-elective patients is made. Elective patients are patients that can be planned for surgeries well in advance. Non-elective patients, which can also be named as emergent and/or urgent, arrive randomly and have to be operated on the day of arrival. According to Van Riet & Demeulemeester (2015) there are three types of OR policies to manage the arrival of non-elective patients: dedicated policy, flexible policy, and hybrid policy (see Figure 3.1). In a dedicated policy, elective and non-elective patients are treated in different ORs, i.e., an elective patient can only be operated in an elective OR and a non-elective patient in a non-elective OR. In a flexible policy both patient groups can be operated in all ORs. A hybrid policy is a combination of both the dedicated and flexible policy. In this policy there are ORs which are dedicated to only elective or non-elective patients, but also ORs that handle both categories. Within the flexible policy Van Riet & Demeulemeester (2015) identify two different options: reserving slack at the end of the OR program and inserting non-electives in the OR program directly or through buffers. HOH uses the hybrid policy. During the afternoon sessions one OR is reserved for emergency patients (See Chapter 2). During the morning sessions the elective program needs to be interrupted for emergency patients with a high urgency level. According to Wullink, Van Houdenhoven, Hans, Van Oostrum, Van der Lans & Kazemier (2007) HOH should close the emergency OR, to increase its efficiency.

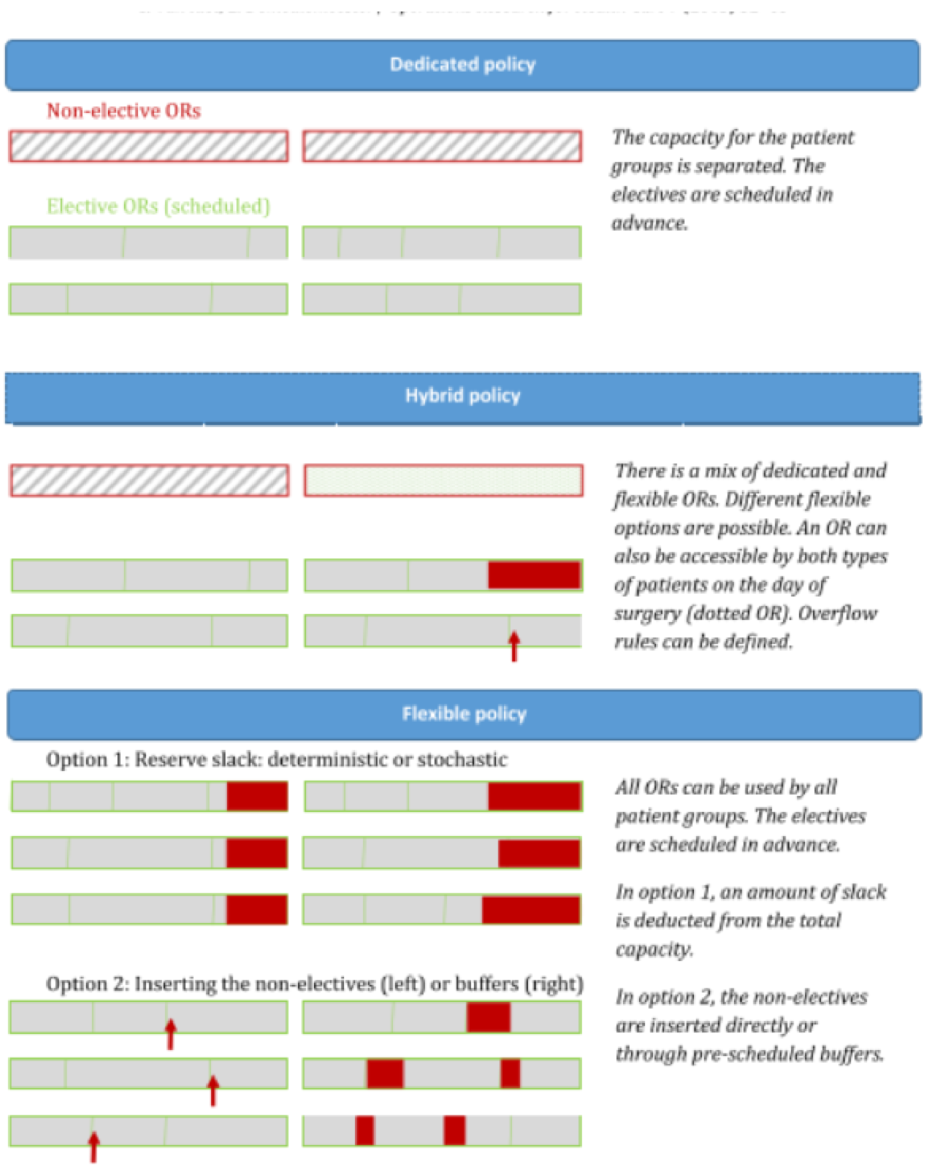


Figure 3.1: Three different policies for handling electives and non-electives (Van Riet & Demeulemeester, 2015)

HOH does not use slack in the hybrid policy. By reserving slack a hospital anticipates on the arrival of non-elective patients. Besides that, slack also serves as a safety margin for the overrun of elective surgeries. Hans, Wullink, Van Houdenhoven & Kazemier (2008) find a way to calculate the amount of slack needed to maximize capacity and minimize the risk of overtime.

Van Essen, Hans, Hurink & Oversberg (2012) analyzed how to guarantee maximum service level for non-elective patients in such policy. They consider so called break-in moments (BIMs), which are the moments between two subsequent surgeries that can be used to interrupt the elective program and start operating a non-elective patient. Van Essen et al. (2012) aim to minimize the maximum time between two consecutive BIMs to ensure that the waiting times for non-elective patients are minimized.

3.1.2. Scheduling system

We identify three different scheduling systems: open scheduling, block scheduling and modified block scheduling (Patterson, 1996; Gupta, 2007). The situation in which OR sessions are not assigned to a specialist and patients are treated according to the First Come First Serve (FCFS) policy is called open scheduling. When OR sessions are blocked for an assigned specialist in advance, we call it block scheduling. Modified block scheduling is a combination of the preceding systems, most OR sessions are blocked, but they can be released at an agreed-upon time before surgery for other specialists. HOH maintains this block scheduling policy. Every specialist is assigned to one OR session per week, however HOH created some flexibility within the block scheme via flex sessions and request lists (see Chapter 2). Nonetheless, HOH does not have an agreed-upon time before surgery that a specialist can release his/her OR session.

Pariente, Torres & Cia (2009) approach OR planning and scheduling policies from a different point of view. They distinguish between P-S-OR policy and P-OR-S policy. In a P-S-OR policy, patients are assigned to a specialist before they are assigned to an OR. When a patient is first assigned to an OR and after that the specialists are allocated over the ORs, is called an P-OR-S policy. Compared to P-OR-S, the P-S-OR policy has an advantage in the field of care, because the patient is operated by the same specialist he/she is examined by (Guinet & Chaabane, 2003; Jebali, Alouane & Ladet, 2006). HOH makes use of an P-S-OR policy (see Chapter 2).

3.1.3. Advanced scheduling

The assignment of patients to ORs is called advanced scheduling (Guerriero & Guido, 2011). A common policy for advanced scheduling is First Come First Serve (FCFS), which is also applied in HOH. This algorithm schedules an arriving patient on the first available OR session which is assigned to the performing specialist and has enough open time available to operate the patient. Dexter, Macario, Traub, Hopwood & Lubarsky (1999) compare four advanced scheduling algorithms, which are defined by Galambos & Woeginger (1995), in an open scheduling system with the help of computer simulation: Next Fit, First Fit, Best Fit and Worst Fit. Next Fit is similar to FCFS described above, except that a patient can be scheduled in all ORs because of the open scheduling system. First Fit schedules an arriving patient in the first available OR and has enough time available. If no such OR can be found, it uses Next Fit. Best Fit assigns the patient to an OR that has enough time available for the surgery, and the least amount of additional time available. Worst Fit works the other way around, compared to Best Fit it schedules the patient to the OR with the most additional time available instead of least additional time available. The results of the simulation do not indicate that an algorithm is better than the other algorithms. That is why they suggest to use Next Fit, since this algorithm is very simple. These four scheduling algorithms are called online algorithms, because the patients are assigned to an OR at the moment they enter the system. Dexter, Macario &

Traub (1999) consider besides these online algorithms also offline algorithms to schedule add-on elective patients, which are patients that can be added to the elective program short before the day of surgery, e.g., 10 AM the working day before surgery. Offline algorithms are algorithms that first sort the patients before scheduling. The best performing algorithm they identify, i.e., that maximizes OR utilization, is Best Fit Descending with a permitted maximum overtime of 15 minutes. The patients are scheduled in a descending order of expected surgery duration and assigned to an OR according to the Best Fit algorithm.

Persson & Persson (2009) design an OR strategy for the orthopedic surgery department in a hospital in Sweden. They discuss a stand-by system, which is used in that hospital. The stand-by patients in this system is comparable with the add-on elective patients. When an opportunity appears, e.g., an elective patient cancels his/her surgery, the stand-by patient fills the gap in the OR program. The stand-by patient has a day of surgery, but also agrees upon dates the patient is stand-by for surgery. If it is not possible to operate the stand-by patient on one of the days the patient is stand-by, the patient is operated on the initial scheduled surgery date. According to Persson & Persson (2009) the stand-by system is especially suitable for orthopedic surgeries due to the characteristics of orthopedic disease and injuries. Besides, they also state that not all patients are suitable for the stand-by system.

Local search methods are used to improve a schedule. An effective local search is simulated annealing (SA) (Kirkpatrick, Gerlatt & Vecchi, 1983). Sier, Tobin & McGurk (1997) and Hans et al. (2008) use SA to optimize the OR schedule. First, an initial schedule is made, e.g., with FCFS. With random swaps, i.e., changing two scheduled surgeries with each other, or random moves, i.e., assigning surgeries to other OR sessions, SA tries to improve the initial schedule. Not all individual swaps or moves directly result in an improved schedule but can contribute to an improved schedule in the long run. Therefore, a swap or move that does not improve the schedule, is accepted with a certain probability.

3.1.4. Allocation scheduling

Allocation scheduling is the process of determining the sequence of the surgeries during an OR session after the advanced schedule is known. HOH schedules according to the following priority: child patients, pregnant patients, patients with a metabolic disorder and surgeries with the longest expected duration. Last surgeries to schedule are MRSA patients and patients under local anesthesia. The scheduling algorithm in which the longest expected duration is scheduled first (longest expected processing times, LEPT), is a common used allocation scheduling algorithm in OR planning. Shortest expected processing times (SEPT) is also an allocation scheduling algorithm, in which the surgeries with the shortest expected durations are scheduled first. However, a disadvantage of this algorithm relative to LEPT can be that more surgeries with long expected duration are cancelled due to overrun of the OR program. Arnaout & Kulbashian (2008) introduce a new algorithm: LEPST, in which they also take the expected setup time into account in their LEPT algorithm. In a computer simulation, their algorithm outperforms LEPT and SEPT. LEPT is the second best algorithm in this study.

Minimizing the maximum distance between BIMs as this is proposed by Van Essen et al. (2012) (see Subsection 3.1.1) is also an allocation scheduling algorithm, because the BIMs depend on the sequence the surgeries are scheduled.

3.1.5. HOH's current scheduling strategy

In this subsection, we summarize HOH's current OR scheduling strategy, so that we know what we need to implement in our basic simulation model. Table 3.1 summarizes the current OR scheduling strategy. In the next section, Section 3.2, we elaborate on the interventions we select for the experiments in our simulation model.

Table 3.1: HOH's current OR scheduling strategy

Hierarchical level	Decisions	Current strategy
Tactical	OR policy	Hybrid ORs without slack
Tactical	Scheduling system	Modified Block
Offline operational	Advanced scheduling	FCFS
Offline operational	Allocation scheduling	LEPT, with exceptions

3.2. Intervention possibilities for experimenting

From the literature study performed in the Section 3.1, we present the intervention possibilities for which we perform experiments in our simulation study in Chapter 4 in this section. In subsections 3.2.1 to 3.2.4, we explain which of the intervention possibilities of the different areas of scheduling are suitable to experiment with. Besides the intervention possibilities identified from the literature, we give in Subsection 3.2.5 two intervention possibilities that followed from the process analysis in Chapter 2.

3.2.1. OR policy

Concerning the OR policy, we consider the amount of slack and changing from a hybrid policy to a flexible policy. We do experiments on different levels of slack to see what the impact is. Slack means that a percentage of the OR capacity is reserved for overrun and emergencies, e.g., the schedule for electives can be no longer than 351 minutes in a 10% slack policy. Furthermore, we wonder what the effect is if the emergency OR disappears from the session roster, i.e., changing from a hybrid policy to flexible policy.

3.2.2. Scheduling system

There are three different scheduling systems according to the literature in Section 3.1: block, modified block and open. For our experiments we only consider modified block, since block scheduling differs very little form modified block scheduling and we think an open scheduling system is not realistic for HOH. Changing the scheduling system from modified block to open involves great implementation problems, e.g., specialists need to be more flexible, and thus the planning concerning the outpatient clinic of the specialists also need to be adjusted.

3.2.3. Advanced scheduling

Regarding the setting for advanced scheduling, we only test FCFS. FCFS is HOH's current advanced scheduling algorithm. This advanced scheduling algorithm is an online scheduling algorithm, which means the patient makes an appointment for surgery during the visit in the outpatient clinic. Most other advanced scheduling algorithms are offline algorithms, which means the specialist need to collect a batch of patients before they start scheduling the patients for surgery. Currently, the advanced scheduling is decentralized, i.e., the specialists schedule their own patients. Switching from online to offline scheduling is not preferable when the advanced scheduling is decentralized, since all specialists' planners need to be educated properly to execute the new way of scheduling. Switching from decentralized to centralized scheduling can also involve many troubles, e.g., specialists need to share their waiting lists with the OR planner.

3.2.4. Allocation scheduling

Arnaout & Kulbashian (2008) discuss three allocation scheduling algorithms: LEPT, SEPT and LEPST. LEPT is the algorithm that is the closest to the one that is used by HOH. The surgeries with longest expected duration are scheduled first, but there are patient groups that have a higher priority. We do not consider other allocation scheduling algorithms in our experiments, because of the exceptions, we expect that changing the allocation scheduling algorithm has little influence on the overall performance, and other experiments are more interesting to simulate.

3.2.5. Other intervention possibilities

Besides the intervention possibilities identified from the literature, i.e., implementing slack and changing from a hybrid OR policy to a flexible OR policy, there are two more interventions we consider in Chapter 4. We select these interventions in consultation with HOH's OR management. In Chapter 2, we explained that HOH uses a request list to reschedule cancelled patients in other specialists' OR sessions. However, specialists need to send a request to the OR planner if they want to make use of the request list. We think it is interesting to simulate the difference between not using the request list and using it consequently. Furthermore, we noticed that there are no rules for specialist to fill their session. If a specialist has a program of one short surgery this has a negative influence on the utilization. Therefore, we suggest multiple levels of minimum booking rates for OR sessions as simulation experiments.

3.3. Added value of this research

The intervention possibilities discussed in Subsection 3.2.5, are identified from a practical point of view. However, since these intervention possibilities are not discussed in the literature, experimenting these intervention possibilities has academic value. Intuitively, minimum booking rate increases utilization because relatively empty sessions are removed from the OR program. Nonetheless, it is interesting to see what happens to the other performance indicators, such as the service level of emergency patients. Experimenting with the request list could also bring up some interesting insights. We think using the request list for all cancelled patients decreases the access time of elective patients. However, we would like to know the overall impact on the OR performance when using the request list consequently opposed to not using the request list. Moreover, combining the four identified intervention possibilities in a simulation study has not been done before, and therefore adds value to the current literature.

3.4. Conclusion

In this chapter, we gave an answer to the third research question: *What are suitable scheduling strategies for elective and emergency surgeries for HOH?* First, we identified four levels of the scheduling strategy from the literature:

1. OR policy
2. Scheduling system
3. Advanced scheduling
4. Allocation scheduling

Then, we selected two intervention possibilities from the level OR policy for our simulation experiments:

- Implementing slack.
- Switching from a hybrid policy to a flexible policy: stop reserving capacity for emergency surgeries by using the emergency OR.

Furthermore, we suggested two other intervention possibilities:

- Using the request list consequently.
- Minimum booking rate for OR sessions.

In the next chapter, Chapter 4, we explain the experiments of the interventions in more detail.

Chapter Four – Simulation Study

To answer the fourth research question, i.e., *What is the effect on OR performance for the suggested scheduling strategies?*, we perform a simulation study to evaluate the suggested scheduling strategies in Chapter 3. We use the seven-step simulation study approach of Law (2003) to perform the simulation study. This approach consists of the following steps: 1. Formulate the problem, 2. Collect information/data and construct conceptual model, 3. Validate the conceptual model, 4. Program the model, 5. Validate the programmed model, 6. Design, conduct, and analyze experiments, 7. Document and present the simulation results (see Figure 4.1). We discussed Step 1, the problem formulation, in Chapter 1. In this chapter, Section 4.1 considers the input data of simulation model (Step 2). Section 4.2 elaborates on the construction of the conceptual model and validates the conceptual model (Step 2 & 3). Section 4.3 discusses the programming and validation of the simulation model (Step 4 and 5). In Section 4.4, we give the experimental design (Step 6). The results (Step 7) are presented in Chapter 5. We give a summary of this chapter in Section 4.5. There are some back loops in the seven-step approach, which means that if the programmed model is not valid, the conceptual model needs adjustments. Therefore, some decisions currently presented in the conceptual model were originally made during the validation phase.

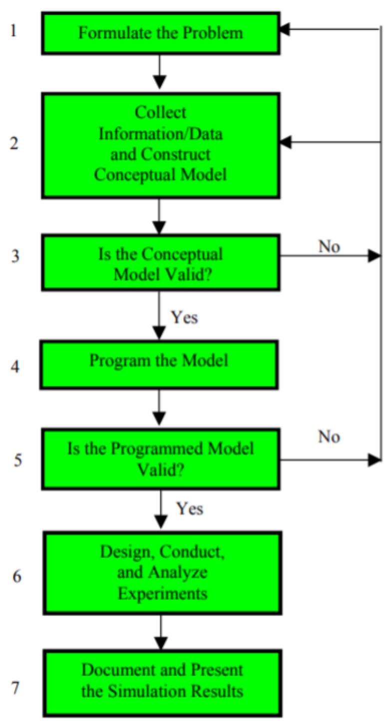


Figure 4.1: Seven-step approach for conducting a successful simulation study (Law, 2003)

4.1. Data

This section describes the data we use for our simulation model. First, we discuss the ORs, session roster, specialties and specialists in Section 4.1.1. Section 4.1.2 explains the arrival of elective and emergency patients, and how we determine the surgery durations per patient. We conclude this section with an explanation on how we model the late (and early) starts of the OR sessions and the changeovers.

4.1.1. ORs, session roster, specialties and specialists

HOH has five inpatient ORs and one outpatient OR. We assume that inpatients and emergency patients are only operated in the inpatient ORs, and outpatients are only operated in the outpatient OR. We use the session roster of January 2016 until June 2017 for the validation phase. Since we use data from the same period for the data analysis in Chapter 2, we make a fair comparison between the simulation model and realization. We use the roster of 2018 for the experiments, to obtain relevant results for current practice.

Table 4.1 shows the specialties and number of specialists per specialty we simulate. In reality, there is one general surgeon who also performs Urology surgeries. For simplicity reasons, we choose to limit the type of surgeries to General Surgery for this specialist. Furthermore, simulating two cardiologists causes an overload for one of the cardiologists, i.e., the number of sessions is not sufficient to schedule all arriving patient. Therefore, we choose to simulate one cardiologist for all Cardiology sessions. This way the sessions of Cardiology are evenly loaded.

Table 4.1: Number of specialists per specialty

Specialties	Number of specialists
General Surgery	6
Ophthalmology	3
Gynecology	5
Orthopedics	4
Plastic Surgery	2
ENT	2
Urology	2
Neurosurgery	1
Pain treatment	1
Cardiology	1

4.1.2. Patient arrival and surgery duration

Elective patients arrive according to a Poisson distribution with λ=0.822 per hour. Emergency patients arrive according to a Poisson distribution with λ=0.225 per hour on average. However, the number of emergency arrivals per hour varies. Therefore, we include a time dependent arrival rate per hour based on historical data. Figure 4.2 shows the emergency arrival pattern of the simulation model and the realization. Not all emergency surgeries are linked to a moment that the decision is made that the patient should undergo surgery, for this reason we give the number of arriving emergency patients per hour as percentage of the total amount of emergency patients and use this percentage to determine the time dependent arrival rate.

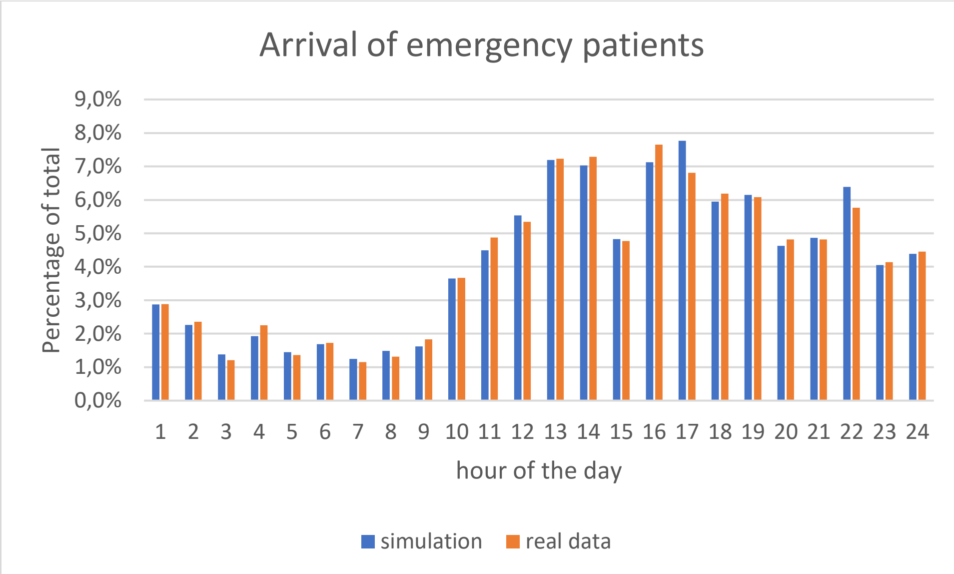


Figure 4.2: Arrival of emergency patients per hour in percentage

We use probabilities, based on historical data, to determine the specialty of an arriving patient. The proportion of sessions in the session roster determines the probability that a patient is assigned to a specialist, which differs from reality. There is no exchange of patients between specialists. Furthermore, we use a probability that a patient has the age of 12 years or younger per specialty, which is information we use for determining sequence of an OR program. All these probabilities are given in Appendix A.

From historical data, we identify 277 different surgery types, based on the surgery code, for which there are at least 20 performed surgeries. From this data, we determine for each surgery type a 3-parameter lognormal distribution by minimizing the Mean Squared Error (MSE). Surgery types with an MSE higher than 0.004, four in total, are excluded. We make a trade-off between including many different surgery types and the smallest MSE as possible, by choosing this MSE as threshold. Figure 4.3 shows the MSEs of all surgery types (every surgery type has a position on the y-axis). We use the same data for the case-mix plot in Figure 2.6. In the data, there are many surgery types with less than 20 performed surgeries, and therefore not included in the simulation model (see Section 2.7). 13% of all surgeries are excluded in the simulation model. The surgery types of these surgeries have longer average surgery durations than the 277 surgery types we use in the model, which means there is a discrepancy of the overall average duration between the simulation and reality. To reduce this difference, we perform a correction to the parameter γ of the 3-parameter lognormal distribution of the surgery duration. The magnitude of the correction depends on the patient type, elective or emergent, and specialty, so that the average surgery duration per specialty of the simulation model does not differ from the reality. However, this could cause differences between reality and simulation on the surgery type level. Appendix A gives the corrections per specialty. We use the mean of the surgery types as the booked durations.

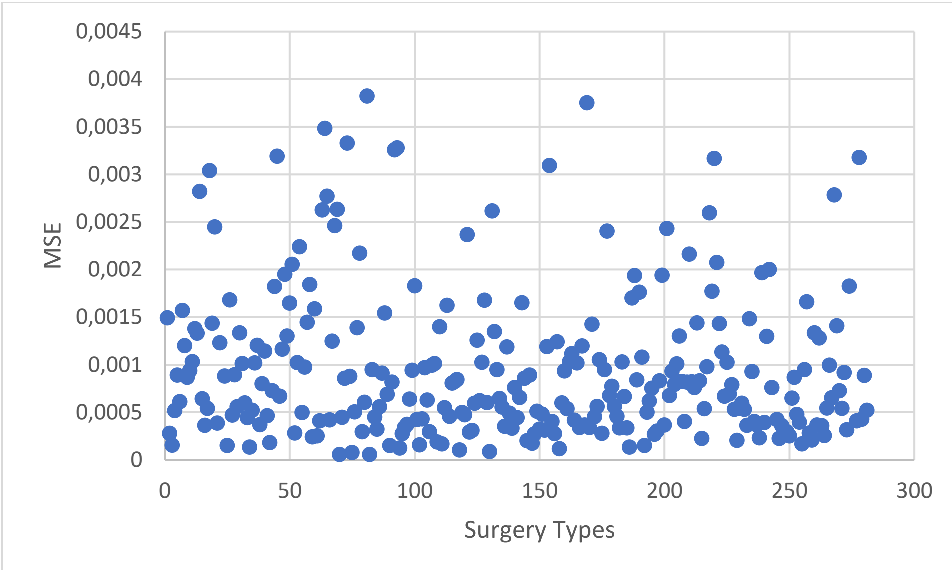


Figure 4.3: Mean Squared Errors of surgery duration distributions

4.1.3. Starts and changeovers

As input for the surgery durations, changeovers, and starts (late and early) we use 3-parameter lognormal distributions. We use one distribution per OR for changeovers, and also one distribution per OR for the starts. Distributions for surgery durations are per surgery type. Appendix A shows the parameters and MSE of these distributions.

4.2. Conceptual model

In this section, we design the conceptual model. With flowcharts, we visualize the three most important processes of the simulation model: scheduling elective patients, scheduling emergency patients and the patient handling during an OR session.

4.2.1. Scheduling elective patients

Figure 4.4 shows the scheduling process of elective patients. A patient arrives at the outpatient clinic of the specialist and the specialist decides if this patient needs to be operated. If this is not the case, the patient does not enter the system in the simulation model. If the patient needs to undergo surgery, the scheduling process starts. So, the simulation model only considers patients that need a surgery. This scheduling process is based upon the First Come First Serve (FCFS) algorithm, which means that the patient is added to the first session in which there is enough remaining capacity. There should be at least 14 days between the visit of the outpatient clinic and the date of surgery. We assume this is realistic since the patient needs to be screened at the POS before surgery. FCFS assumes that the patient is always available on the first suitable session. However, we take into account that the patient might be occupied that day. Therefore, we use probabilities to simulate this behavior. With a probability of 90% we assume that the patient is available for the first suitable session and a probability of 10% that the patient is available for the second suitable session, but not on the first.

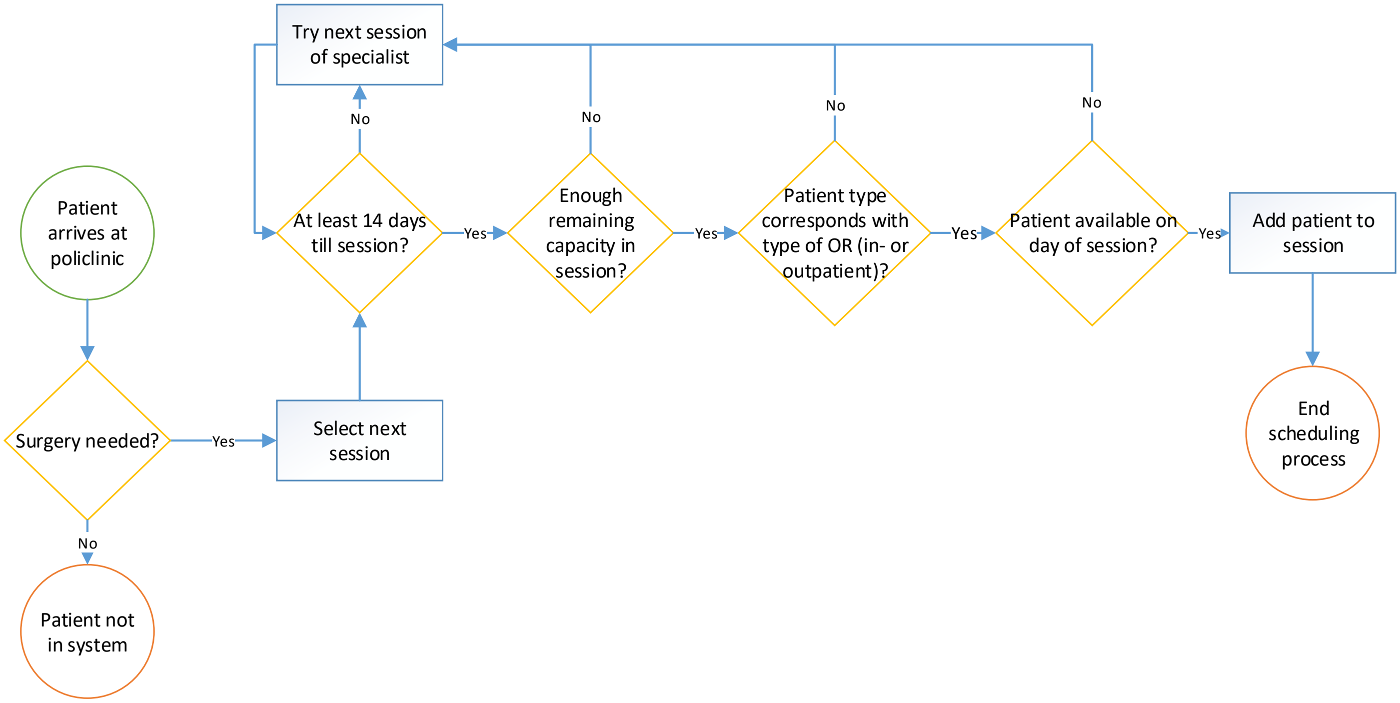


Figure 4.4: Scheduling process of elective patients

4.2.2. Scheduling emergency patients

Figure 4.5 visualizes the scheduling of emergency patients. It is important to meet the service requirements of the urgency levels of emergency patients. Table 4.2 recapitulates the requirements per urgency level. If there is an emergency OR available, HOH chooses to only interrupt the elective program for urgency A. When there is no emergency OR, emergencies with urgency B get priority over elective surgeries if they arrive before 10:00. Otherwise, these emergencies are treated after the elective program. The elective program is never interrupted for urgency levels C and D. These emergencies are operated the same day if the expected end time is before 21:00. Otherwise, these patients are treated the next day after the elective program. However, this is only the case if the OR is open on both days. Urgency D emergencies need to be operated within 72 hours. However, in most cases this group of patients is treated the same as Urgency C. This means if such an emergency arrives on Saturday, it is possible to wait until Monday to operate this patient, but in reality, the patient is treated on Saturday or Sunday.

Table 4.2: Service requirements per urgency level

Urgency	Start of surgery
A	Right away
B	Within 2 - 6 hours
C	Within 24 hours
D	Within 72 hours

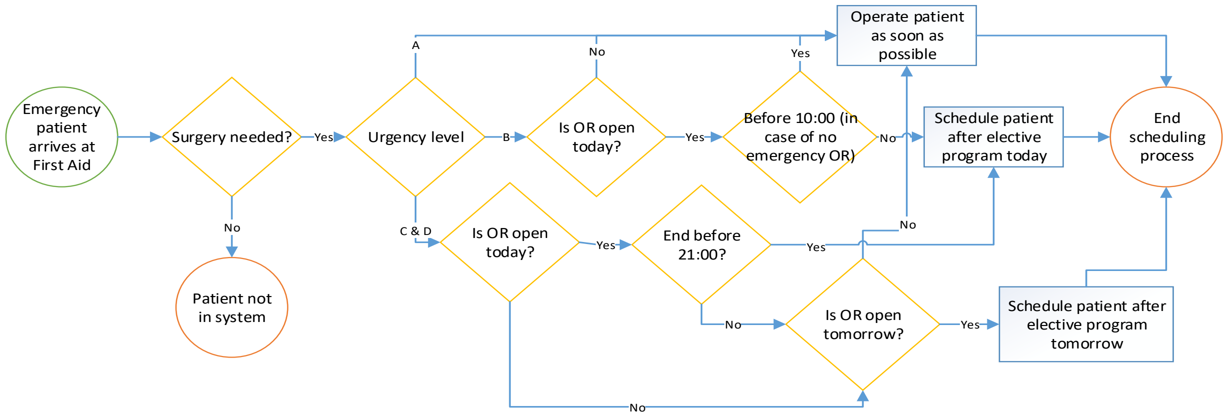


Figure 4.5: Scheduling process of emergency patients

4.2.3. Patient handling

Figure 4.6 shows a flowchart to visualize the patient handling process. At the start of the OR day, the flex sessions are assigned to specialists with the most patients on the waiting list in combination with the time until the last patient of the specialist is scheduled. In this way, specialists with few sessions on the session roster also have the possibility to get a flex session assigned. A waiting list contains patients that are scheduled for a surgery. Patients are added to the waiting list after they are assigned to a specialist. When a flex session is assigned to a specialist, all patients on his/her waiting list are rescheduled.

Before the first patient is send to the OR, we determine the sequence of the patients based on the age of the patient and the booked duration of the surgery. Children with age up to 12 years are scheduled at the beginning of the day. Then, the patients are scheduled on the booked duration, i.e., Longest Estimated Processing Time (LEPT). When we send a patient to the OR there is a possibility that the patient cancels, e.g., due to illness. These patients are rescheduled FCFS as if they enter the system at the moment of cancellation, so they are set back to the end of the queue, as in practice. It is also possible that the patient cancels and does not return for a new appointment. These patients are removed from the system. There is also a possibility that the surgery needs to be cancelled and this is not the patient's fault, e.g., there are not sufficient materials in stock. In that case we schedule the patient in the next session of the performing specialist.

When a patient is operated and the OR is cleaned, we first check if there are emergencies with urgency level A, and/or B in case of no emergency OR, waiting. If this is the case, such a patient gets priority. If this is not the case, the next elective patient is operated in the OR. Elective patients with an expected end time after 15:00 are not operated and rescheduled in the next session of the performing specialist. This results in rescheduling another patient from the next session to a session later on, to prevent this session from overbooking.

At 14:30, we check if there are still patients that need to be operated. These patients are also cancelled and scheduled in the next session of the performing specialist. In reality, a specialist can request extra operating time for these types of cancellations via the request list. Patients on the request list are scheduled in a session of another specialist as soon as possible if there is enough remaining capacity. However, these requests are not done consequently and therefore we decide to exclude this from the basic simulation model.

When the elective program is finished, the emergencies that are still waiting are operated. OR1 stays open after 14:30 to handle these emergencies, the other ORs close at 14:30 and handle emergencies if these finish before 14:30. There is one exception: OR6, the outpatient OR, does not handle any emergencies.

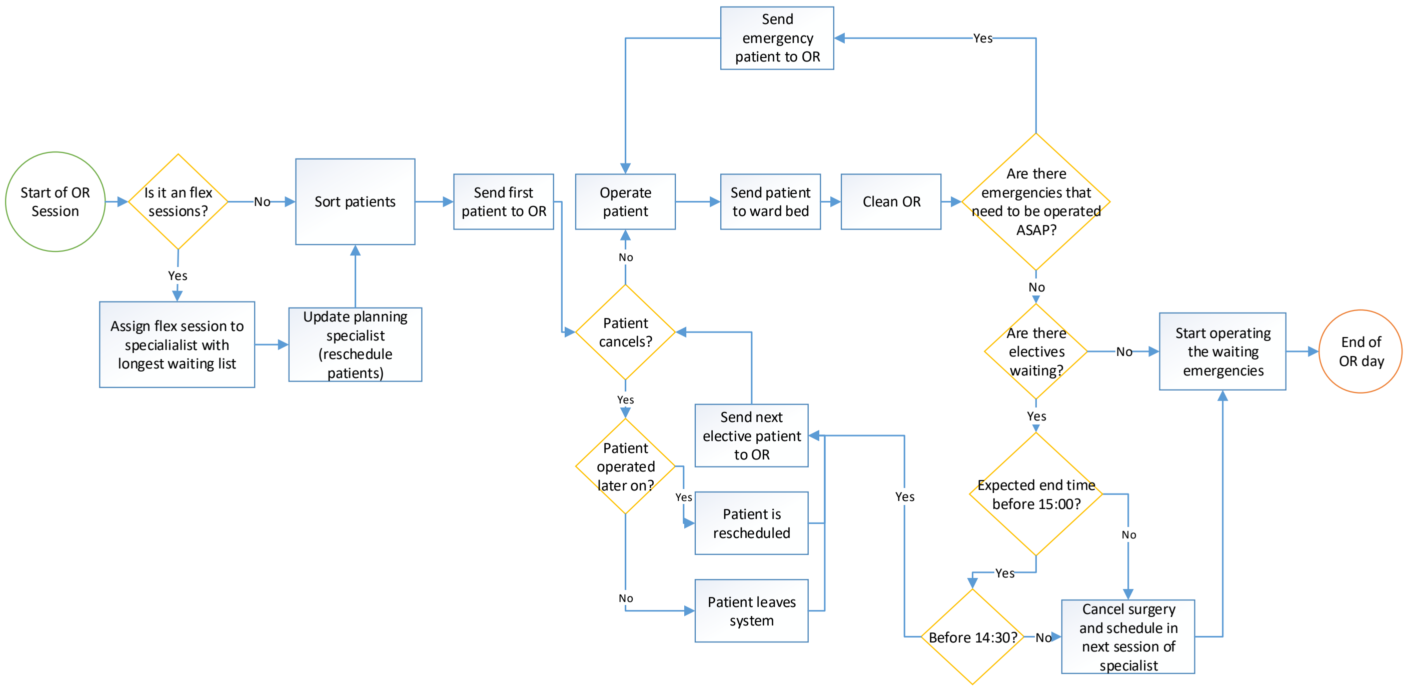


Figure 4.6: Patient handling during an OR session

4.2.4. Assumptions

This subsection recapitulates on the assumptions we make in our conceptual model. All these assumptions are validated with OR management of HOH.

- Inpatients are operated in the inpatient ORs, outpatients are operated in the outpatient OR.
- Emergency patients cannot be operated in the outpatient OR.
- Flex sessions are assigned to the specialist with the longest waiting list (number of patients in combination with time to the last scheduled patient).
- Elective surgeries for which the expected end time is after 15:00 are cancelled.
- Elective surgeries that did not start at 14:30 are cancelled.
- We assume a cancellation rate of 6,3% (based on historical data), of which the patient is responsible in 60% of the cases.
- 45% of the cancellations do not return for surgery and leave the system. All these cancellations have 'patient' as cause.

- POS, personnel, instruments and capacity of ward beds are not considered as separate parameters in the model but included in the cancellation rate.
- Booked duration is based on the average duration of the surgery type.
- Outside OR hours OR1 is used for operating emergency patients.
- The access time for elective patients is at least 14 days.
- There is no exchange of patients between specialists.
- Emergency patients are not assigned to a specialist, we assume there is always a specialist available to operate emergency patients.

4.3. Validation

We program the simulation model in Siemens Tecnomatix Plant Simulation. See Appendix B for the technical description of the model. We use a warm-up period of 102 days and replicate the model five times, as discussed in Appendix C.

In the remaining part of this section, we validate the simulation model: To what extend does the model reflect the realization? Since we use data of the period January 2016 - June 2017 for measuring the current situation, we use the session roster of this period for the validation. This includes the emergency OR that was introduced from July 2016. We compare the number of elective- and emergency patients that enter the system, i.e., the input of the system, with the realization. Then, we discuss the performance of the ORs, i.e., the output of the simulation model, and compare this with the realization. All performance measurements are presented in averages over the five replications. In Subsection 4.3.3, we conclude whether our simulation model is valid.

4.3.1. Input

Table 4.3 shows the number of elective and emergency patients per specialty and compares the simulation input with the realization. There are 308 patients in the realization for which their surgery was cancelled and are not operated at all. We do not know the specialties of these surgeries, and therefore we assume that these are proportional divided over the specialties. Table 4.4 shows how the emergency patients are divided over the different urgency levels and compares the simulation input with the realization. The number of elective- and emergency patients per specialty, and the number of emergency patients per urgency level of the simulation are comparable with the realization.

Table 4.3: Comparison realization and simulation per specialty

Specialty	#Electives - Realization	Electives input - Simulation	#Emergencies - Realization	Emergencies input - Simulation
General Surgery	2701	2799.4	1383	1388.0
Ophthalmology	2276	2334.4	96	86.6
Gynecology	1249	1280.4	794	809.2
Orthopedics	1284	1325.0	299	302.2
Plastic surgery	708	707.6	73	79.6
ENT	701	734.4	61	58.6
Urology	626	660.6	118	118.4
Neurosurgery	402	421.2	58	57.0
Pain Treatment	417	432.2	32	30.6
Cardiology	99	99.2	30	29.4
Other	24	N/A	24	N/A
Cancelled, unknown Specialty	308	N/A	N/A	N/A
Total	**10,795**	**10,794.4**	**2968**	**2959.6**

Table 4.4: Emergency patients per urgency level

Urgency	Realization	Simulation
A	419	387
B	1105	1100.6
C	1091	1146
D	353	326
Total	**2968**	**2959.6**

Table 4.5 shows the average surgery durations of the realization and simulation per specialty for both patient types. To see whether there is a significant difference in average durations, we perform two two-sample t-test, electives and emergencies, for all specialties. All specialties pass both tests, which means we state that with a significance of α=5% there is no difference between the averages of simulation and realization. See Appendix D for the results of the two-sample t-tests.

Table 4.5: Average surgery durations per specialty

Specialty	Average Surgery Duration (min) Electives - Realization	Average Surgery Duration (min) Electives - Simulation	Average Surgery Duration (min) Emergencies - Realization	Average Surgery Duration (min) Emergencies - Simulation
General Surgery	64.3	64.1	70.5	70.1
Ophthalmology	23.0	22.9	22.4	24.8
Gynecology	63.5	63.2	50.1	49.8
Orthopedics	76.5	76.8	90.8	91.4
Plastic Surgery	79.9	80.3	103.3	105.9
ENT	46.9	46.8	46.3	46.3
Urology	76.2	75.3	53.9	55.8
Neurosurgery	90.1	94.1	91.4	91.4
Pain Treatment	28.8	28.8	27.9	27.9
Cardiology	82.6	85.2	84.6	87.9
Average	**57.0**	**57.2**	**65.1**	**65.5**

The number of elective- and emergency patients in our simulation model is comparable to the reality and we have proven that there is no difference in the average surgery durations between simulation and reality. Concluding, there is no difference between simulation and reality concerning the input of patients.

4.3.2. Output

Table 4.6 and Table 4.7 show the differences between the output of the simulation model and the realization per OR. The overall utilization of the realization is higher than the utilization of the simulation model. Furthermore, the simulation model shows a higher percentage of early end, and less overtime. In Appendix D we perform 2-sample t-tests on the average utilization per OR to see if there is a difference between simulation and realization. The results of these tests show that there is a significant difference. In the remainder of this section, we explain this difference.

Table 4.6: Simulation results current situation in minutes

OR	Sessions	Late start	Utilization	Changeover	Early End	Overtime
OR1	367.2	3%	71%	21%	5%	3238
OR2	360.8	4%	67%	20%	9%	2017
OR3	368.6	4%	67%	19%	10%	2877
OR4	363.8	4%	65%	18%	13%	2703
OR5	369	5%	68%	18%	9%	2927
OR6	338	8%	52%	17%	23%	614
Total	**2167.4**	**5%**	**65%**	**19%**	**11%**	**14,377**

Table 4.7: Realization current situation in minutes

OR	Sessions	Late start	Utilization	Changeover	Early End	Overtime
OR1	371	3%	75%	18%	4%	7233
OR2	355	4%	70%	19%	7%	5034
OR3	371	4%	72%	19%	5%	6452
OR4	357	4%	73%	18%	6%	5236
OR5	373	4%	73%	20%	3%	7698
OR6	328	11%	49%	19%	21%	1054
Total	**2155**	**5%**	**69%**	**19%**	**7%**	**32,707**

Table 4.8 shows the difference in throughput of the simulation and realization. Note that we only consider the elective patients that arrive and leave the system during the simulation period, as there are also patients that arrived during the warm-up period and are operated during the simulation period and patients that arrived during the simulation period, but are not operated yet at the end of the simulation.

We identify three categories of cancelled patients: 'cancellations with no planning cause', 'cancellations due to planning' and 'cancelled, not operated'. The first category is independent from the planning. Examples of causes for these cancellations are 'patient is ill' and 'materials out of stock'. The second category contains patients that were cancelled because the OR program overran. The third category are patients that are also part of the first category and leave the system after cancellation. These groups of patients are never operated. Table 4.8 shows that the number of patients in the first and third category are equal in percentage, and there is a big difference in the second category between realization and simulation.

As we showed in Chapter 2, the probability that a program finishes in time is bigger when it has a high booking rate, so personnel are probably more eager to finish in time. Our simulation model does not consider this phenomenon. Another reason for the difference could be that in reality patients are not always cancelled when the expected end time is after 15:00.

Table 4.8: Operated patients and cancelled patients

	Realization	Simulation
Electives Input	10,795	10,794.4
Total Operated	10,487	10,018.6
Cancellations with no planning cause	685 (6.3%)	676.6 (6.3%)
Cancellations due to planning	251 (2.3%)	791.2 (7.3%)
Cancelled, not operated	308 (2.9%)	308.8 (2.9%)
Total cancelled	936 (8.6%)	1467.8 (13.6%)

The total number of elective patients operated in the simulation model is less, while the total OR capacity is slightly more (see Table 4.6 and Table 4.7), which explains the lower utilization, higher percentage early ends and less overtime. Less flexibility in the simulation model compared to reality clarifies this difference in operated patients. In reality, specialists exchange OR session time which helps reducing the waiting lists. The simulation model does not allow specialists to operate in sessions of another specialist. With the help of Table 4.9, we explain the difference in flexibility between simulation and reality.

Table 4.9 gives the number of sessions, the average booking rate of these sessions, the number of flex sessions assigned, the waiting list and utilization per specialty. In the booking rate changeover times are included, but lunchbreaks are excluded, i.e., if an OR session has 390 booked minutes, it has a booking rate of 100%. In utilization, only the surgery time is included, i.e., if during an OR session 210 minutes are used for surgery, the utilization is 50%. The column 'Waiting List' represent the number of patients waiting for surgery at the end of the simulation. Although the waiting lists are snapshots, they give an indication about the distribution of OR sessions between specialties. Cardiology, Plastic Surgery, Orthopedics, Urology, Neurosurgery and General Surgery have a long waiting list in relation to their input. Ophthalmology and Pain Treatment have a short waiting list in relation to their input. We suspect from this that the session roster is suboptimal, and OR sessions should be allocated differently to operate more patients. Some specialties should have more sessions and others could have less.

Table 4.9: Simulation output per specialty

Specialty	Sessions	Booking Rate	Flex Sessions	Waiting List	Waiting list in % of input	Utilization
General Surgery	572.1	83%	47.2	294	11%	68%
Ophthalmology	254	66%	0	84	4%	50%
Gynecology	269.9	82%	0.8	113	9%	70%
Orthopedics	310.1	87%	22.4	173	13%	71%
Plastic surgery	171.2	83%	11	124	18%	73%
ENT	115.6	84%	2	58	8%	68%
Urology	149.3	87%	6	80	12%	73%
Neurosurgery	114.3	81%	4.8	51	12%	75%
Pain Treatment	64.8	64%	0	19	4%	51%
Cardiology	23.2	85%	1.8	18	18%	73%
Emergency OR	122.9					31%
Total/average	**2167.4**	**76%**	**96**	**1014**	**9%**	**65%**

In this section, we have shown that the output of the simulation model differs from the reality. Shorter changeover times and earlier starts, when the OR session has a high booking rate, help to prevent patients being cancelled. This happens in reality, but the simulation model does not take this into account. Furthermore, there is a difference in utilization, early ends and overtime. The reason for this is more flexibility in assigning OR time to specialists. With flexibility, more patients are operated, the length of the waiting lists are reduced and ORs are better utilized.

4.3.3. Conclusion

There is no significant difference between the input of the simulation model and the reality. However, there is a significant difference in the average utilization of the ORs between the simulation and realization, because in reality there is more flexibility in allocating OR session time. Despite these differences, we continue with this model for our experiments. However, we need to keep the deviation between realization and simulation in mind when we interpret the results of the experiments. Especially experiments that add flexibility to the system can have less influence in reality, because there is already additional flexibility in reality.

4.4. Experiments

We identify two types of experiments for our simulation study. The first category is called Scheduling Interventions. With this type of experiments, we measure the impact of a change in the scheduling strategy (Subsection 4.4.1). In Subsection 4.4.2 we elaborate on the second category: Potentials for Improvement. These experiments do not consider the scheduling strategy, but give HOH insights on how they can improve the overall OR performance if they improve in certain areas. We give the settings of the baseline experiment is Subsection 4.4.3 and Subsection 4.4.4 gives the KPIs to measure the OR performance of the experiments.

4.4.1. Scheduling Interventions

We experiment with the following four different interventions concerning the scheduling strategy, selected in Chapter 3:

1. Emergency OR: reserving capacity for emergency surgeries during the afternoon session in one of the inpatient ORs. The elective program only needs to be interrupted for urgency A emergencies. For other urgency levels, we wait until the afternoon session to operate them in the emergency OR. In the setting without the emergency OR, the elective program needs to be interrupted for urgency A emergencies, but also urgency B emergencies if they arrive before 10:00.
2. Request List: using the request list for all patient that were cancelled with an organizational cause. If a surgery was canceled, e.g., due to material not in stock or program overrun, the patient is added to the request list. At the end of every day, we try to reschedule these patients the next day in a session of another specialist. If this is not possible, we try the day after that. If there is not enough capacity available to schedule such a patient until the next session of the performing specialist, the patient is rescheduled in this session. The simulation setting without the request list reschedules the cancelled patients in the next session of the performing specialist.
3. Minimum Booking Rate (MBR): if the booking rate of a session is below the minimum booking rate at the beginning of the OR day, the session is given to another specialist. We select the specialist that receives the OR session, the same way we assign flex sessions to specialists, according to the length of the waiting list and the last date the last patient of the waiting list is scheduled (see Subsection 4.2.3).
4. Slack: the maximum booking rate decreases with a certain percentage to cope with overrun of surgeries and/or interruption of the elective program due to arrival of emergency patients.

Table 4.10 shows the different possible settings per scheduling intervention. For Emergency OR and Request List, we use the settings True and False, which indicates if we make use of an emergency OR and/or request list or not. The values of MBR and Slack are given in percentages of the OR capacity, excluding lunchbreaks. Thus, in an experiment with 50% MBR and 10% Slack, the total number of booked surgery and changeover minutes of one session should be at least 195, but no more than 351. We perform a full factorial experiment on the Scheduling Interventions, which results in 140 different experiments.

Table 4.10: Values per setting scheduling intervention

Setting	**Values**	**Number of values**
Emergency OR	True - False	2
Request List	True - False	2
MBR	0%-20%-30%-40%-50%	5
Slack	0%-2.5%-5%-7.5%-10%-12.5%-15%	7

4.4.2. Potentials for Improvement

The experiments Potentials for Improvement are not related to the scheduling strategy, but are of influence to the overall OR performance. If HOH succeeds in improving in one of the potentials, HOH's overall OR performance might increase. We select the following experiments:

1. Perfect Start: all OR sessions start at exactly 7:30.
2. Fast Changeovers: changeover time decreases.
3. Increased Booking Accuracy: the difference in deviation between booked duration and actual surgery duration decreases.

We perform these experiments to give HOH some insight. Further research is needed on what HOH should do to realize starting on time, accomplishing faster changeovers and increasing the booking accuracy. We assume that these experiments are independent, e.g., if Perfect Start and Fast Changeovers have a positive influence on the utilization separately, combining these two also has a positive influence. Therefore, we change the value of one setting at the time and keep the values of the other settings in the baseline situation. We make one exception: we do one experiment with the best settings, to see what the maximum performance can be. Table 4.11 shows the possible values for the Potentials for Improvement. In total, there are 13 experiments (1 baseline experiment, 1 Perfect Start, 5 Fast Changeovers, 5 Increased Booking Accuracies, 1 best settings).

Table 4.11: Values per setting Potentials for Improvement

Setting	**Values**	**Number of values**
Perfect Start	True - False	2
Fast Changeovers	0%-5%-10%-15%-20%-25%	6
Increased Booking Accuracy	0%-10%-20%-30%-40%-50%	6

4.4.3. Baseline experiment

The baseline experiment represents the settings for the current situation at HOH. We give the settings and corresponding values in Table 4.12. HOH reserves one inpatient OR during the afternoon session for emergency surgeries, thus the value for the setting 'Emergency OR' is true. The request list is already in use at HOH (see Chapter 2 and Section 4.2), however it is not used consequently, i.e., not all cancelled patients with organizational cause are added to the request list. Since we want to see what happens if all these patients are added to the request list, we simulate the baseline experiment without the request list. In experiments with the setting 'Request List = True' all patients that were cancelled for organizational reasons are added to the request list and operated as soon as possible (see Section 4.2). There is no minimum booking rate for OR sessions and no slack, which means the specialist can book their OR session from 1 minute (there should be at least one surgery in a session) up to 390 minutes, including changeovers. The settings for the Potentials for Improvement reflect the current situation at HOH, which means these settings are according to the identified distributions for starts, changeovers and surgery duration (see Section 4.1). Booking accuracy is the difference between the real surgery duration and booked surgery duration, which is the mean of the distribution.

Table 4.12: Baseline settings

Setting	**Value**
Emergency OR	True
Request List	False
MBR	0%
Slack	0%
Perfect Start	False
Changeover Savings	0%
Increased Booking Accuracy	0%

The total number of experiments is 152, since the baseline experiment is the first experiment of both the Scheduling Interventions and Potentials for Improvement (140+13-1).

4.4.4. Simulation output

Per experiment we store the defined KPIs, i.e., utilization, overtime, cancelations, service degree emergencies and access time electives (see Section 2.8). Besides the KPIs, we store the number of elective patients operated. There is a maximum realizable utilization, because the number of elective patients is limited. To put the utilization in perspective, we also store the elective patients operated as a percentage of the total elective patients.

We measure the output variables as following:

1. Elective patients operated: percentage of elective patients operated during the simulation time in comparison to the number of arrived elective patients.
2. Utilization: utilized OR capacity, surgery time of elective and emergency patients (excluding changeover time), within opening hours of the OR.
3. Overtime: total of surgery time after 14:30, emergency surgery time excluded.

4. Cancellations: number of patients that are cancelled due to overrun of the OR program.
5. Service degree of emergency patients (SDE): number of emergency patients that do not meet the service requirements.
6. Average access time (AAT): average time between patient arrival and surgery day of elective patients, in days.

4.5. Conclusion

In this chapter, we developed a simulation model according to the Seven-step approach (Law, 2003). Although the simulation model did not pass all validity tests, we can use it for our experiments. We showed that the simulation has less flexibility compared to the reality and therefore we need to keep in mind that experiments that add flexibility to the system can have less impact in reality. Furthermore, we formulated two types of experiments: Scheduling Interventions and Potentials for Improvements. Scheduling Interventions has four different settings:

1. Emergency OR
2. Request List
3. Minimum Booking Rate (MBR)
4. Slack

Potentials for Improvements has three different settings:

1. Perfect Start
2. Fast Changeovers
3. Increased Booking Accuracy

Per experiment we store the following output variables:

1. Elective patients operated
2. Utilization
3. Overtime
4. Cancellations
5. Service Degree of Emergency Patients (SDE)
6. Average Access Time (AAT)

In total, we simulate 152 experiments. The next chapter elaborates on the results of these experiments.

Chapter Five – Results

In Chapter 4, we showed the data we use, constructed the conceptual model, programmed the simulation model, validated this model, selected the experiments and defined the output variables to measure the performance of the experiments. Following the steps from Law (2007), we perform the experiments, analyze the results and select the intervention possibilities for implementation in this chapter. Therefore, this chapter answers research question 4: *What is the effect on OR performance for the suggested scheduling strategies?* First, we show the simulation output of the Scheduling Interventions in Section 5.1. Section 5.2 assigns weights to the KPIs. After that, we discuss the scoring method in Section 5.3. Section 5.4 analyzes the results of the experiments. Then, in Section 5.5, we show some overall results of the scheduling interventions on the KPIs. To check whether the settings of the best performing experiment is a robust solution, we do a sensitivity analysis in Section 5.6. Section 5.7 discusses Potentials for Improvement. Finally, we give a summary of this chapter in Section 5.8. In Chapter 6, we discuss how the suggested intervention possibility should be implemented.

5.1. Simulation output

In Appendix E, we show the settings of all 140 Scheduling Interventions and the corresponding output (see Section 4.4 for a recapitulation of the settings and output variables). Electives Operated is given as a percentage of the input of elective patients, e.g., if 1000 patients enter the system and 900 are operated in the simulation period, this output variable gives 90%. Reaching 100% is impossible, because there are patients that leave the system without being operated. SDE gives the number of emergency patients for which the service degree was not met (see Subsection 4.2.2 for the service requirements per urgency level). An SDE of 0.2 means that there is one emergency patient in five years for which the service requirement was not met. Utilization is a percentage of the total session capacity, Overtime is given in minutes, Cancellations are cancelled patients and AAT is in days. The first experiment shows the settings and results of the baseline situation.

5.2. Weights assignment

Before we assign weights to the KPIs, we consider the correlation between the output variables of the simulation model. Table 5.1 shows these correlations. Output variables with a high correlation might be related, which we need to keep in mind when assigning the weights to the KPIs. We do not exclude the KPIs that were defined in Section 2.9, since we want that the most important stakeholders should be represented with the KPIs and we believe these are the best to do that.

There is a great positive correlation between Electives Operated and Utilization, which means when the number of operated patients is high, the utilization is also high. If more elective patients are operated within OR session time, the utilization increases. Also, Overtime and Cancellations are correlated. This seems logical, because the moment of cancellation and rules for overtime do not differ between the various experiments, i.e., a patient is cancelled if the expected end time is after 15:00 or the surgery did not start before 14:30. There is a high negative correlation between Utilization and AAT, which indicates that a high utilization shortens the access time of elective patients.

Table 5.1: Correlation between the output variables

	Electives Operated	Utilization	Overtime	Cancellations	SDE	AAT
Electives Operated	1.00					
Utilization	0.99	1.00				
Overtime	0.83	0.80	1.00			
Cancellations	0.70	0.68	0.96	1.00		
SDE	0.75	0.72	0.55	0.41	1.00	
AAT	-0.99	-0.97	-0.85	-0.72	-0.76	1.00

By assigning weights to the KPIs, we make distinctions of importance between the KPIs. Since a low utilization of the OR resources is the motive for this research, we consider Utilization as the most important KPI and give this KPI the weight of 0.5. Cancellations is the second most important KPI and receives a weight of 0.2. We consider Overtime, SDE and AAT as equally important but less important than Cancellations and Utilization, therefore we give these three KPIs a weight of 0.1. The weights sum up to 1, which means if there is an experiment which is the best on all five KPIs, it gets an overall score of 100%. Table 5.2 summarizes the weights per KPI.

Table 5.2: Weights per KPI

KPI	Weight
Utilization	0.5
Overtime	0.1
Cancellations	0.2
Service Degree Emergency	0.1
Average Access Time	0.1

5.3. Scoring method

Before we calculate the performance of the different experiments in Section 5.4, we define the method of scoring the experiments in this section. First, we determine the relative score of the experiments on the individual KPIs. We use a linear scale between the best and the worst score, and rate the best score with 100% and the worst score with 0%. For example, Experiment 18 has 616.6 cancellations, which is the most of all experiments and therefore gets a 0% score on this KPI, Experiment 129 has the best score on this KPI with 180.6 cancellations and thus receives a score of 100%. All other experiments get the relative score between 0% and 100% according to their number of cancellations. Now, we determine the overall score by summing the individual scores on the KPIs multiplied with the weights of the KPIs:

$$Experiment\ overall\ score = \sum_{i=KPIs} Weight_i * Experiment\ Score_i$$

5.4. Analysis of the results

In this section, we use the weights of the KPIs of Section 5.2 and the method of scoring in Section 5.3 to determine the overall scores of the experiments. In Table 5.3, we show the scores of the best experiments and in Table 5.4 we show the settings of these experiments. In both tables, we give besides the five best experiments, also the baseline experiment, Experiment 1.

All five experiments have no Emergency OR and make use of the Request List in their settings. The MBR is three times 50%, one time 40% and one time 30% and the Slack is between 5% and 12.5%. The overall scores of the best experiments are very close to each other, i.e., between 73% and 75%.

Table 5.3: Scores of the best five experiments

Ranking	Experiment	Utilization	Overtime	Cancellations	SDE	AAT	Score
1	60	69.3%	8524	418.6	1	28.8	75%
2	96	67.6%	6331	315.8	0.4	34.6	75%
3	80	68.8%	7532	378.4	1.2	31.9	73%
4	120	67.0%	5708	247.4	0.6	38.3	73%
5	52	68.6%	8753	411.6	0.4	29.4	73%
129	1	64.8%	8460	521.6	0	43.2	47%

Table 5.4: Settings of the best five experiments

Ranking	Experiment	Emergency OR	Request List	MBR	Slack
1	60	FALSE	TRUE	50%	5.0%
2	96	FALSE	TRUE	40%	10.0%
3	80	FALSE	TRUE	50%	7.5%
4	120	FALSE	TRUE	50%	12.5%
5	52	FALSE	TRUE	30%	5.0%
129	1	TRUE	FALSE	0%	0%

The best performing experiment, Experiment 60, has an improvement of 6.5% on the utilization compared to the baseline experiment, Experiment 1. Furthermore, we notice the following changes when we compare these experiments: the amount of overtime increases with 0.8%, the cancellations decrease with 19.7%, the SDE increases with 1, and AAT decreases with 33.3%. Table 5.5 summarizes these mutations. The direction of the arrow indicates an increase or decrease of the KPI. The color indicates an improvement or deterioration of the KPI, i.e., green means improvement and red means deterioration.

Table 5.5: Mutation of KPIs best performing experiment opposed to the baseline experiment

KPI	Decrease/increase
Utilization	6.5%↑
Overtime	0.8%↑
Cancellations	19.7%↓
SDE	1↑
AAT	33.3%↓

Table 5.4 shows that none of the top 5 experiments has an emergency OR. This is because the emergency OR has a great negative influence on the utilization, i.e., the emergency OR has a utilization of 31% in the validation model, see Table 4.9. To keep the overtime, cancellations and service degree for emergency patients under control, slack is needed to anticipate to incoming emergency patients and overrun of surgeries, but also the overrun of changeovers. The best experiment, Experiment 60, has 5% slack, however it would not hurt to add some extra slack, since this decreases the overtime and cancellations. As we have shown in Chapter 2, there is an underestimation of the booked changeover times. We expect that less slack is needed if the changeovers are better estimated.

If we only consider experiments with an emergency OR, we see that less slack is preferable. Instead of slack between 5% and 12.5%, in this case, the best experiments have settings between 0% and 5% slack. A little bit of slack seems recommendable since the experiment with 2.5% and 5% has a higher overall score than the setting with 0% slack. Furthermore, we see that a high MBR and Request List still have a positive influence on the overall OR performance.

We conclude that Request List has a positive influence on the overall OR performance, since all experiments in the top 5 in Table 5.4 have this setting. By using the request list, elective patients are operated earlier compared to the situation without the request list, which has a positive influence on AAT. Furthermore, the elective patients that are cancelled are rescheduled in sessions that have capacity left, so this capacity would not have been used without the request list.

We notice that a high MBR has a positive influence on the overall OR performance, since the experiments with 50% MBR end up higher in the ranking than experiments with lower MBR. Thus, we conclude the higher the MBR, the better. However, we suspect there is a limit to the overall OR performance if the MBR ever increases. Therefore, it is unfortunate that we did not select experiments with MBR higher than 50% to see what the limit is.

It is noticeable that the three settings with 50% MBR have 5%, 7.5% and 12.5% Slack and the experiment with 50% MBR and 10% Slack is not in the top 5. This experiment, Experiment 100, finishes on the 9th place. The reason for this is the SDE of 1.4 for this experiment, which is relatively high compared to the other experiments. It is a coincidence that the output of this KPI for this experiment is high, i.e., the scheduling algorithm for emergency patients in our simulation model is not very robust, which can lead to long waiting times for individual emergency patients. This is also the reason that Experiment 56 (No emergency OR, Request List, 40% MBR, 5% Slack), the experiment that lies in the middle of Experiment 52 and Experiment 60, is not close to winning with a ranking of 23, because it also has an SDE of 1.4. Although the absolute difference in SDE is small, the relative difference is huge. The worst score on this KPI has an SDE of 2.4, the best score has an SDE of 0. Thus, an experiment with an SDE of 0.4 scores 83% on this KPI and an experiment with an SDE of 1.4 scores only 42% on this KPI. Even though SDE has a weight of 0.1, a difference of 1 can make a big difference on the overall score.

Furthermore, we realize that SDE is not always a good KPI to measure the service of emergency patients, which we show by comparing Experiment 60 and Experiment 80. Experiment 60 has the best overall score and also the highest utilization, but the worst score on overtime and cancellations of the five best experiments. Experiment 80 ends third and has the same settings as Experiment 60 except it has 2.5% more slack. Experiment 80 has less utilization, overtime, cancellations and a more average access time than Experiment 60, which is exactly what we would expect according to Table 5.4. However, the SDE is higher for Experiment 80 than Experiment 60, which is unexpected. The difference for this KPI between the two experiments is very small, therefore we show the average and maximum waiting time per urgency level for both experiments in Table 5.6 and Table 5.7 to get some more insights. These tables show that Experiment 80 has better average waiting times for urgencies A, B and C. However, the number of times that the service requirements are not met is slightly higher for Experiment 80 and therefore Experiment 60 gets a better score on the KPI SDE.

Table 5.6: Performance emergency surgeries Experiment 60

Urgency	Average Waiting Time (min)	Maximum Waiting Time (min)	SDE
A	2.01	76.11	0
B	18.06	494.20	0.6
C	168.24	1452.28	0.4
D	163.67	1177.66	0

Table 5.7: Performance emergency surgeries Experiment 80

Urgency	Average Waiting Time (min)	Maximum Waiting Time (min)	SDE
A	1.88	100.28	0
B	17.90	566.48	1.2
C	165.82	1389.01	0
D	164.80	1160.40	0

Knowing that a small absolute difference in SDE can make a big difference on the overall score, and SDE is not always the best KPI when measuring the service of emergency patients, we keep this in mind when we analyze the results. Besides that, we perform a sensitivity analysis in the next section in which we show what happens if we exclude SDE as KPI.

The scheduling algorithm for emergency patients in our simulation model is not robust, but we expect that OR management can steer the scheduling decisions in practice, if necessary. For example, if OR management notices that service requirements for B or C urgencies are at risk, they can anticipate to this by letting one OR team work in overtime, so that the emergency patient can be operated earlier.

In Chapter 4, we stated that experiment that increase flexibility have less impact in reality because there is already more flexibility in reality compared to the simulation model. Experiments with MBR and/or Request List add this flexibility by exchanging OR session time between specialists. The ORs are 69.3% of the time utilized in Experiment 60, which is an increase of almost 7% compared to the baseline experiment. We realize that the utilization will not increase with the same magnitude if we would implement the settings of Experiment 60 in reality. In the next section, we perform a sensitivity analysis before we decide what the best solution for HOH is.

5.5. Input - output relations

In this section, we show the overall effect of the input variables on the KPIs. Per input variable we take the extreme values and do a paired comparison between the experiments. The input variables have the following extreme values:

1. Emergency OR: False - True
2. Request List: False – True
3. Minimum Booking Rate: 0% - 50%
4. Slack: 0% - 15%

There is a positive effect on utilization if the maximum value of the input variable gives a higher utilization than the minimum value of the input variable. For the other output variables, there is a positive effect if the output value is lower for the maximum value than the minimum value, e.g., if using the request list shortens the average access time, we recognize this as positive. Table 5.8 shows the results of these effects of input variables on output variables. If there is a positive effect for all paired comparisons, the table shows '++'. '--' indicates that there is a negative effect for all paired comparisons. If most comparisons, but not all, are positive or negative, we give the relation '+' or '-', respectively. When there is no clear negative or positive effect, we mark the relation with '0'. Keep in mind that the values in the table do not indicate the magnitude of the effect, but only if there is a positive or negative effect in all cases or in most cases. The paired comparisons between the extreme values of the input variables and effects on the output variables are visualized in Appendix F.

Table 5.8: Input-output relations

Input/KPI	Utilization	Overtime	Cancellations	SDE	AAT
Emergency OR	--	++	+	++	--
Request List	+	-	0	0	++
MBR	++	-	-	-	++
Slack	--	++	++	+	--

We relate the results in Table 5.8 to the booking rate of the OR sessions. If more elective surgeries are scheduled in the OR sessions, the booking rate increases and all KPIs increase, thus the effect on utilization and AAT are positive, but the effect on overtime, cancellations and SDE are negative. The input variables Emergency OR and Slack reserve OR capacity for emergency surgeries and thus the booking rate decreases. The booking rate increases with MBR, because sessions with low booking rate disappear. The same number of patients are scheduled when using Request List compared to not using Request List, since all cancelled patient are rescheduled, but Request List reschedules these patients earlier. Therefore, Request List shows a clear positive effect on AAT, but no clear increase or decrease of cancellations and

SDE. The effect on utilization is positive in most cases, because cancelled patients are rescheduled in sessions that have enough remaining capacity, but this also increases the probability of overtime for these sessions and thus the overtime increases.

5.6. Sensitivity analysis

To check whether our best solution is a robust solution, we perform a sensitivity analysis. We want to know what the effect on the result is if a KPI is not important at all. We change the weight of the unimportant KPI to 0 and adjust the other KPIs, so that the relative difference in weights between these KPIs remain the same. We do this for all KPIs and analyze the new top 5 of best experiments and give the ranking of the initial top 5 in Table 5.9.

Table 5.9: Sensitivity analysis

	Weights				
KPI	**Utilization=0**	**Overtime=0**	**Cancellations=0**	**SDE=0**	**AAT=0**
Utilization	0	0.56	0.63	0.56	0.56
Overtime	0.20	0	0.13	0.11	0.11
Cancellations	0.40	0.22	0	0.22	0.22
SDE	0.20	0.11	0.13	0	0.11
AAT	0.20	0.11	0.13	0.11	0
Ranking	*Experiments*				
1	138	**60**	38	**60**	**96**
2	140	**52**	**60**	**80**	**120**
3	122	38	18	100	118
4	128	**80**	14	78	140
5	136	**96**	**52**	**96**	138
Experiment	*Ranking*				
60	93	1	2	1	8
96	48	5	16	5	1
80	87	4	9	2	10
120	36	12	33	8	2
52	79	2	5	12	18

From Table 5.9, we conclude that the best experiment identified in Section 5.4, Experiment 60, is also a robust solution. This experiment finishes 1st, 2nd, 1st and 8th when the weights of the KPIs overtime, cancellations, SDE and AAT change to 0, respectively. Except when utilization becomes unimportant, Experiment 60 is far away from winning, which is also the case for the other experiments in the top 5.

In Section 5.4, we showed that SDE is a doubtful KPI and therefore the column ‘SDE=0’ from Table 5.9 is interesting. This column shows that Experiment 60 is also the winner when we exclude SDE as a KPI. Experiment 80 and Experiment 100 finish second and third in this ranking. These experiments have the same settings as Experiment 60, except these experiments have 7.5% and 10% Slack, respectively.

Therefore, we propose the settings of these experiments and a Slack range between 5% and 10%, for implementation.

5.7. Potentials for Improvement

We show the output results of the Potentials for Improvement in Table 5.10. Perfect Start gives the best result on increasing the utilization and decreasing the overtime and cancellations. This seems logical because starting later than expected, increases the probability of ending later than expected. Besides Perfect Start, Fast Changeovers and Increased Booking Accuracy also have a significant influence on the overall OR performance. As we showed in Chapter 2, the realized changeovers take longer than the booked changeovers. If this gap decreases, we expect that the program more often ends before the end of the OR session, which reduces the overtime and cancellations. Increasing the booking accuracy ensures that HOH knows better when a surgery ends. Accordingly, the probability of ending in time increases. How the Potentials for Improvement can be realized is out of the scope of this research. Therefore, we propose these topics as further research areas.

Table 5.10: Output results Potentials for Improvement

Exp. No.	Perfect Start	Fast Changeovers	Increased Booking Accuracy	Electives Operated	Utilization	Overtime	Cancellations	SDE	AAT
1	FALSE	0%	0%	91%	64.8%	8460	521.6	0	43.2
2	TRUE	0%	0%	92%	66.2%	6910	316	0	40.8
3	FALSE	5%	0%	91%	65.0%	8362	476.6	0	42.4
4	FALSE	10%	0%	91%	65.2%	8029	445.2	0.2	42.4
5	FALSE	15%	0%	92%	65.6%	7551	392	0	41.5
6	FALSE	20%	0%	91%	65.7%	7379	361.6	0.2	41.3
7	FALSE	25%	0%	92%	66.0%	7383	321.8	0.2	40.8
8	FALSE	0%	10%	91%	64.8%	7593	548.2	0.2	43.0
9	FALSE	0%	20%	91%	64.9%	6724	521.8	0.2	43.6
10	FALSE	0%	30%	91%	64.9%	6488	495	0	44.1
11	FALSE	0%	40%	90%	64.7%	5924	467.4	0.2	44.3
12	FALSE	0%	50%	90%	64.7%	5403	454.4	0.4	45.0
13	TRUE	25%	50%	91%	66.8%	2617	108.2	0.2	41.3

5.8. Conclusion

In this chapter, we answered research question 4: *What is the effect on OR performance for the suggested scheduling strategies?* First, we selected the following KPIs with corresponding weights to measure the overall OR performance:

1. Utilization – 0.5
2. Overtime – 0.1
3. Cancellations – 0.2
4. Service Degree Emergency (SDE) – 0.1
5. Average Access Time (AAT) – 0.1

We used a relative scoring method to score the experiments on their OR performance and showed that the best performing experiments have the following characteristics:

- Emergency OR – False
- Request List – True
- MBR – The higher, the better, however there is probably a maximum
- Slack – Between 5% and 10%

Comparing the best performing experiment, Experiment 60, with the baseline experiment, Experiment 1, we saw that the following mutations of OR performance on the KPIs: increase of 6.5% on utilization, increase of 0.8% on overtime, decrease of 19.7% on cancellations, increase of 1 on SDE and decrease of 33.3% on AAT.

We expect that experiments that add flexibility, i.e., experiments with the settings MBR and Request List, have less impact in reality compared to the improvement in the simulation model. Therefore, we think the utilization will not increase with the same magnitude, if we would implement such experiment, e.g., Experiment 60, at HOH.

If HOH does not want to lose the emergency OR, the request list and a high minimum booking rate are still of positive influence on the OR performance. Also, slack has a positive influence, but less slack is needed. The best performing experiments with the setting without an emergency OR have 2.5% and 5% slack.

We presented the impact of the input settings on the KPIs, which we relate to the booking rate. If the booking rate increases, the performance on utilization and AAT increase, and the performance on overtime, cancellations and SDE decrease.

We showed that SDE is a doubtful KPI, but with a sensitivity analysis we proved that excluding SDE as a KPI does not change the overall findings of the simulation study.

Furthermore, the Potential for Improvement experiments show that there are other areas than the scheduling strategy in which HOH can invest to improve its OR performance. Perfect Start has a great positive influence on the overall OR performance, but also Fast Changeovers and Increased Booking Accuracy show improvements on the overall OR performance. We propose these topics for further research.

The main findings from this chapter show that HOH can improve its OR performance by changing its scheduling strategy. In the next chapter, Chapter 6, we recommend organizational changes for HOH, so that HOH can implement a scheduling strategy that improves the OR performance.

Chapter Six – Implementation

In this chapter, we recommend on how HOH can implement the suggested changes and therefore answers research question 5: *How should HOH apply the best performing scheduling strategies in practice?* Per experiment setting, i.e., Emergency OR, Request List, MBR and Slack, we discuss from Section 6.1 to Section 6.4 what changes compared to the current situation and what organizational changes should be made to get the desired result. Section 6.5 discusses a step-by-step plan for the implementation and the last section of this chapter, Section 6.6, summarizes of this chapter.

6.1. Emergency OR

The simulation results suggest that HOH can improve its performance on the selected KPIs if the emergency OR is closed. In July 2016, the emergency OR was introduced at HOH. Until then, HOH did not have OR capacity blocked for emergency surgeries, which means HOH is known with this situation. We do not expect that there is much resistance against this decision. By removing the emergency OR, specialists get more OR session time to operate their elective patients. Nonetheless, the specialists' OR programs could be interrupted for emergency surgeries which reduces the OR session time for elective patients of the specialists. Still, the simulation study shows that more elective patients are operated when there is no emergency OR.

6.2. Request List

The simulation study shows that if cancelled patients are rescheduled with the request list, OR performance increases. The biggest gain from using the request list is the decrease in average access time for elective patients. In the current situation HOH makes use of the request list, but not consequently for all cancelled patients with organizational cause. So, HOH is familiar with the request list, but it should organize the use of it differently. Currently, specialists can register their cancelled patients on the request list and the OR planner tries to fit this patient in a session of another specialist.

If HOH wants to use the request list consequently, registering the cancelled patients should be organized centrally. This task could be performed by the OR planner. However, the simulation model assumes that the specialists are always available to operate on sessions that are not their own. In practice the OR planner needs to confer with the specialists about their availability. Besides the availability of the specialist, the patient also needs to be available, which could cause some problems in rescheduling the patient. Furthermore, the OR planner should keep in mind that cancelling the same patient a second time is not desirable. Currently, the cancelled patients are scheduled after the program of the specialist to which the session belongs. If this program overruns, the probability of cancelling increases. Preferably, the cancelled patient should be operated earlier, but the 'owner' of the session should also agree to this. We suggest to start a pilot with a couple of specialists to test what the best scheduling strategy is for rescheduling the patients on the request list. Besides that, a pilot can help to identify and remove the teething problems before implementing this intervention for all specialists.

6.3. Minimum Booking Rate

In the current situation, a specialist needs to hand in his/her OR program three working days in advance and keeps his/her session no matter the booking rate of the session. The simulation shows that MBR has a positive effect on the overall OR performance and therefore we suggest a session should be given to another specialist if the minimum booking rate is not met. The simulation model assigns this session to the specialist that has a long waiting list and the last scheduled patient of the specialist has a long waiting time. Reassigning the session based on the waiting list is currently not possible, since HOH has no insight in the waiting lists of specialists. Specialists should give these insights if HOH wants to reassign the sessions based on the waiting list.

Registering for the sessions on a FCFS base could also be an option. In this way, specialists do not have to share their waiting lists. We suggest an online application in which the sessions are blocked for the specialists according to the session roster until three working days before the OR day, which is also the current deadline. If a specialist does not succeed in filling his/her session up to at least the minimum booking rate, other specialists can claim this session if they are able to do so. The sessions are assigned to the 'fastest' specialists and not the specialists with the longest waiting lists, which is a disadvantage. An advantage of this method is that specialists are forced to hand in their OR program in time. Currently there are no consequences if specialists do not meet the deadline for handing in their program, which happens many times. With this solution the OR planner saves time in contacting the specialist if he/she did not meet the deadline for handing in his/her OR program.

Implementing a minimum booking rate for the OR sessions leads to allocation of OR capacity and changes in the session roster. Besides that, it gives insight in the necessary capacity per specialist, which could lead to allocating the capacity differently. For instance, HOH could decide to make changes in the session roster in advance if exchanges of sessions between the same specialists occur many times.

6.4. Slack

Removing the emergency OR from the session roster leads to more overtime and cancellations and therefore slack is needed to reduce the amount of overtime and number of cancellations as shown in the simulation study. Implementing slack in the OR program is simple: the maximum booked surgery time including changeovers and excluding lunchbreaks should decrease, e.g., from 390 to 370.5 minutes in case of 5% slack. However, this could lead to resistance from the specialists. Intuitively, slack leads to less OR session time for specialists. However, HOH can convince them by showing that the total amount of time for operating elective patients increases by removing the emergency OR from the session roster.

As we showed in Chapter 2, the probability that an OR program takes longer than expected is higher for programs with low booking rate. Therefore, a drawback of implementing slack could be that OR personnel thinks they can take more time to finish the program. Thus, HOH needs to convince OR personnel that they may not take more time than before, and slack is needed to anticipate to the arrival of emergency patients.

6.5. Step-by-step plan

To implement the suggested changes, we propose a step-by-step plan, with the following steps:

1. Create a roadmap together with the OR committee.

Since the OR committee makes the decisions concerning the OR complex (see Subsection 2.2.6), this organ should be central in the implementation. Together with the OR committee we need to decide the sequence of implementing the changes and the time span for realizing the changes by creating a roadmap. Before we create a roadmap with the OR committee, we need to involve the OR committee in this research. First, we present the results of the context analysis, Chapter 2, to show the current OR performance. Then, we present the most important findings from Chapter 5, which include the experiments, the results and the main conclusions. Together with the OR committee, we determine the amount of slack and the minimum booking rate to implement. The roadmap should at least include how to involve specialists and OR personnel, what is needed to train the OR planners and evaluate the changes after a certain period. In case of implementing minimum booking rate, we suggest to develop an application in which the specialist fills in his/her OR program and start a pilot. We shortly discuss these steps below.

2. Involve specialists and OR personnel.

The specialists are represented in the OR committee by three specialists that have a place in this committee. However, we should also involve all other specialists in the implementation. Besides the specialists, we need to involve OR personnel. Especially, the OR planners need to know what changes and what the OR planners need to do differently. We think the staff meetings, that already take place, are suitable to involve specialists and OR personnel.

3. Develop the online application (MBR).

We suggest an online application in which specialist can hand in their OR program for realizing minimum booking rate (see Section 6.3). This application should be integrated with the Chipsoft data, so that the length of the OR program is calculated automatically. Therefore, we think the development of this application can take a lot of time. Besides the time of implementation, this intervention involves the most changes. The specialists, or planners of the specialists, need to hand in their OR program via an online application, which means they need to learn how to use the application. We suggest to start a pilot with specialists that recognize the potential of this innovation and evaluate the pilot before implementing it for all specialists.

4. Evaluate the changes.

During the implementation process, we need to evaluate several times with the OR committee to moderate the progress of the implementations. During these evaluation sessions, OR committee can decide to make changes in the implementations. For example, if OR committee thinks more or less slack is needed, this can be discussed.

6.6. Conclusion

In this chapter, we answered research question 5: *How should HOH apply the best performing scheduling strategies in practice?* All in all, HOH has to make a few changes if it wants to implement the suggested changes. At HOH they are familiar with the situation without the emergency OR. According to the simulation study HOH should use slack, which could lead to resistance from the specialists. They need to be convinced that the new situation results in more OR session time for operating elective patients. HOH already makes use of the request list, but should organize this more centrally by giving the OR planner the task to reschedule all cancelled patients with organizational cause. A drawback of this change is that the OR planner spends more time on consultation with the specialists and patients in finding a new date for the surgery. Implementing minimal booking rate requires the most changes. We suggest an online application in which specialists can hand in their OR program until three working days in advance. If they do not succeed in meeting the minimum booking rate or forget to hand in their OR program, other specialists can claim their session on a FCFS base. For implementing the request list and minimum booking rate, we propose to run pilots. To realize the interventions, we suggest a step-by-step plan that contains the following main steps:

1. Create a roadmap together with the OR committee.
2. Involve specialists and OR personnel.
3. Develop the online application (MBR).
4. Evaluate the changes.

Chapter 7 – Conclusions & Recommendations

In this chapter, we summarize the most important findings of all previous chapters and answer the research questions, that we composed in Chapter 1, in Section 7.1. Then, in Section 7.2 we propose topics for further research. Finally, Section 7.3 discusses the added value of this research to practice and literature. In the next chapter, Chapter 8, we discuss the limitations of this research.

7.1. Conclusions

In this section we repeat all research questions and summarize the answers to these questions. Furthermore, we give the most important findings of this research.

1. *What is the current OR planning process for elective and emergency surgeries, and what resources are used?*

By using HOH's internal report 'Optimalisatie OK-planning' (Groenveld, 2018) and applying the healthcare framework (Hans et al., 2012) on HOH, we identified HOH's resource capacity planning on different hierarchical levels in Chapter 2. Besides that, we created a flowchart to map the OR planning process.

2. *What is the OR performance of the current scheduling strategy?*

Furthermore, we performed a data analysis in Chapter 2, in which we showed several overviews about HOH's specialties, case mix, urgency levels of emergency patients, utilization, late start, early end, overtime, cancellations, booking rate and booking accuracy.

The average utilization is 69%. The inpatient ORs show an average utilization of 73%, the outpatient OR is 49% of the time utilized. The total amount of overtime is 33,603 minutes, which is 4% of the OR session capacity and 15 minutes on average per session. 251 elective patients, 2.4% of all elective patients, needed to be cancelled because of planning reasons. Besides these three KPIs, we selected service degree emergencies and access time electives as KPI.

3. *What are suitable scheduling strategies for elective and emergency surgeries for HOH?*

In Chapter 3, we identified the following scheduling strategies as intervention possibilities for our simulation experiments:

- Switching from a hybrid policy to a flexible policy: stop reserving capacity for emergency surgeries by using the emergency OR (Emergency OR).
- Using the request list consequently (Request List).
- Minimum booking rate for OR sessions (MBR).
- Implementing slack (Slack).

4. *What is the effect on OR performance for the suggested scheduling strategies?*

In Chapter 5, we analyzed the results of the simulation study we performed in Chapter 4 to answer this question. First, we identified the following KPIs with corresponding weights:

- Utilization – 0.5
- Overtime – 0.1
- Cancellations – 0.2
- Service Degree Emergency (SDE) – 0.1
- Average Access Time (AAT) – 0.1

Subsequently, we determined the relative scores of all Scheduling Improvement experiments on the KPIs and calculated the overall score of the experiments. The results showed that experiments with no Emergency OR, a Request List, high MBR and Slack between 5% and 10% gives high OR performance.

Furthermore, we concluded that SDE is not a preferable KPI. We measure the SDE by counting the number of times the service degree for emergency patients is not met. However, the absolute differences between the experiments are very small and therefore the relative difference are large. Besides that, the scheduling algorithm for emergency patients is not very robust and thus coincidence is an important factor for meeting the service requirements. However, the sensitivity analysis showed that the results do not differ much when we exclude SDE as KPI.

Experiment 60 has the best performance and the following settings:

- Emergency OR – False
- Request List – True
- MBR – 50%
- Slack – 5%

Table 7.1 shows the improvement potential of the best experiment, Experiment 60, opposed to the baseline experiment per KPI.

Table 7.1: Mutation of KPIs best performing experiment opposed to the baseline experiment

KPI	**Decrease/increase**
Utilization	6.5%↑
Overtime	0.8%↑
Cancellations	19.7%↓
SDE	1↑
AAT	33.3%↓

Table 7.2 shows the individual effect of the input variables on the KPIs. We relate the effects on the KPIs to the booking rate. If the booking rate increases, the performance on utilization and AAT increase, and the performance on overtime, cancellations and SDE decrease.

Table 7.2: Input – output relations

Input/KPI	Utilization	Overtime	Cancellations	SDE	AAT
Emergency OR	--	++	+	++	--
Request List	+	-	0	0	++
MBR	++	-	-	-	++
Slack	--	++	++	+	--

Concluding, according to the results of the experiments: HOH should stop using the emergency OR, make more use of the request list, make use of slack and adopt a minimum booking rate, since this increases the OR performance.

5. *How should HOH apply the best performing scheduling strategies in practice?*

According to the results of the simulation study, HOH should close the emergency OR. HOH is familiar with this situation, therefore we do not expect much is needed to implement this intervention. Furthermore, the results showed that slack is needed to ensure that the amount of overtime and number of cancellations stay in control. Specialists should be convinced that their OR session time increases when the emergency OR closes and slack is implemented. A drawback of implementing slack is that OR employees could think they have more time for the same amount of surgeries. So, they need to be convinced that this extra time is meant for operating emergency patients.

HOH uses the request list not consequently, but should do this according to the results. The OR planner seems the person to perform the job of rescheduling the cancelled patients. For implementing minimal booking rate, we suggest an online application in which specialists can hand in their OR program. If specialists do not succeed in meeting the minimum booking rate or handing in their program in time, their session becomes available for other specialists to claim it. For implementing the request list and minimum booking rate, we propose to run pilots.

To realize the interventions, we suggested a step-by-step plan that contains the following main steps:

1. Create a roadmap together with the OR committee.
2. Involve specialists and OR personnel.
3. Develop the online application (MBR).
4. Evaluate the changes.

By answering all research questions, we succeeded in accomplishing the research goal.

Research goal:

Evaluate the current surgical scheduling process and design a scheduling strategy to improve the OR performance.

7.2. Further research

7.2.1. Perfect Start

As we concluded in Chapter 5, the Potentials for Improvement experiments all show good results, concerning the OR performance. First of all, starting on time shows the best results. Therefore, we propose that HOH should do further research in the starts of the sessions. However, this is not as simple as it seems. OR personnel need to be present in time, the specialist needs to be present in time, the patient needs to be ordered in time, the patient needs to be brought to the OR from the nursing department in time and the anesthesiologist needs to perform the anesthesia in time. There are three anesthesiologists available during a regular OR day, which implies they cannot perform the anesthesia for all five inpatient ORs at the same time. Besides that, HOH should investigate what the reason is that sometimes the patient is not brought to the OR in time. The OR management is already stressing that OR personnel and the specialists arrive in time at the OR complex. They should continue doing this.

7.2.2. Fast Changeovers

The second Potential for Improvement is the experiment Fast Changeovers. Especially the number of cancellations decrease, when the time for changeovers decrease. However, HOH needs to investigate if it is possible to realize faster changeovers. As we showed in Chapter 2, most changeover do not meet the required time of 9 or 6 minutes. Thus, HOH should do research why these changeovers take longer than expected. Then, HOH could try to decrease the changeover times or increase the booking accuracy by better estimating the changeover times. They should also take a look if the booked changeover times should be OR or specialty dependent.

7.2.3. Increased Booking Accuracy

Increasing the booking accuracy for surgeries is also an area in which great improvement potential lies. Currently, the booked surgery times are based on the historical data of the surgery code of the main operation. A surgery can have multiple operations, which influences the historical data and the booking accuracy negatively, i.e., surgeries are shorter than expected. However, since we used the mean of the distributions as booked durations, this is not the case in our simulation model. HOH should involve specialists in increasing the booking accuracy of surgeries, since they are the people that perform the surgeries and know best how long the different surgeries take.

7.2.4. Slack levels per OR

In Chapter 5, we propose to implement slack. We stated that a range between 5% and 10% is preferable, when we consider the simulation results. We implemented the same amount of slack for all ORs per experiment. However, maybe this should be different per OR for better results, e.g., emergency patients are not regularly operated in OR6, so we suspect less slack is needed in this OR. Also, when HOH succeeds in increasing the booking accuracy of surgeries and changeovers, less slack is needed, because the variability decreases. However, there is still some slack needed to anticipate to the arrival of emergency patients.

7.2.5. Implementation online application

In Chapter 6, we propose an online application in which specialists can fill in their OR program to check whether the OR programs meet the minimal booking rate. Besides that, they are forced to fill in their OR program in time, otherwise the OR session becomes available for other specialists to claim. If HOH thinks this is a good idea to implement, they should investigate how it needs to be implemented and work out the details. Additionally, HOH should involve specialists in the implementation process and think about how misuse could be prevented.

7.2.6. Session roster

We concluded during the validation phase of the simulation model in Chapter 4 that the session roster is suboptimal, i.e., the available OR capacity could be allocated better. Moreover, the data analysis in Chapter 2 shows that OR6 is less utilized than the other ORs. The simulation study also shows that the amount of capacity needed for performing the outpatient surgeries is less than the available capacity. Therefore, HOH can benefit from further research on optimizing the session roster. This could be done, e.g., by making multiple session rosters and run experiments with these rosters in the simulation model we used for our research. Initializing other session rosters in the simulation model can be done very easily.

7.2.7. Other intervention possibilities

Besides experimenting with the session roster in the simulation model, it is also possible to implement other experiments concerning the planning in the simulation model. For example, trying other scheduling algorithms for assigning emergency patients to the ORs, e.g., BIMs, to increase the service level for this patient group. As we saw in Chapter 5, the current scheduling algorithm is not very robust and the service requirements are not always met.

Another interesting intervention we identified during the literature study in Chapter 3, but not considered in the experiments, are stand-by patients. These patients could be inserted in the OR program when there is OR capacity left, e.g., due to cancellations.

7.2.8. Reschedules

A drawback of the scheduling algorithm that we use in our simulation model, is the high number of reschedules of elective patients. Every time a flex session, or a session that does not meet the minimum booking rate, is assigned to specialist, we reschedule the whole waiting list of this specialist. This implies that the surgery date of patients can change multiple times after their visit to the outpatient clinic, which is not patient friendly. Therefore, we think research to a scheduling algorithm which reduces the amount of reschedules, but does not affect the OR performance negatively, would be useful.

Additionally, the input data and scheduling algorithms used in the simulation model could be adjusted, so that the model better matches the reality. However, from experience we know that it is often hard to understand code from another programmer and therefore not easy to update the model or implement other scheduling algorithms.

7.2.9. Centralized planning

Currently, the OR planning is decentralized, i.e., specialists make their OR program and send it to the OR planner. Centralizing the OR planning, i.e., the OR planner makes the schedules of all specialists, could have benefits, such as more insights for HOH in the patients that need to be operated. Then, HOH can keep an eye on, e.g., the patients that did not undergo a pre-operative screening, but need to be operated in a couple of days. A centralized OR planning might also give opportunities for increasing the OR utilization. So, further research on what the benefits, disadvantages and implementation of centralized planning are, seems useful.

7.3. Contributions to practice and literature

This research provides HOH insight about their current performance with the context analysis in Chapter 2. Moreover, this research suggests how HOH could improve their OR performance with the experiments of the scheduling strategies. Finally, we give a couple of suggestions for further research, so that HOH can continue its ongoing improvement program 'Hunto Miho'.

The most important contribution to literature are the experiments with the two intervention possibilities that we identified when performing the context analysis, i.e., minimum booking rate and request list. Furthermore, we elaborated on how we created the simulation model in Chapter 4 and give an extensive description of the model in Appendix B. In this way, other researchers can use our approach to perform a simulation study with different experiments in a different setting.

Chapter 8 – Limitations

In this chapter, we consider the limitations of this research. The first limitation we want to appoint is the data we used for this research. The data seems quite accurate. However, we know that data is not perfect. For example, in Chapter 2, we do adjustments for the changeover times of the inpatient ORs, because we want to exclude negative changeover times. Since the number of negative changeover times of OR6 are much more than the inpatient ORs and there is much overlap between surgeries, we do no adjustments for the changeover times of OR6 (see Section 2.6). Data is never perfect and it is always a puzzle to handle it properly. Van Keulen (2012) suggests a method that accepts uncertainties in data and assigns probabilities to data entries. Using this method, the researcher calculates a confidence interval for the results. In that case, the researcher can keep an eye on uncertainties in the data.

Another limitation of this research is the validity of the simulation model, since our simulation model did not pass all validity tests in Chapter 4. The impact of implementing the proposed solution could be less than expected. The validation settings of the simulation model showed less utilization compared to reality.

We assume that the changeover times are lognormally distributed. However, the MSEs of the changeover times are quite high, i.e., between 0.0013 and 0.0023. Furthermore, we see two peaks in the figures of the realization of the changeover times in Appendix A. We suspect this is because of the lunchbreaks that take place during the changeovers. We cannot distinguish a changeover with a lunchbreak from a changeover without a lunchbreak. This is a limitation, because a small difference in the changeover times has great influences on the number of cancellations.

In our simulation model, we assign flex sessions on the day of the session. After the flex session is assigned, we reschedule the waiting list of the specialist. This is not realistic, since patients need to be informed in time when the date of their surgery changes. So, in reality, the number of patients that cancel their surgery would be higher. Besides that, the number of reschedules is very high and the surgery date of a patient can change multiple times.

In Chapter 5, we showed that SDE is a doubtful KPI. It measures the number of times the service requirements of emergency patients is not met, but we showed this is not always consistent with the average waiting time of emergency patients. Thus, experiments that have a short average waiting time could score badly on SDE and therefore end up at the bottom of the ranking. Furthermore, the absolute difference between the experiments on this KPI is small, and thus the relative difference is large due to the scoring method we use. Using another scoring method in which the score between the best and worst experiments on this KPI is smaller, could be a solution for this problem.

We based the assignment of the weights to the KPIs on what seemed logically to us. We did not use a scientific method and involved HOH's OR management after the analysis of the results. However, they declared that they are quite satisfied with the ratio between the weights.

References

Arnaout, J.P., Kulbashian, S. (2008). Maximizing the utilization of operating rooms with stochastic times using simulation. In: Proceedings of the 40th conference on winter simulation, pp 1617–1623.

Cardoen, B., Demeulemeester, E., & Beliën, J. (2009). Optimizing a multiple objective surgical case sequencing problem. Int J Prod Econ 119(2):354–366.

Cardoen, B., Demeulemeester, E., & Beliën, J. (2010). Operating room planning and scheduling: A literature review. *European Journal of Operational Research, 201(3)*, 921-932.

Dexter, F., Macario, A., & Traub, R.D. (1999). Which Algorithm for Scheduling Add-on Elective Cases Maximizes Operating Room Utilization? *Anesthesiology, 91*(5), 1491.

Dexter, F., Macario, A., Traub, R.D., Hopwood, M., & Lubarsky, D.A. (1999). An Operating Room Scheduling Strategy to Maximize the Use of Operating Room Block Time. *Anesthesia & Analgesia, 89*(1), 7-20.

Galambos, G., & Woeginger, G.J. (1995). On-line bin packing: a restricted survey. Math Methods Oper Res 1995; 42:25–45.

Groenveld, S. (2018). Optimalisatie OK-planning. Internal report (not publicly accessible), HOH, Aruba.

Guerriero, F., & Guido, R. (2011). Operational research in the management of the operating theatre: a survey. Health care management science, 14(1), 89-114.

Guinet, A., & Chaabane, S. (2003). Operating theatre planning. International Journal of Production Economics, 85(1), 69-81.

Gupta, D. (2007). Surgical Suites Operations Management. *Production and Operations Management,16*(6), 689-700.

Hans, E.W., Van Houdenhoven, M., & Hulshof, P.J. (2012). A framework for healthcare planning and control. In Handbook of healthcare system scheduling (pp. 303-320). Springer US.

Hans, E.W., Wullink, G., Van Houdenhoven, M., & Kazemier, G. (2008). Robust surgery loading. *European Journal of Operational Research,185*(3), 1038-1050.

Health Care Financial Management Association (2005). Achieving operating room efficiency through process integration, Technical Report.

HOH (2017). About HOH. Retrieved December 19, 2017, from http://www.arubahospital.com/index.php/about-hoh

Jebali, A., Alouane, A.BH., & Ladet, P. (2006). Operating rooms scheduling. International Journal of Production Economics, 99(1), 52-62.

Kamphorst, B., Kortbeek, N., Lucas, S., & Van der Sloot, R. (2015). Beschrijvende data-analyse klinische opnames HOH. Internal report (not publicly accessible), HOH, Aruba

Karis, J., & Huizingh, E. (2015). Situatieanalyse OK-planning. Bachelor's Thesis, University of Twente.

Kirkpatrick, S., Gerlatt, C.D., & Vecchi, M.P. (1983). Optimization by simulated annealing. Science 220, 671–680.

Leeftink, A.G., & Hans, E.W. (2017). Case mix classification and a benchmark set for surgery scheduling. *Journal of Scheduling*.

Macario, A., Vitez, T.S., Dunn, B., & McDonald, T. (1995). Where Are the Costs in Perioperative Care? Analysis of Hospital Costs and Charges for Inpatient Surgical Care. *Survey of Anesthesiology,40*(5), 283.

May, J.H., Strum, D.P., & Vargas, L.G. (2000). Fitting the lognormal distribution to surgical procedure times. Decision Sciences, 31, 129–148.

Pariente, J.M., Torres, J.M., & Cia, T.G. (2009). Policies and decision models for solving elective case Operating Room scheduling. *2009 International Conference on Computers & Industrial Engineering*.

Patterson, P. (1996) What makes a well-oiled scheduling system. OR Manager 12(9):19–23.

Persson, M.J., & Persson, J.A. (2009). Analysing management policies for operating room planning using simulation. *Health Care Management Science,13*(2), 182-191.

Sier, D., Tobin, P., & McGurk, C. (1997). Scheduling surgical procedures. J Oper Res Soc 48(9):884–891 110.

Stepaniak, P.S., Heij, C., Mannaerts, G.H.H., Quelerij, M D., & Vries, G.D. (2009). Modeling procedure and surgical times for CPT-anesthesia-surgeon combinations and evaluation in terms of case-duration prediction and operating room efficiency. *Anesthesia Analgesia*, 109(4), 1232-1245.

Van Essen, J.V., Hans, E.W., Hurink, J., & Oversberg, A. (2012). Minimizing the waiting time for emergency surgery. *Operations Research for Health Care,1*(2-3), 34-44.

Van Houdenhoven, M., Hans, E.W., Klein, J., Wullink, G., & Kazemier, G. (2007). A Norm Utilisation for Scarce Hospital Resources: Evidence from Operating Rooms in a Dutch University Hospital. *Journal of Medical Systems, 31*(4), 231-236.

Van Keulen, M. (2012). Managing Uncertainty: The Road Towards Better Data Interoperability. It - Information Technology, 54(3), 138-146.

Van Riet, C., & Demeulemeester, E. (2015). Trade-offs in operating room planning for electives and emergencies: A review. Operations Research for Health Care, 7, 52-69.

Wullink, G., Van Houdenhoven, M., Hans, E.W., van Oostrum, J.M., van der Lans, M., & Kazemier, G. (2007). Closing emergency operating rooms improves efficiency. Journal of Medical Systems, 31(6), 543-546.

Appendix A: Simulation Input Data

This appendix shows the input data that we use for our simulation model.

Surgery Types

Table A.1 shows the parameters of the 3-parameter lognormal distributions of the surgery types (t). These distributions use the following formulas for the mean (m) and standard deviation (s) of the distributions.

$$m_t = \gamma_t + e^{\mu_t + \frac{\sigma_t^2}{2}} \qquad s_t = \sqrt{\left(e^{\sigma_t^2} - 1\right) * e^{2*\mu_t + \sigma_t^2}}$$

The mean (in minutes) of the surgery types are equal to the booked surgery duration.

Table A.1: Parameters of the distributions of the surgery types

Surgery Type	μ	σ	γ	Mean
1613	3.288	0.253	8.452	36
1660	2.627	0.47	13	28
1694	3.277	0.887	19	58
1830	2.141	0.56	2.181	12
1901	2.757	0.679	12	31
3154	3.236	0.823	26.429	62
5124	3.811	0.689	14	71
5258	2.427	0.495	4.415	17
5285	2.489	0.563	13.188	27
5749	3.787	0.398	19.871	67
5861	4.021	0.583	19.22	85
5862	4.533	0.304	0	97
5881	3.533	0.285	0	35
5882	3.704	0.239	0	41
5924	2.543	0.383	9	22
8157	4.364	0.355	2.924	86
8191	3.1	0.495	6	31
8200	2.182	0.64	21	31
8389	3.781	0.507	0	49
8740	3.154	0.95	12.192	48
8846	2.588	0.714	0	17
11022	2.972	0.332	14.647	35
14630	2.854	0.61	1.805	22
14711	3.282	0.342	0	28
16129	3.528	0.271	0	35
16520	3.12	1.028	6	44
16971	4.285	0.294	0	75
16976	3.464	0.366	0	34
50120	4.198	0.285	0	69
50231	3.774	0.644	69.666	123
50300	4.575	0.238	28.358	128
50302	4.264	0.494	28	108
50309	4.172	0.462	38.503	110
50350	3.303	0.335	17.413	46
50610	4.326	0.31	24.075	103
50622	4.412	0.45	16.173	107
50911	2.501	0.482	1	14
50912	2.314	0.52	2.076	13
50948	3.729	0.64	24	75
51220	2.256	0.563	7	18
51221	3.057	0.459	5.904	29
51332	3.829	0.249	26.157	73
51450	1.938	0.725	13.168	22
51451	2.747	0.742	14.73	35
51452	2.903	0.285	3	21
51470	3.655	0.215	0	39
51811	3.129	0.718	10	39
51912	2.967	0.753	39.626	65
51950	4.28	0.19	0	73
52001	2.102	0.769	11	21
52002	2.627	0.601	7.348	23
52101	2.189	1.044	8	23
52122	3.716	0.665	0	51
52143	4.089	0.261	0.353	62
52239	4.04	0.298	0	59

52301	3.369	0.481	9.564	42
52810	3.753	0.197	0	43
52811	3.744	0.227	0	43
52819	2.953	0.547	29.298	51
52820	3.51	0.273	0	34
52821	3.082	0.286	19.026	41
52829	3.755	0.248	0	44
52939	3.847	0.203	0	47
53765	3.904	0.474	90	145
53774	3.531	0.529	50	89
53944	4.751	0.488	0	130
53946	4.329	0.447	23.558	107
54010	3.34	0.663	16	51
54455	3.61	0.444	58.059	98
54456	3.457	0.661	57.149	96
54457	4.558	0.162	2.049	98
54651	4.541	0.609	4.66	117
54700	3.192	0.638	34	63
54704	3.84	0.392	20.11	70
54900	3.28	0.284	0	27
54901	3.593	0.44	0	40
54910	2.488	0.643	15.617	30
54911	3.72	0.491	0	46
54934	3.651	0.352	0	40
55110	4.954	0.401	0	153
55112	3.928	0.475	25.63	82
55300	2.87	1.089	30	61
55310	4.196	0.282	0	69
55342	3.286	0.439	16.571	46
55343	3.59	0.462	14.376	54
55344	3.748	0.34	13.725	58
55360	4.63	0.538	0	118
55400	3.723	0.653	19.464	70
55410	4.697	0.432	0	120
55412	4.734	0.508	0	129
55493	4.114	0.196	0	62
55494	3.88	0.395	0	52
55600	3.905	0.609	24.703	84
55602	3.745	0.597	27.288	77
55603	4.563	0.355	0	102
55604	3.985	0.358	5.956	63
55731	3.765	0.475	13.235	61
55732	3.281	0.637	28.214	60

55840	3.324	0.218	0	28
55841	3.326	0.837	14.095	53
55981	3.553	0.459	10	48
56010	4.511	0.336	0	96
56042	4.909	0.168	97.922	235
56305	3.717	0.597	16.449	65
56361	3.311	0.324	5.894	34
56362	2.578	0.736	18.626	35
56400	3.118	0.386	0.553	24
56402	3.858	0.199	0.559	48
56531	3.406	0.852	54.425	97
56631	3.734	0.219	0	42
56632	3.252	0.315	14.228	41
56710	2.201	0.739	24	35
56723	2.995	0.318	8.698	29
56741	3.215	0.263	0	25
56814	4.572	0.372	3.644	107
56820	4.352	0.522	25.488	114
56830	4.715	0.294	0	116
56840	3.64	0.414	34.097	75
56841	4.185	0.259	24.227	92
56843	4.661	0.147	0	106
56901	2.751	0.412	4	21
56902	2.876	0.505	5.079	25
56910	2.255	0.679	10	22
57040	2.936	0.743	34.39	59
57041	3.124	0.642	33.015	60
57049	3.832	0.521	33.112	85
57110	3.349	0.37	0	30
57111	2.764	0.525	10.596	28
57410	4.062	0.223	0	59
57411	4.147	0.194	0	64
57560	2.929	0.633	12.514	35
57582	3.456	0.516	19.622	55
57824	4.073	0.197	0	59
58031	4.973	0.262	0	149
58034	3.794	0.618	51	104
58040	3.555	0.185	0	35
58150	4.851	0.365	21.072	157
58160	4.567	0.32	13.021	114
58181	4.031	0.222	11.627	69
58222	3.388	0.385	0	31
58241	4.778	0.507	0	135

58242	3.409	0.92	32.729	78
58258	2.995	0.896	25.612	55
58450	3.053	0.524	9.199	33
58463	3.74	0.311	1.494	45
58470	4.248	0.363	11.587	86
58480	3.941	0.404	15.707	71
58601	3.765	0.35	0	45
58603	4.005	0.435	0	60
58604	4.47	0.272	0	90
58605	3.858	0.585	27	83
58692	2.821	0.824	29.133	52
58693	4.771	0.575	0	139
58743	4.051	0.483	149.205	213
58841	2.814	0.454	2.883	21
58900	4.028	0.713	12.979	85
59019	3.1	0.607	3.38	30
81011	1.869	0.811	0.978	9
81350	3.272	0.57	22	53
81351	2.447	0.893	8	25
82032	2.872	0.694	16	38
82260	3.309	0.461	0	30
503021	4.546	0.381	17.544	118
503022	3.495	0.54	53.739	91
503023	4.075	0.426	58.11	122
503101	2.952	0.257	9.08	28
503103	2.752	0.32	6.166	22
503801	3.149	0.397	0	25
503803	2.571	0.44	8.853	23
504111	2.72	0.393	12.897	29
504123	3.253	0.233	0	26
504127	3.121	0.366	10.766	35
504128	4.137	0.201	0	63
504350	2.953	0.692	4.839	29
521512	3.232	0.407	11.611	39
521700	4.315	0.182	0	76
522432	4.025	0.294	0	58
537741	3.876	0.206	0	49
538430	4.113	0.217	0	62
538431	3.515	0.438	27.451	64
539226	4.659	0.255	0	109
539227	4.392	0.523	31.7	124
539282	4.361	0.369	29.814	113
539932	3.561	0.546	19.57	60

539934	3.728	0.329	7.328	51
539937	4.166	0.413	0	70
544541	4.847	0.201	0	129
545544	5.051	0.248	0	161
545573	4.617	0.595	86.06	206
546522	5.307	0.394	0	218
553010	4.225	0.317	0	71
553011	3.675	0.512	48.567	93
553014	3.365	0.802	58.889	98
553015	3.393	0.404	43	75
553431	3.505	0.588	27	66
553501	4.459	0.362	0	92
553521	3.258	0.815	33.929	70
554911	4.165	0.268	0	66
555002	4.684	0.444	57.254	176
555400	4.869	0.323	79.57	216
559501	4.189	0.254	0	68
559502	4.009	0.299	0	57
565112	3.973	0.472	31.486	90
574411	4.294	0.195	0	74
574431	2.986	0.729	49	74
578128	2.689	0.718	35	54
578711	5.127	0.273	0	174
578713	4.642	0.603	158.078	282
578800	3.781	0.533	0	50
578813	3.395	0.604	0	35
578816	3.672	0.399	0	42
578823	3.601	0.413	9	48
578826	3.771	0.942	15	82
578827	3.661	0.45	0	43
578828	2.546	0.895	6.776	25
579003	3.442	0.535	24.638	60
579004	3.166	0.729	25.723	56
579011	3.664	0.789	80.64	133
579013	5.005	0.456	0	165
579022	4.258	0.373	0	75
579025	3.945	0.932	37.728	117
579203	4.443	0.451	14.922	109
579206	4.097	0.562	19.417	89
579212	4.174	0.637	66	145
579213	4.679	0.364	0	114
579214	3.815	0.636	46	101
579216	4.519	0.536	27.195	133

579217	4.508	0.396	0	98
579223	3.996	0.642	47	113
579260	4.05	0.735	50.947	126
580340	3.503	0.913	56.583	106
580503	3.191	0.49	6.961	34
580504	2.69	0.529	11.622	28
581011	5.07	0.331	0	168
581421	3.65	0.289	68.347	108
581452	4.613	0.096	7.244	108
581454	4.239	0.249	34.353	105
581812	4.035	0.219	16.335	74
582901	2.737	0.495	8	25
582902	2.573	0.927	18.117	38
583228	3.035	0.504	9.74	33
586020	3.089	0.654	20	47
587912	5.3	0.221	0	205
588210	3.334	0.509	2.563	34
588211	3.446	0.516	0	35
588212	3.29	0.465	1.735	31
588213	3.352	0.415	0.707	31
588214	3.2	0.517	6.261	34
588223	3.028	0.599	1.842	26
588224	3.06	0.561	0.356	25
588312	3.816	0.523	0	52
588313	3.898	0.704	4.769	67

588314	3.092	0.633	11.445	38
588328	3.532	0.467	27.782	65
588331	3.668	0.282	26.345	67
588402	3.203	0.571	0	28
588420	2.945	0.525	1.652	23
588421	2.692	0.688	10	28
588422	2.942	0.692	4	28
588423	3.282	0.313	0	27
588424	2.719	0.607	5.461	23
588425	2.965	0.548	3.623	26
588426	3.05	0.433	0	23
588492	2.977	0.621	5.112	28
588494	2.358	0.7	7.808	21
588511	4.2	0.562	0	78
589110	2.616	0.559	19.134	35
589111	2.768	0.456	15	32
589314	3.995	0.465	12.673	73
590132	5.259	0.231	31	228
817981	3.57	0.377	0	38
858416	3.1	0.382	0	23
5376102	3.85	0.662	47.012	105
5399321	2.913	1.03	13	44
5399341	2.767	0.379	5	22
5836931	4.244	0.768	30	123
8584171	2.773	0.397	0	17

Specialties

Table A.2 shows the cumulative probabilities per specialty for assigning arriving elective and emergency patients. Also, the table shows the probabilities that an arriving patient is a child and the correction in minutes for the surgery duration for elective and emergency patients to make sure that the average surgery duration per specialty for the simulation is equal to the realization.

Table A.2: Probabilities per specialty

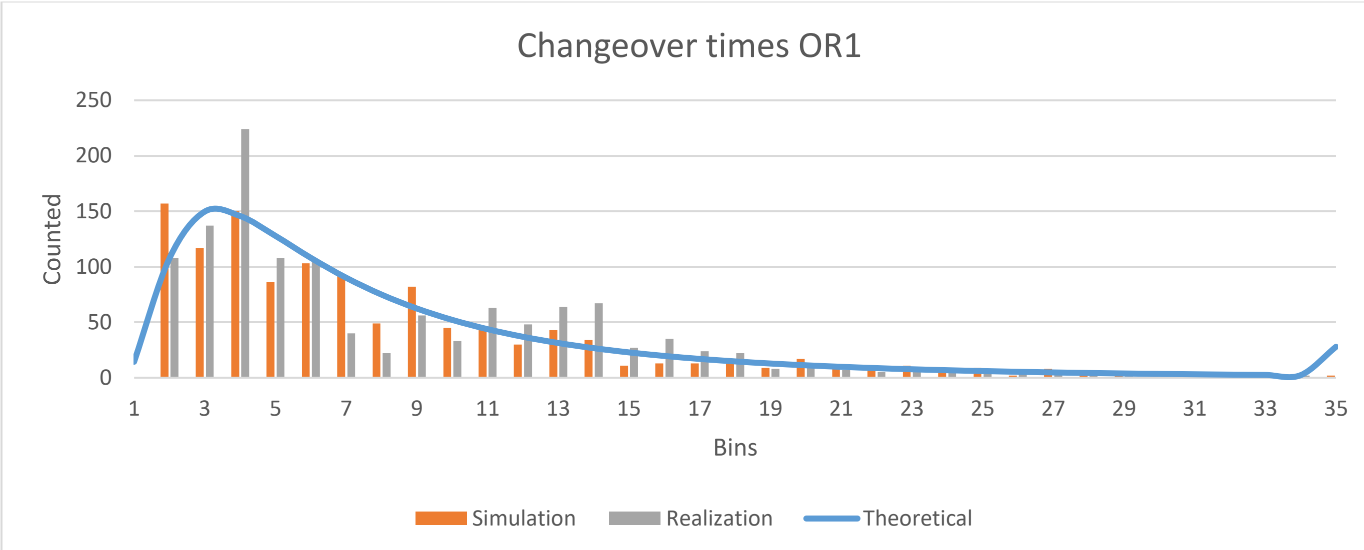
Specialty	Cum. Probability Elective	Cum. Probability Emergency	Probability Child	Correction Elective	Correction Emergency
General Surgery	0.258	0.47	0.029	2.93268	5.43244
Ophthalmology	0.476	0.502	0.0075	1.10313	-7.92513
Gynecology	0.595	0.772	0.0016	5.87313	2.89071
Orthopedics	0.718	0.874	0.0161	6.38617	-5.48883
Plastic surgery	0.785	0.899	0.0209	18.42814	12.27211
ENT	0.852	0.919	0.3584	5.53201	11.24456
Urology	0.912	0.959	0.102	9.88707	-2.27562
Neurosurgery	0.951	0.979	0	-16.22335	-14.52365
Pain treatment	0.991	0.99	0.0024	1.66219	3.42116
Cardiology	1	1	0	-13.28507	-1.92449

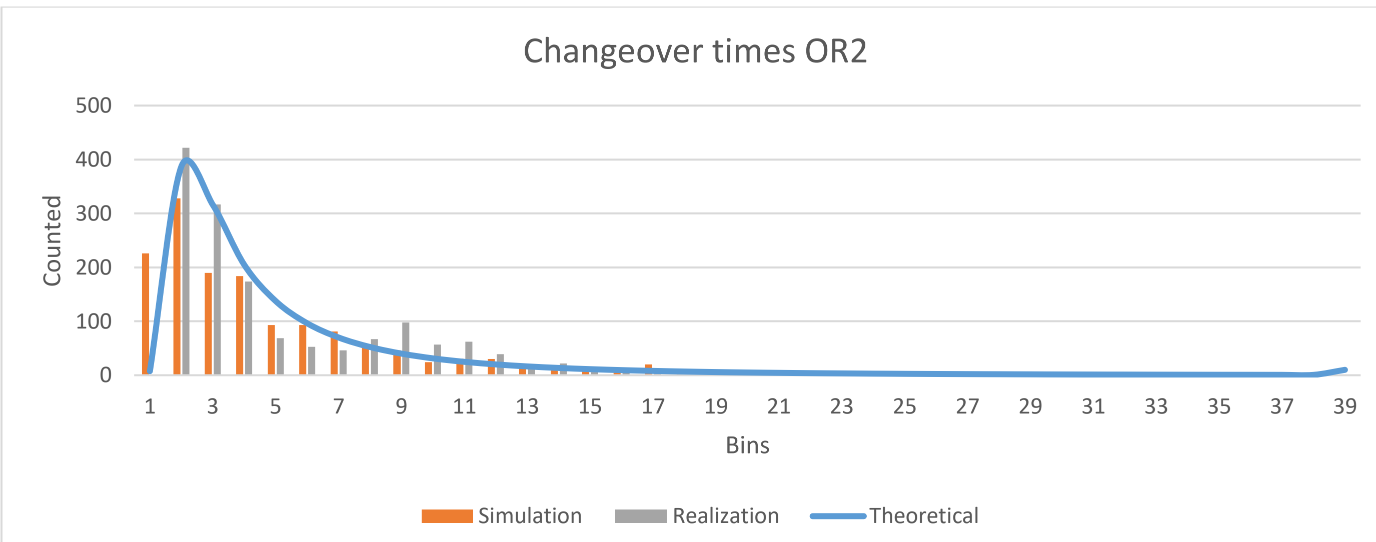
Changeover Times

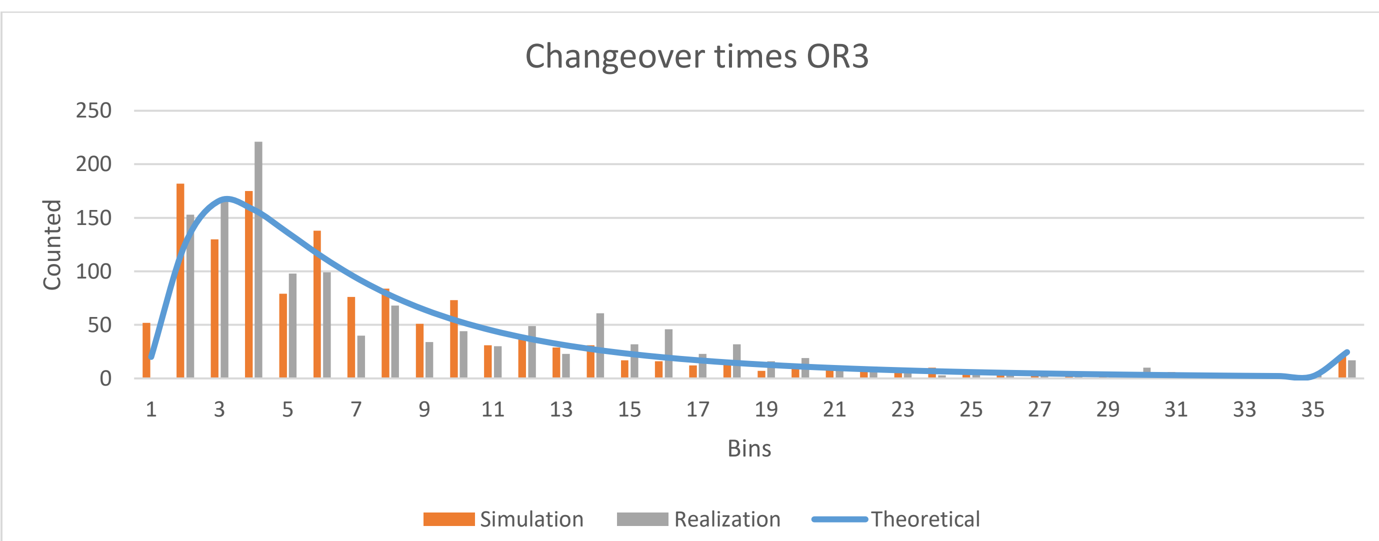
In Table A.3, we show the parameters and MSE of the 3-parameter lognormal distributions of the changeover times per OR. Per OR we make bins with equal widths, and count the number of changeovers of the theoretical distribution, simulation and realization that are between the ranges of the bins. The number of changeovers per bin are visualized in the figures below.

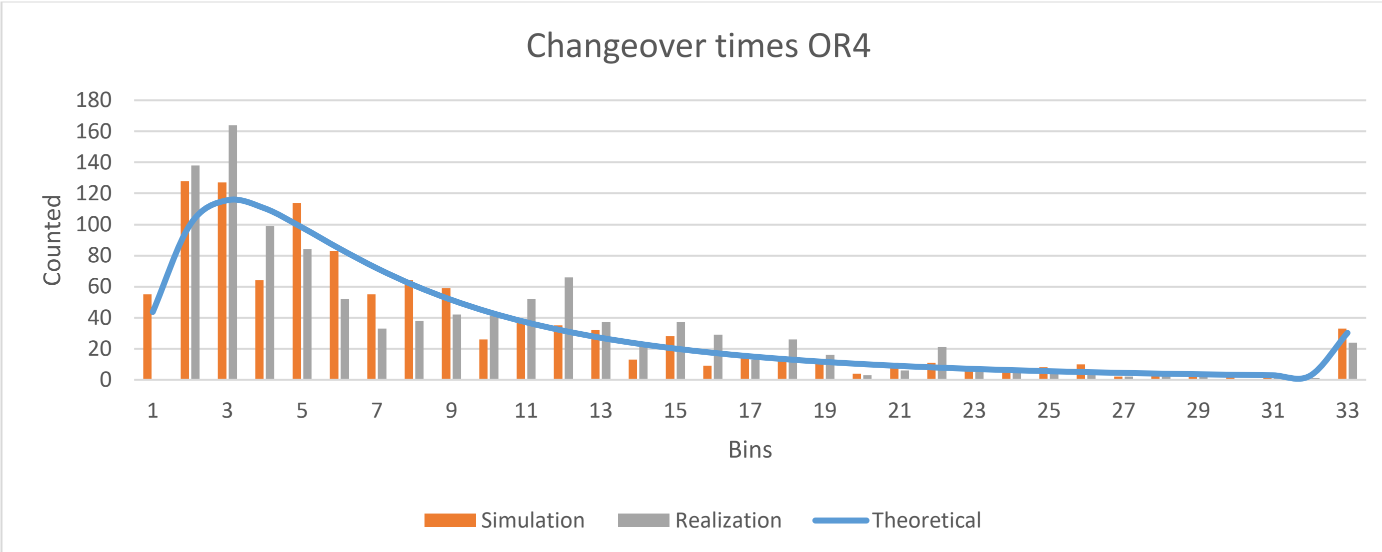
Table A.3: Parameters and MSEs of the distributions of the changeover times per OR

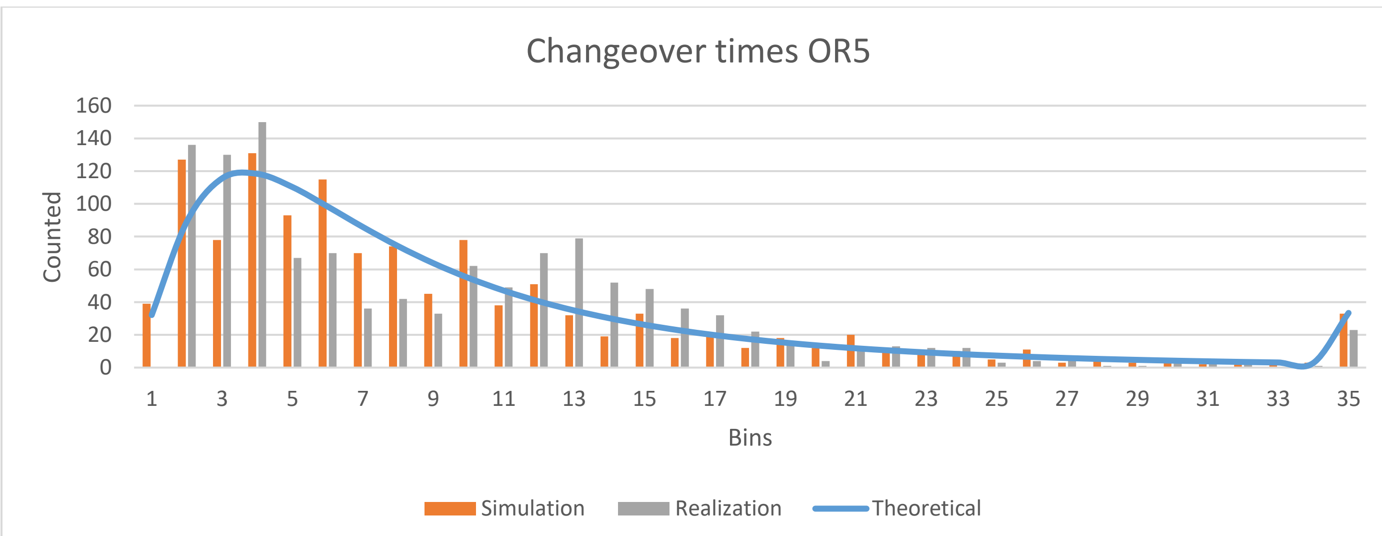
OR	μ	σ	γ	MSE
OR1	2.6541	0.8977	0.7336	0.0014
OR2	2.1164	1.1217	3.1271	0.0015
OR3	2.587	0.8981	0.6092	0.0013
OR4	2.8163	0.865	0	0.0015
OR5	2.875	0.8293	0	0.0022
OR6	1.2505	1.2876	1	0.0023

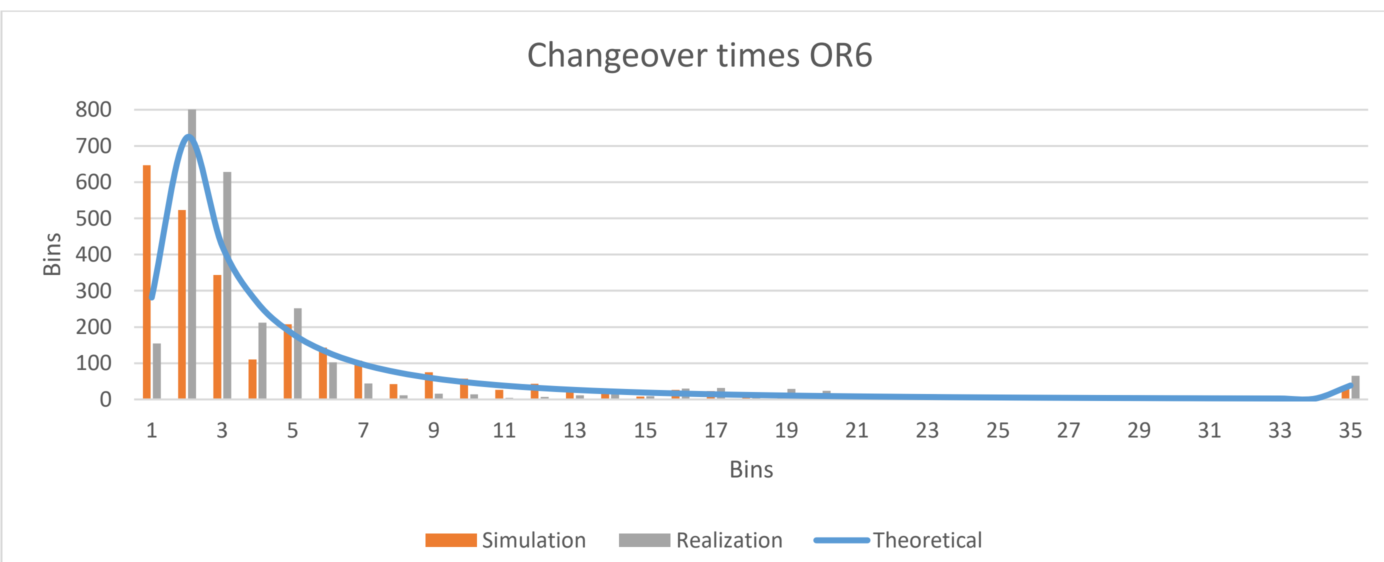

Changeover times OR1
250
200
150
100
50
0
Counted
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Bins
Simulation
Realization
Theoretical


Changeover times OR2
500
400
300
200
100
0
Counted
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Bins
Simulation
Realization
Theoretical


Changeover times OR3
250
200
150
100
50
0
Counted
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Bins
Simulation
Realization
Theoretical


Changeover times OR4
180
160
140
120
100
80
60
40
20
0
Counted
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
Bins
Simulation
Realization
Theoretical


Changeover times OR5
160
140
120
100
80
60
40
20
0
Counted
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Bins
Simulation
Realization
Theoretical

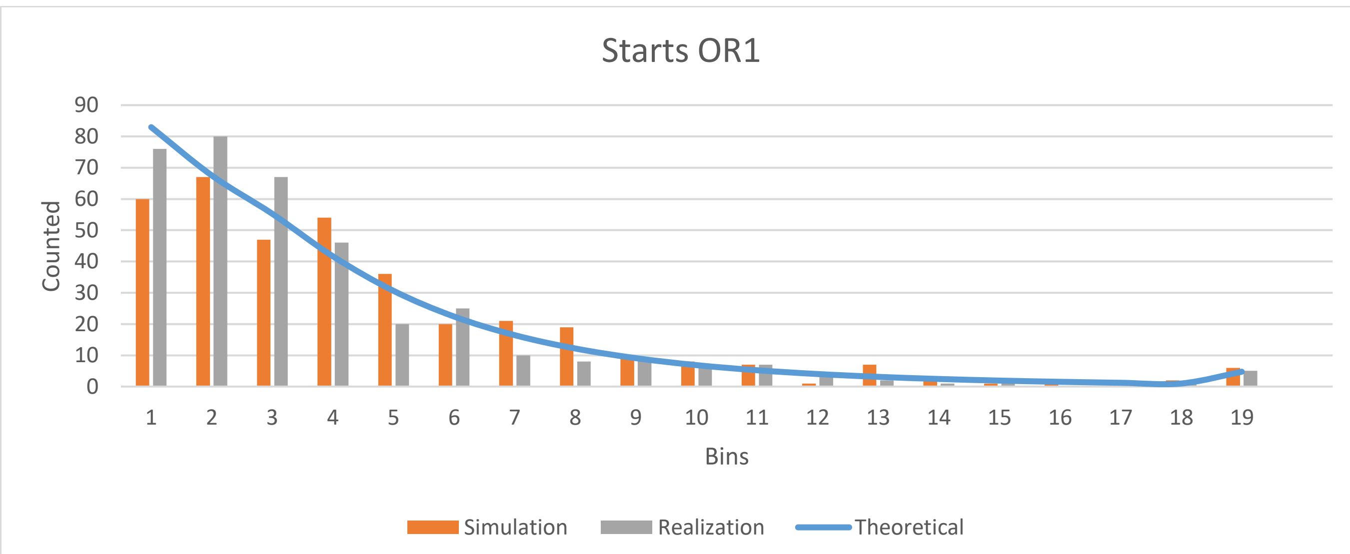

Changeover times OR6
800
700
600
500
400
300
200
100
0
Bins
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Bins
Simulation
Realization
Theoretical

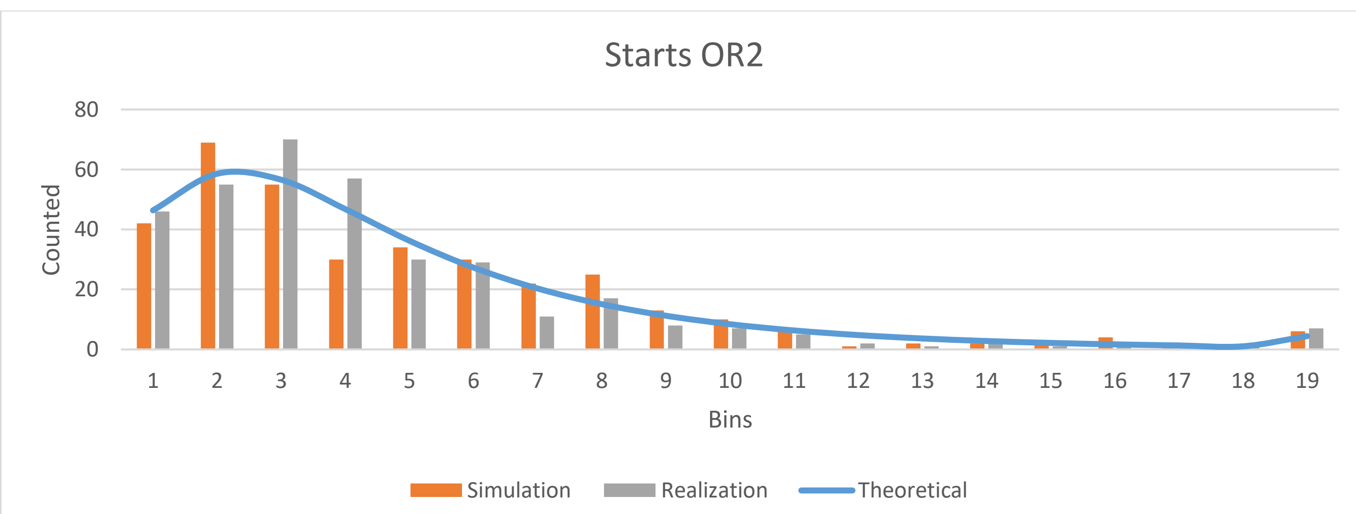
Early and Late Starts

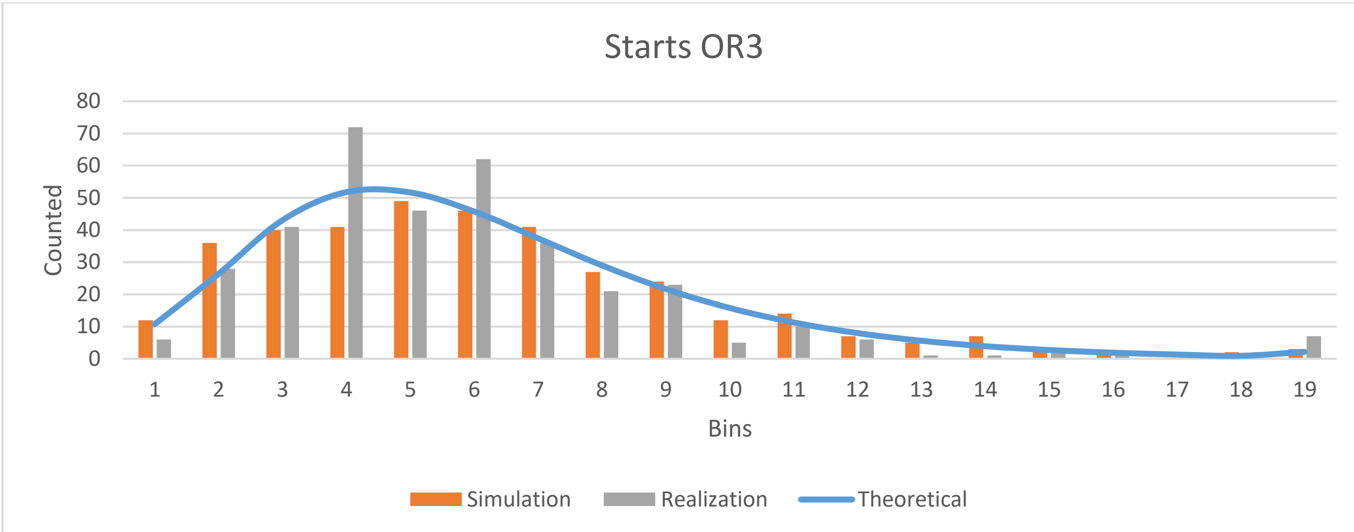
Table A.4 shows the 3-lognormal parameters and MSEs of the starts per OR. We perform a correction (subtraction) on the distributions since a session could also start before 7:30. Also for the starts we visualize the difference in theoretical distribution, simulation and realization per OR in the figures below.

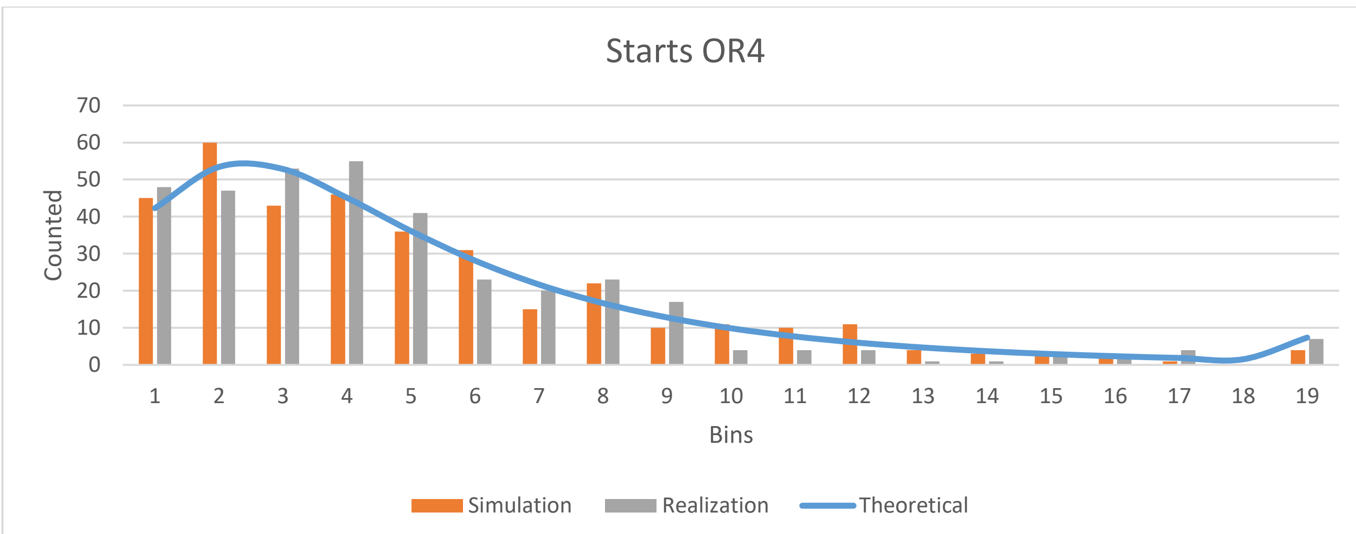
Table A.4: Parameters and MSEs of the distributions of the changeover times per OR

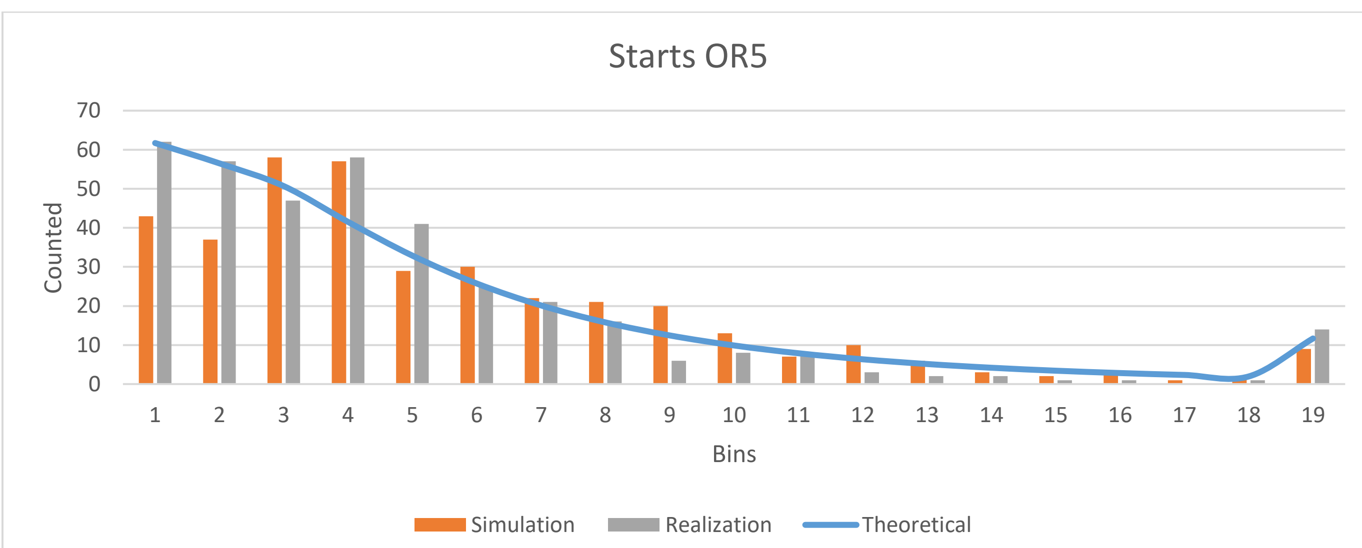
OR	μ	σ	γ	Correction	MSE
OR1	2.9712	0.7313	10	25	0.0012
OR2	3.14	0.6479	10	24	0.0011
OR3	3.7634	0.3899	10	40	0.0014
OR4	3.2253	0.6797	10	26	0.0004
OR5	3.1732	0.773	10	26	0.0011
OR6	3.6321	0.9751	10	26	0.0013

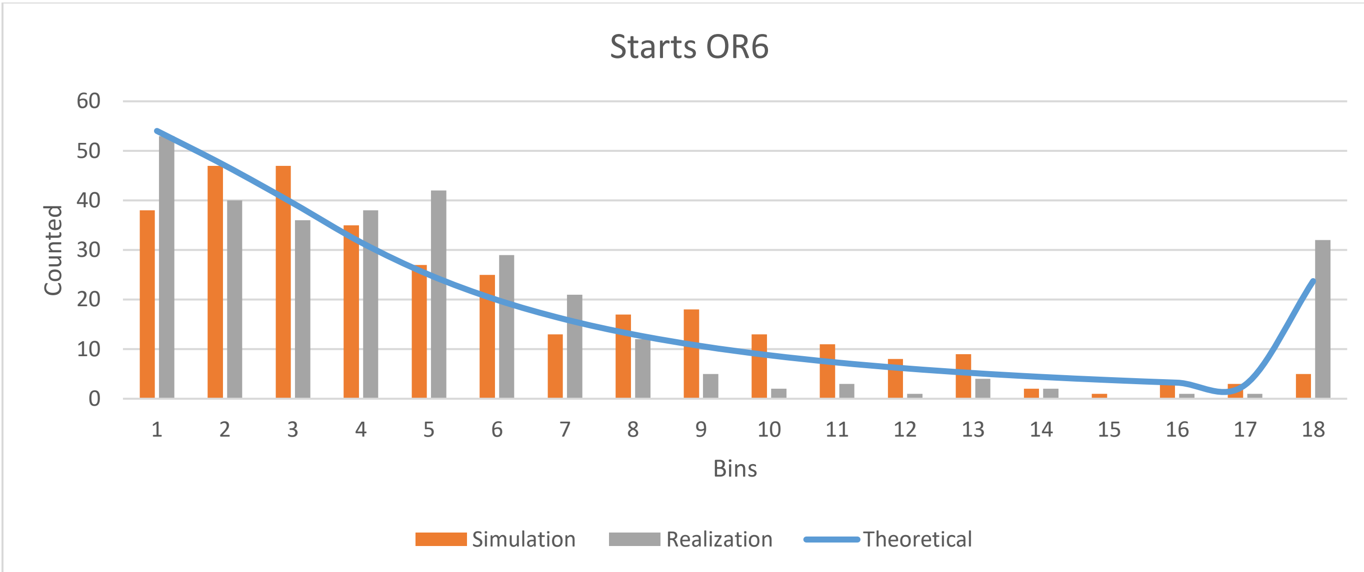





Starts OR3
Counted
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Bins
Simulation
Realization
Theoretical


Starts OR4
Counted
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Bins
Simulation
Realization
Theoretical


Starts OR5
Counted
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Bins
Simulation
Realization
Theoretical



Starts OR6
60
50
40
30
20
10
0
Counted
1
2
3
4
5
6
7
8
9
10
11
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Bins
Simulation
Realization
Theoretical

Appendix B: Model Description

This appendix broadly describes the functionality of the simulation model. Not all details are described. We discuss the most important logic and objects (indicated with **bold letters**). If there are obscurities when reusing the simulation model, please contact the author.

Initializing the session roster

The method **Init** makes the creates empty sessions for the specialists according to the session roster. If the value of the checkbox **Validation** is true, **Init** copies the table **SessionRoster20162017** to the table **SessionRoster**, otherwise it copies the table **SessionRoster2018** to **SessionRoster**. In our simulation study, we use the session roster of 2016 – 2017, including warm-up period, for the validation of the model. We use the session roster of 2018, including warm-up period, for the experiments. The specialists of the sessions are indicated with an integer in the tables. The corresponding specialties of the integers of the specialists are stored in the table **Specialists**. -1 indicates that there is no session. Flex sessions are not assigned to a specialist yet and are indicated with 0. The table **SessionRoster** is emptied at the beginning of the simulation and updated during the simulation, e.g., if a flex session is assigned to a specialist or a session is cancelled. **SessionRoster20162017** and **SessionRoster2018** are not updated and only used for initializing the session roster. These tables may not be emptied. Since OR6 can have two half sessions on one day, we indicate the morning session with **OR6** and the afternoon session with **OR6-2** in the tables. The sessions of the specialists are created in the table **Specialists** in the column **ORSchedules**, in which a new table is created. This table stores the date of the session with corresponding simulation day, the OR of the session, the length of the program, booking rate of the session and indicates if the session is an entire session or a half session. OR6 has half sessions, but also the inpatient ORs can have half sessions if the afternoon session is reserved as the emergency OR. The patients that are assigned to the session are stored in the table **ORProgram** in **ORSchedules**.

Patient arrival

The MUs **ElectivePatient** and **EmergencyPatient** present the elective and emergency patients and arrive in the system via the sources **Electives** and **Emergencies** according to the corresponding Poisson distributions. The arrival of these MUs trigger the method **PatientArrival**. In this method we assign the patient to a specialty. Every specialty has a probability that corresponds the historical data, e.g., the probability that the specialty General Surgery is assigned to an arriving patient is higher than the specialty Cardiology is assigned to the patient. Elective and emergency patients have their own probabilities per specialty, which are stored in the table **Specialties**. In Table B.1, we show the probabilities of the elective patients per specialty. With a random number we decide to which specialty the patient is assigned. Then, the surgery type is assigned to the arriving patient, also with a random number. The probabilities per surgery type are stored in the table **SurgeryTypes**. After that, the method assigns the booked duration to the patient, which is the mean of the surgery type, and the processing time, real surgery duration, with the help of the three parameters (μ, σ, γ) of the 3-parameter lognormal distribution, which are stored in the table **LogNormalParameters**. If the arriving patient is an elective patient, the method assigns a specialist to the patient, by using a random number and probabilities that match the proportion of sessions in the session roster, these data is stored in the table **Specialists**. Specialists can only perform surgeries of their own specialty. If the arriving patient is an emergency patient, the method assigns an urgency level (A, B, C or D) to the patient, with help of a random number and the probabilities that are stored in the table **SurgeryTypes**. Specialists are not assigned to emergency patients, we assume that there is always a specialist available to perform surgery on an emergency patient. Because the arrival of emergency patients is not equally divided during the day, we use the table **EmergencyArrival** to influence this. A random number and probability per hour of the day decide if the patient can enter the system or not. If the patient may not enter the system, the MUs is deleted. Finally, **PatientArrival** triggers **AssignPatientToSession** for elective patients and **SchedulingEmergencies** for emergency patients.

Table B.1: Probabilities of patient assignment to specialties

SpecialtyID	Specialty	Probability Elective Patients	Cumulative probabilities
1	General Surgery	0.258	0.258
2	Ophthalmology	0.218	0.476
3	Gynecology	0.119	0.595
4	Orthopedics	0.123	0.718
5	Plastic surgery	0.067	0.785
6	ENT	0.067	0.852
7	Urology	0.060	0.912
8	Neurosurgery	0.039	0.951
9	Pain treatment	0.040	0.991
10	Cardiology	0.009	1

Patient scheduling

AssignPatientToSession schedules the patient in the first available session of the performing specialist in which the patient fits (FCFS). The sum of the booked durations of the patients and the total changeover time (9 minutes per changeover, 6 minutes for OR6 and specialty ENT) may not exceed the OR capacity (390 minutes for entire sessions, 195 minutes for half sessions). Inpatients can only be scheduled in the inpatient ORs and outpatient patients can only be scheduled in OR6. There should be at least 14 days between the day of arrival and day of surgery, to ensure that there is enough time for the patient to undergo the pre-operative screening. In the table **Specialists**, the patients are added to the tables **ORProgram** in **ORSchedules** and **WaitingList**. In **ORSchedules** the booking rate and length of the program are updated.

In the method **SchedulingEmergencies**, emergency patients are scheduled according to their urgency level (see the flowchart in Figure 4.5). When the emergency patient is scheduled, it is added to table **EmergenciesToSchedule**. After the patient is operated, the patient is removed from the table. **SchedulingEmergencies** calls **EmergencyProgram**, which checks if there are emergency patients that need to be operated right away and sends these patients to an OR, if this OR is available.

Patient handling

The generator **StartORSession** triggers the method **StartDay** every day at 7:00. **StartDay** writes the schedule with patients per session that need to be operated that day with the help of the table **SessionRoster** from the table **Specialists** to the table **TodaysSchedule**. Before the session is copied to **TodaysSchedule**, the patients are sorted from longest booked duration to shortest booked duration (LEPT), but children get priority. When there is a flex session in **SessionRoster**, indicated with 0, the session is given to another specialist via the method **ReassignSession** (combination of length of waiting list and number of days to last inpatient scheduled). **ReassignSession** is also called when the minimum booking rate is not met (combination of value of checkbox **MinBookingRate** is true and variable **MinimalBookingRate**). Now we can bring the first patients to the ORs by calling the method **PatientHandling**.

PatientHandling first calculates the early or late start by using the parameters of the 3-parameter lognormal distribution in the table **ChangeoverLateStart**. Then, **PatientHandling** calls **FindElective** to select the first elective patient that needs to be operated, which is stored in **TodaysSchedule**. The variable **CancellationRate** and a random number decide if the patient is cancelled (for other reasons than planning). If the random number is below the product of the variables **PatientCause** and **CancellationRate,** the patient is responsible for the cancellation and the patient is rescheduled as if it enters the system for the first time (FCFS). Otherwise, the patient is rescheduled as soon as possible. If the random number is below the product of the variables **NOReturn** and **CancellationRate**, the patient is deleted from the system and not operated at all.

If a patient is selected, it is send to the corresponding OR (SingleProc). The surgery duration (processing time of the ORs) depends on the individual processing time of the patients, which is stored as attribute in the patients (MUs). After the surgery is finished, the method **WritePerformance** writes the OR performance to the tables **ORDayPerformance, UtilizationPerDay, SpecialtyResults** and **EmergencyResuts**. **PatientHandling** then sends the patient to **BedHouse** (buffer with infinity capacity) and leave the system via **Drain**.

Now, we select the next patient that needs to be operated. First, we call **EmergencyProgram** to check whether there are emergency patients that have priority. If this is not the case, we call **FindElective** if there are elective patients waiting. If a patient is found, we determine the changeover time by using the 3-parameter lognormal distribution of the OR, which is stored in **ChangeoverLateStart**, and send the patient to the OR. If there is no patient found, we calculate and store the early end (when applicable).
The generator **StartAfternoonSession** is only of use when there is an afternoon session in OR6, but no morning session. In that case, the generator calls **PatientHandling** at 11:00, so that the first patient of that afternoon session is send to OR6.

When the simulation time reaches 14:30, the generator **EndORSession** calls the method **EndDay.** This method cancels all elective patients for which the surgery did not start yet. These patients are added to the table **CancelledPatients**, the variable **Cancellations** is updated and the method triggers **Reschedule.**

This method schedules the cancelled with patient cause in the first available session. If the value of the checkbox **RequestList** is false, then the cancelled patients with no patient cause or scheduled in the first coming session of the performing specialist. If the value of the checkbox **RequestList** is true, **Reschedule** tries to find a session for the cancelled patient in a session of another performing specialist by using the next fit algorithm. If it is not possible to find a session for the patient before the next session of the performing specialist, the patient is scheduled in the next session of the performing specialist by calling the method **AssignPatientToSession.** If the session the cancelled patient (no patient cause) exceeds the OR capacity (195 minutes or 390 minutes in case of no slack), the patient with smallest booked surgery duration that ensures that the program does not exceed OR capacity by removing that patient from the program, is removed from the program. This patient is rescheduled according to the next fit method, so assigned to the first session that has enough remaining capacity. At midnight, the generator **MidNight** calls the method **NewDay,** which calculates the utilization of the day and writes the results of the day, stored in **ORDayPerformance**, to **ORResults**, and deletes **TodaysSchedule** and **ORDayPerformance.**

Running experiments

In the table **ExperimentSettings** the settings of the 152 experiments are stored. To run all experiments, the variable **ExperimentNo** needs to be set to 1, the checkbox **Validation** needs to be false and the random number variant of the **EventController** needs to be 1. The checkboxes **BookingCorrection**, **FastChangeovers**, **MinBookingRate** and **Slack** need to be true. Now, we can execute all experiments by running the method **RunAllExperiments**. After every run, the method **EndSim** is called. This method stores the results of the run in **OverallResults** and **SpecialtyResults**, and starts the next run. After five runs, the method calculates the average results of the five runs and stores the results of the experiment in the table **ExperimentResults.** Subsequently, it adds 1 to the variable **ExperimentNo**, changes the settings of the experiment according to the new **ExperimentNo,** and starts running the new experiment with random number variant 1. The settings are determined by the variables **BookCor**, **ChangeOverSavings**, **MinimalBookingRate** and **SlackFactor**, and the checkboxes **PerfectStart**, **RequestList** and **EmergencyRoom.** When all experiments are executed, the model stops running. It is also possible to execute one experiment by setting **ExperimentNo** to a number higher than 152 and selecting the preferred settings manually. We set the random number variant back to 1 and run **RunAllExperiments.** Now, five runs of the preferred experiment are executed.

3D animation

To enable the 3D mode of the simulation model, the checkbox **Animation** needs to be true. When running the simulation model, **Init** creates **Beds** (Transporters) for the patients and stores them in the buffer **Beds.** When a patient needs to be operated a **Bed** is moved to **Track** and the patient is put on the bed. Now, the **Bed** with the patient enters the frame **OperatingTheatre**. We can open this frame in 3D to see how the patients are brought to the ORs. When the surgery is finished, the Bed drives back via the tracks to the main frame, the patient moves to the buffer **BedHouse** and the **Bed** returns to the buffer **Beds.** For simplicity reasons, we do not store the results of the experiments in the tables when the simulation model is in the 3D mode.

Appendix C: Warm-up Period and Replications

Warm-up period

Because the waiting lists are 0 at the start of the simulation and it takes at least 14 days between the arrival of the patient and surgery, the simulation model has a warm-up period before it reaches a steady state. Therefore, the utilization is lower at the beginning of the simulation than later on. We need to exclude this period from the results.

To determine the warm-up period of the system, we use Welch's graphical method. First, we take 5 runs of simulation, each simulation has a duration of 649 days. Then, we calculate the average utilization of these runs per day and plot this in a graph (the blue graph in Figure C.1). Before we can determine the warm-up period, we need to smoothen the graph. We use the moving average method with a window (w) of 25. With the following formula, we calculate the moving average (the red graph in Figure C.1).

$$\bar{Y}_i(w) = \frac{1}{2w+1} \sum_{s=-w}^{w} \bar{Y}_{i+s}$$

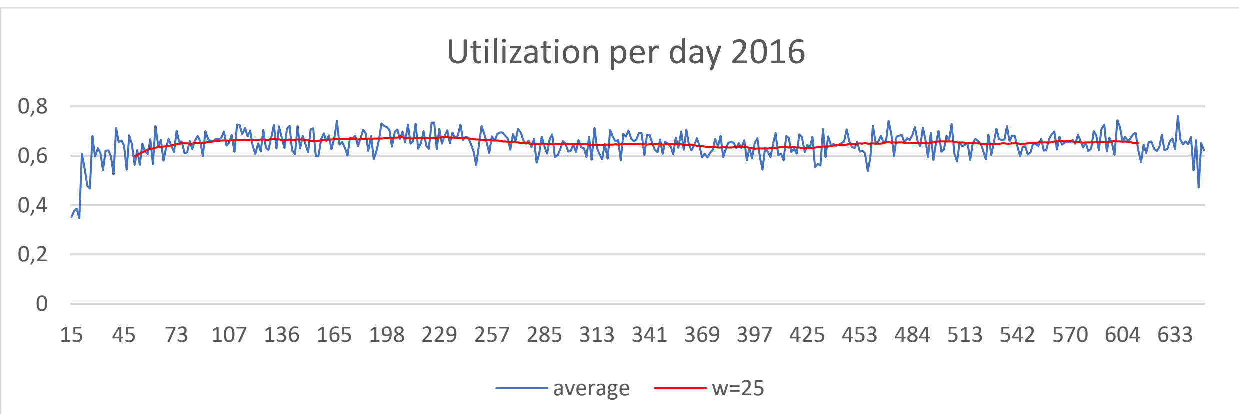


Figure C.1: Welch's graphical method to determine warm-up period 2016

The red graph seems to become stable after 67 days. To be sure, we take some extra days and make sure the 31st of December, 2015 is on a Thursday, since this was also the case in real-life. Thus, we take a warm-up period of 102 days. We take the first 102 days of the session roster of 2016 and insert this before 2016, so that the simulation starts on the 21st of September, 2015 and results are taken from the 1st of January 2016. Figure C.2 shows that a warm-up period of 102 days is also sufficient for the session roster of 2018, the roster for which we perform the experiments.

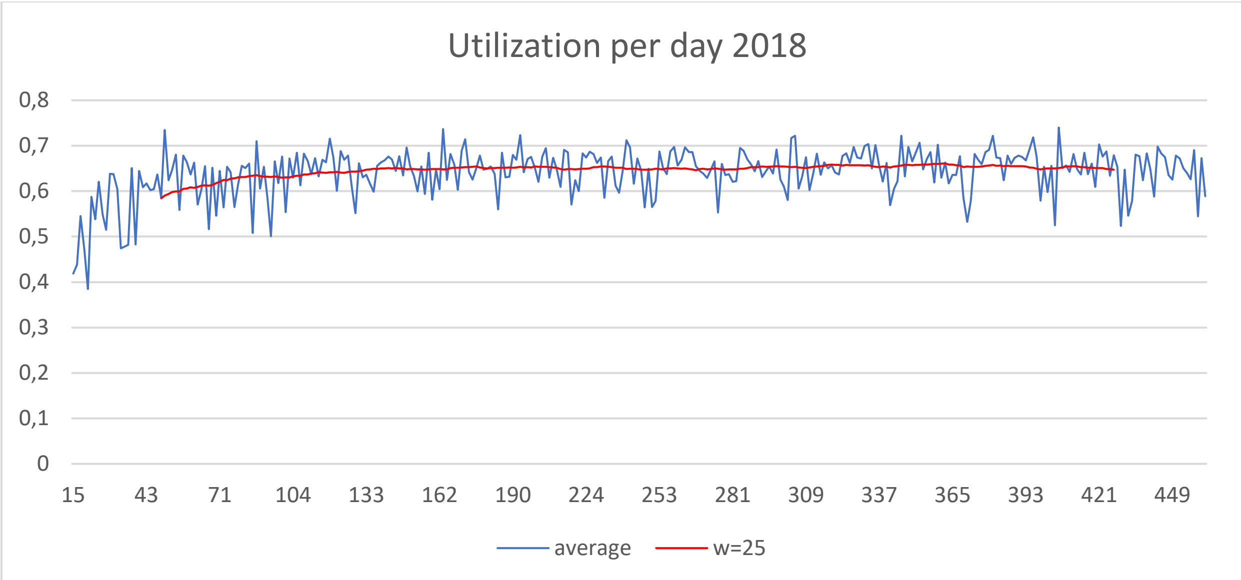


Figure C.2: Welch's graphical method to determine warm-up period 2018

Number of replications

To determine the number of replications, we use the formula below. This formula considers the deviation between the runs and examines the number of replications (n) necessary to meet the relative error (γ').

$$\frac{t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}}}{\overline{X}} < \gamma'$$

We take the total amount of overtime per run as measurement for the number of replications with $\gamma'=0.0476$ ($\gamma=0.05$) and $\alpha=0.05$. We choose to take overtime instead of utilization, since utilization is an average number and deviates less between the runs than overtime. The number of replications is sufficient if the score from Table C.1 is less than the relative error. So, we can conclude that four replications are sufficient for the average (of four runs) of overtime to be within the confidence interval of 95%. To be extra sure that the average is within the confidence interval, we choose to do five replications per experiment instead of four. Table C.2 shows that 5 replications are also sufficient for the situation of 2018.

Table C.1: Overtime per run 2016

Run	Overtime in minutes	Score
1	13,463	
2	14,093	0.145
3	12,195	0.050
4	12,784	0.034
5	13,538	0.024

Table C.2: Overtime per run 2018

Run	Overtime in minutes	Score
1	8,636	
2	8,014	0.237
3	8,078	0.062
4	8,153	0.037
5	8,940	0.025

Appendix D: 2-Sample T-Tests

Surgery duration per specialty

The tables below show the results of the 2-sample t-tests assuming equal variances of the surgery duration per specialty for elective and emergency patients. We simulate one run, including warm-up period, of surgery durations and compare the averages of this run with the reality. For all tests, we use a significance level of α=5%. In all cases 't Stat' is within the 95% confidence interval, which means none of the simulated average durations differ from the reality.

General Surgery	*data - elec*	*sim - elec*
Mean	64.26324	63.76262
Variance	2441.968	1743.505
Observations	2701	3349
Pooled Variance	2055.319	
Hypothesized Mean Difference	0	
df	6048	
t Stat	0.426983	
P(T<=t) two-tail	0.669407	
t Critical two-tail	1.960356	

Ophthalmology	*data - emer*	*sim - emer*
Mean	22.41667	22.50794
Variance	576.0982	914.5385
Observations	96	189
Pooled Variance	800.9278	
Hypothesized Mean Difference	0	
df	283	
t Stat	-0.02573	
P(T<=t) two-tail	0.979489	
t Critical two-tail	1.968382	

General Surgery	*data - emer*	*sim - emer*
Mean	70.6002	70.45119
Variance	1752.035	2401.953
Observations	3024	1383
Pooled Variance	1955.936	
Hypothesized Mean Difference	0	
df	4405	
t Stat	0.10379	
P(T<=t) two-tail	0.917341	
t Critical two-tail	1.960503	

Gynecology	*data - elec*	*sim - elec*
Mean	63.49159	64.03093
Variance	1684.782	1650.902
Observations	1249	1487
Pooled Variance	1666.367	
Hypothesized Mean Difference	0	
df	2734	
t Stat	-0.34424	
P(T<=t) two-tail	0.730695	
t Critical two-tail	1.960832	

Ophthalmology	*data - elec*	*sim - elec*
Mean	22.97012	22.78231
Variance	152.3428	119.1768
Observations	2276	2793
Pooled Variance	134.0678	
Hypothesized Mean Difference	0	
df	5067	
t Stat	0.574404	
P(T<=t) two-tail	0.56572	
t Critical two-tail	1.960432	

Gynecology	*data - emer*	*sim - emer*
Mean	50.04912	49.60517
Variance	558.077	580.6255
Observations	794	1740
Pooled Variance	573.5635	
Hypothesized Mean Difference	0	
df	2532	
t Stat	0.432834	
P(T<=t) two-tail	0.665173	
t Critical two-tail	1.960901	

Orthopedics	*data - elec*	*sim - elec*
Mean	76.51947	77.20395
Variance	2958.1	2665.318
Observations	1284	1569
Pooled Variance	2797.075	
Hypothesized Mean Difference	0	
df	2851	
t Stat	-0.34392	
P(T<=t) two-tail	0.730935	
t Critical two-tail	1.960796	

ENT	*data - elec*	*sim - elec*
Mean	46.87447	46.74209
Variance	779.7214	353.2409
Observations	701	853
Pooled Variance	545.5968	
Hypothesized Mean Difference	0	
df	1552	
t Stat	0.11117	
P(T<=t) two-tail	0.911496	
t Critical two-tail	1.961494	

Orthopedics	*data - emer*	*sim - emer*
Mean	90.83612	94.63913
Variance	2757.131	3227.398
Observations	299	690
Pooled Variance	3085.412	
Hypothesized Mean Difference	0	
df	987	
t Stat	-0.98886	
P(T<=t) two-tail	0.322976	
t Critical two-tail	1.96237	

ENT	*data - emer*	*sim - emer*
Mean	46.27869	44.43357
Variance	572.6044	758.1346
Observations	61	143
Pooled Variance	703.0266	
Hypothesized Mean Difference	0	
df	202	
t Stat	0.455048	
P(T<=t) two-tail	0.649564	
t Critical two-tail	1.971777	

Plastic Surgery	*data - elec*	*sim - elec*
Mean	79.92373	83.14678
Variance	5413.706	5601.229
Observations	708	838
Pooled Variance	5515.362	
Hypothesized Mean Difference	0	
df	1544	
t Stat	-0.85019	
P(T<=t) two-tail	0.395354	
t Critical two-tail	1.961502	

Urology	*data - elec*	*sim - elec*
Mean	76.15335	75.62835
Variance	2875.81	2268.492
Observations	626	783
Pooled Variance	2538.267	
Hypothesized Mean Difference	0	
df	1407	
t Stat	0.194359	
P(T<=t) two-tail	0.845923	
t Critical two-tail	1.961651	

Plastic Surgery	*data - emer*	*sim - emer*
Mean	103.3425	114.5385
Variance	4082.339	5012.262
Observations	73	169
Pooled Variance	4733.285	
Hypothesized Mean Difference	0	
df	240	
t Stat	-1.16193	
P(T<=t) two-tail	0.24642	
t Critical two-tail	1.969898	

Urology	*data - emer*	*sim - emer*
Mean	53.91525	51.42259
Variance	1445.155	1316.455
Observations	118	239
Pooled Variance	1358.872	
Hypothesized Mean Difference	0	
df	355	
t Stat	0.601007	
P(T<=t) two-tail	0.548219	
t Critical two-tail	1.966669	

Neurosurgery	*data - elec*	*sim - elec*
Mean	90.06219	92.69101
Variance	1646.078	2491.591
Observations	402	534
Pooled Variance	2128.582	
Hypothesized Mean Difference	0	
df	934	
t Stat	-0.8629	
P(T<=t) two-tail	0.388413	
t Critical two-tail	1.962507	

Neurosurgery	*data - emer*	*sim - emer*
Mean	91.44828	90.27731
Variance	1254.217	1792.66
Observations	58	119
Pooled Variance	1617.281	
Hypothesized Mean Difference	0	
df	175	
t Stat	0.181824	
P(T<=t) two-tail	0.855931	
t Critical two-tail	1.973612	

Pain Treatment	*data - elec*	*sim - elec*
Mean	28.76019	29.22268
Variance	123.5385	107.4875
Observations	417	485
Pooled Variance	114.9066	
Hypothesized Mean Difference	0	
df	900	
t Stat	-0.64605	
P(T<=t) two-tail	0.518414	
t Critical two-tail	1.962603	

Pain Treatment	*data - emer*	*sim - emer*
Mean	27.9375	25.55
Variance	144.125	30.72627
Observations	32	60
Pooled Variance	69.78583	
Hypothesized Mean Difference	0	
df	90	
t Stat	1.305619	
P(T<=t) two-tail	0.19501	
t Critical two-tail	1.986675	

Cardiology	*data - elec*	*sim - elec*
Mean	82.62626	84.83471
Variance	1331.175	2192.556
Observations	99	121
Pooled Variance	1805.33	
Hypothesized Mean Difference	0	
df	218	
t Stat	-0.38354	
P(T<=t) two-tail	0.701695	
t Critical two-tail	1.970906	

Cardiology	*data - emer*	*sim - emer*
Mean	84.63333	91.63793
Variance	763.7575	1079.498
Observations	30	58
Pooled Variance	973.0275	
Hypothesized Mean Difference	0	
df	86	
t Stat	-0.99851	
P(T<=t) two-tail	0.320832	
t Critical two-tail	1.987934	

Utilization per OR

The results of the 2-sample t-tests assuming unequal variances per OR, performed in Excel, are shown below. We take the utilization per OR session as observations to perform the tests on. We include the OR session of the simulation if the session has a capacity of 420 and there are results of five replications. Therefore, the number of OR sessions and average utilization can deviate from Table 4.6. We use a significance level of α = 5% to check if the average utilization per OR in the simulation is different from the realization. 't Critical two-tail' indicates the upper bound of the confidence interval of 95%. The lower bound of the confidence interval is the negative value of 't Critical two-tail. So, the 95% confidence interval for OR1 is: [-1.964;1.964]. There is no significant difference if 't Stat' is within this interval. Knowing this, we can conclude that the average utilization of the simulation differs from the realization for all ORs.

OR1	*sim*	*data*
Mean	0.709438	0.7450969
Variance	0.005935	0.0181195
Observations	366	371
Hypothesized Mean Difference	0	
df	591	
t Stat	-4.42106	
P(T<=t) two-tail	1.17E-05	
t Critical two-tail	1.963986	

OR2	*sim*	*data*
Mean	0.668866	0.7040241
Variance	0.005736	0.0194829
Observations	361	355
Hypothesized Mean Difference	0	
df	544	
t Stat	-4.17921	
P(T<=t) two-tail	3.41E-05	
t Critical two-tail	1.964334	

OR3	*sim*	*data*
Mean	0.662426	0.719465
Variance	0.012727	0.021429
Observations	367	371
Hypothesized Mean Difference	0	
df	695	
t Stat	-5.93257	
P(T<=t) two-tail	4.7E-09	
t Critical two-tail	1.963383	

OR4	*sim*	*data*
Mean	0.647483	0.725337
Variance	0.01693	0.02246
Observations	350	357
Hypothesized Mean Difference	0	
df	695	
t Stat	-7.3801	
P(T<=t) two-tail	4.53E-13	
t Critical two-tail	1.963383	

OR5	*sim*	*data*
Mean	0.679698	0.732223
Variance	0.007702	0.015951
Observations	368	373
Hypothesized Mean Difference	0	
df	664	
t Stat	-6.58128	
P(T<=t) two-tail	9.47E-11	
t Critical two-tail	1.963543	

OR6	*sim*	*data*
Mean	0.530344	0.492211
Variance	0.009215	0.03753
Observations	314	328
Hypothesized Mean Difference	0	
df	483	
t Stat	3.180335	
P(T<=t) two-tail	0.001566	
t Critical two-tail	1.964888	

Appendix E: Simulation Output

This appendix shows the simulation output of the Scheduling Intervention experiments.

Exp. No.	Emergency OR	Request List	MBR	Slack	Electives Operated	Utilization	Overtime	Cancellations	SDE	AAT
1	TRUE	FALSE	0%	0.0%	91%	64.8%	8460	521.6	0	43.2
2	FALSE	FALSE	0%	0.0%	96%	67.8%	9899	562.2	1.2	32.1
3	TRUE	TRUE	0%	0.0%	93%	66.2%	9505	577	0.2	36.8
4	FALSE	TRUE	0%	0.0%	97%	68.5%	10893	549.8	1.6	26.1
5	TRUE	FALSE	20%	0.0%	92%	65.4%	9023	514.8	0.4	41.1
6	FALSE	FALSE	20%	0.0%	97%	68.4%	9903	560.6	1.4	29.9
7	TRUE	TRUE	20%	0.0%	94%	66.5%	9731	562.8	0	35.9
8	FALSE	TRUE	20%	0.0%	97%	68.6%	10640	539.8	2	25.4
9	TRUE	FALSE	30%	0.0%	92%	65.9%	8806	536.8	0	40.9
10	FALSE	FALSE	30%	0.0%	97%	68.8%	9771	560.8	1	29.2
11	TRUE	TRUE	30%	0.0%	94%	66.5%	9773	570.2	0.4	35.8
12	FALSE	TRUE	30%	0.0%	97%	68.8%	10531	538.6	1.2	25.1
13	TRUE	FALSE	40%	0.0%	93%	66.4%	8686	543.2	0	40.5
14	FALSE	FALSE	40%	0.0%	97%	69.3%	9923	574.6	0.8	28.6
15	TRUE	TRUE	40%	0.0%	94%	66.9%	10097	575	0	36.1
16	FALSE	TRUE	40%	0.0%	97%	69.1%	10328	549.8	1.8	25.0
17	TRUE	FALSE	50%	0.0%	93%	67.0%	8742	574.6	0.2	40.2
18	FALSE	FALSE	50%	0.0%	97%	69.7%	9818	616.6	1.2	28.6
19	TRUE	TRUE	50%	0.0%	94%	67.4%	9938	576	0.2	35.9
20	FALSE	TRUE	50%	0.0%	97%	69.5%	10317	563.6	1.6	24.9
21	TRUE	FALSE	0%	2.5%	90%	64.2%	7604	444.4	0.2	45.5
22	FALSE	FALSE	0%	2.5%	95%	67.4%	8796	492.2	1.8	34.0
23	TRUE	TRUE	0%	2.5%	92%	65.3%	8352	477.4	0.2	39.5
24	FALSE	TRUE	0%	2.5%	97%	68.4%	9548	487.8	1	28.1
25	TRUE	FALSE	20%	2.5%	91%	64.8%	8136	448	0	44.0
26	FALSE	FALSE	20%	2.5%	96%	68.0%	8943	491.4	1.2	32.2
27	TRUE	TRUE	20%	2.5%	92%	65.6%	8303	477.8	0	38.8
28	FALSE	TRUE	20%	2.5%	97%	68.6%	9659	484.4	2	27.0
29	TRUE	FALSE	30%	2.5%	91%	65.1%	8007	474.2	0	43.5
30	FALSE	FALSE	30%	2.5%	96%	68.5%	8771	496.4	1	30.9
31	TRUE	TRUE	30%	2.5%	93%	66.0%	8120	463.4	0.2	38.7
32	FALSE	TRUE	30%	2.5%	97%	68.6%	9618	507.6	2.4	27.1
33	TRUE	FALSE	40%	2.5%	91%	65.7%	7870	467.8	0.2	43.1
34	FALSE	FALSE	40%	2.5%	97%	69.1%	9387	487	1.2	30.5
35	TRUE	TRUE	40%	2.5%	93%	66.2%	8987	477.6	0.2	38.6
36	FALSE	TRUE	40%	2.5%	97%	69.1%	9225	491	1.4	26.6
37	TRUE	FALSE	50%	2.5%	92%	66.1%	7974	485.2	0.2	43.2

38	FALSE	FALSE	50%	2.5%	97%	69.4%	9121	510.4	0.6	30.1
39	TRUE	TRUE	50%	2.5%	93%	66.6%	8321	490.4	0.6	38.3
40	FALSE	TRUE	50%	2.5%	97%	69.4%	9638	489.2	1.4	26.6
41	TRUE	FALSE	0%	5.0%	89%	63.5%	6709	380.2	0	47.5
42	FALSE	FALSE	0%	5.0%	94%	66.7%	7924	401	0.8	36.3
43	TRUE	TRUE	0%	5.0%	91%	64.4%	7066	383	0.4	42.4
44	FALSE	TRUE	0%	5.0%	96%	67.9%	8616	412	2.2	30.5
45	TRUE	FALSE	20%	5.0%	90%	64.1%	6636	381.2	0.4	46.0
46	FALSE	FALSE	20%	5.0%	95%	67.8%	7508	401.2	2.4	33.6
47	TRUE	TRUE	20%	5.0%	91%	64.8%	7173	419.8	0.2	41.7
48	FALSE	TRUE	20%	5.0%	96%	68.3%	8380	418.8	0.8	29.5
49	TRUE	FALSE	30%	5.0%	90%	64.5%	6710	383.2	0	45.6
50	FALSE	FALSE	30%	5.0%	96%	68.2%	7826	402.2	1.2	33.5
51	TRUE	TRUE	30%	5.0%	91%	65.1%	7181	395.2	0.2	41.4
52	FALSE	TRUE	30%	5.0%	97%	68.6%	8753	411.6	0.4	29.4
53	TRUE	FALSE	40%	5.0%	91%	65.0%	7068	394.6	0	45.6
54	FALSE	FALSE	40%	5.0%	96%	68.6%	8156	431	1.4	33.1
55	TRUE	TRUE	40%	5.0%	92%	65.5%	7283	392.2	0.4	41.1
56	FALSE	TRUE	40%	5.0%	97%	68.9%	8459	433.2	1.4	29.1
57	TRUE	FALSE	50%	5.0%	91%	65.4%	7429	409.6	0	45.5
58	FALSE	FALSE	50%	5.0%	96%	69.1%	8152	450	1.6	32.7
59	TRUE	TRUE	50%	5.0%	92%	65.7%	7264	427.8	0	41.2
60	FALSE	TRUE	50%	5.0%	97%	69.3%	8524	418.6	1	28.8
61	TRUE	FALSE	0%	7.5%	88%	62.7%	5539	319.6	0.2	50.4
62	FALSE	FALSE	0%	7.5%	93%	66.5%	7187	335.2	1.2	38.5
63	TRUE	TRUE	0%	7.5%	90%	63.8%	6081	329.4	0	45.1
64	FALSE	TRUE	0%	7.5%	95%	67.4%	7232	348.2	1	33.2
65	TRUE	FALSE	20%	7.5%	89%	63.2%	5904	307.4	0	48.2
66	FALSE	FALSE	20%	7.5%	94%	67.2%	7047	336.6	0.8	36.7
67	TRUE	TRUE	20%	7.5%	90%	64.0%	6390	313	0.2	44.3
68	FALSE	TRUE	20%	7.5%	95%	67.8%	7925	371.2	1.8	32.2
69	TRUE	FALSE	30%	7.5%	89%	63.8%	5922	313.4	0.2	48.2
70	FALSE	FALSE	30%	7.5%	95%	67.5%	7103	361	1.4	35.8
71	TRUE	TRUE	30%	7.5%	90%	64.3%	6463	333.2	0	44.4
72	FALSE	TRUE	30%	7.5%	96%	67.9%	7602	354.8	1	32.2
73	TRUE	FALSE	40%	7.5%	89%	64.3%	6025	308.4	0.2	48.2
74	FALSE	FALSE	40%	7.5%	95%	68.0%	7153	367.6	0.6	35.6
75	TRUE	TRUE	40%	7.5%	90%	64.5%	6399	351.6	0.2	44.3
76	FALSE	TRUE	40%	7.5%	96%	68.2%	7702	362.2	1.2	31.8
77	TRUE	FALSE	50%	7.5%	90%	64.6%	6403	333.4	0	48.3
78	FALSE	FALSE	50%	7.5%	95%	68.5%	6731	375.4	1.2	35.2
79	TRUE	TRUE	50%	7.5%	90%	64.9%	6504	349.8	0.2	44.5
80	FALSE	TRUE	50%	7.5%	96%	68.8%	7532	378.4	1.2	31.9

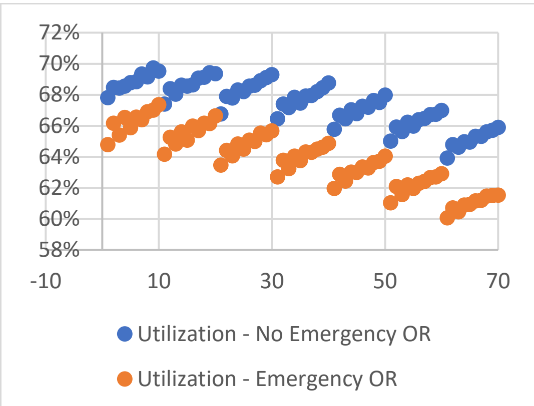
81	TRUE	FALSE	0%	10.0%	87%	62.0%	5047	250.4	0.4	52.7
82	FALSE	FALSE	0%	10.0%	92%	65.8%	6086	272.2	0.8	41.4
83	TRUE	TRUE	0%	10.0%	88%	62.9%	5727	269	0	48.1
84	FALSE	TRUE	0%	10.0%	94%	66.7%	6640	298.8	0.8	36.2
85	TRUE	FALSE	20%	10.0%	88%	62.4%	4900	268	0.2	51.5
86	FALSE	FALSE	20%	10.0%	93%	66.5%	6107	295	1	39.4
87	TRUE	TRUE	20%	10.0%	89%	63.0%	5364	276.6	0.2	47.7
88	FALSE	TRUE	20%	10.0%	94%	67.0%	6961	286.2	0.6	35.1
89	TRUE	FALSE	30%	10.0%	88%	63.0%	5068	274	0	51.3
90	FALSE	FALSE	30%	10.0%	93%	66.8%	5992	314.2	0.4	39.1
91	TRUE	TRUE	30%	10.0%	89%	63.3%	5341	270.2	0.2	47.5
92	FALSE	TRUE	30%	10.0%	94%	67.3%	7002	298.4	0.6	34.9
93	TRUE	FALSE	40%	10.0%	88%	63.3%	5307	280	0.2	51.1
94	FALSE	FALSE	40%	10.0%	94%	67.2%	5976	304.4	1.4	38.3
95	TRUE	TRUE	40%	10.0%	89%	63.6%	5451	275.6	0	47.2
96	FALSE	TRUE	40%	10.0%	95%	67.6%	6331	315.8	0.4	34.6
97	TRUE	FALSE	50%	10.0%	88%	63.7%	5087	288	0	51.2
98	FALSE	FALSE	50%	10.0%	94%	67.5%	6551	313	0.8	38.7
99	TRUE	TRUE	50%	10.0%	89%	64.0%	5395	280.4	0	47.6
100	FALSE	TRUE	50%	10.0%	95%	68.0%	6832	310.2	1.4	34.6
101	TRUE	FALSE	0%	12.5%	85%	61.0%	4311	228.4	0	55.9
102	FALSE	FALSE	0%	12.5%	91%	65.0%	5301	244.2	0.2	44.2
103	TRUE	TRUE	0%	12.5%	87%	62.1%	4568	223.8	0	51.1
104	FALSE	TRUE	0%	12.5%	92%	65.9%	5481	233.8	0	39.6
105	TRUE	FALSE	20%	12.5%	86%	61.6%	4882	220	0.2	54.3
106	FALSE	FALSE	20%	12.5%	92%	65.6%	5658	236.2	0.8	42.3
107	TRUE	TRUE	20%	12.5%	87%	62.2%	4755	228.8	0	51.0
108	FALSE	TRUE	20%	12.5%	93%	66.2%	5634	251.8	0.4	38.9
109	TRUE	FALSE	30%	12.5%	87%	62.0%	4512	216	0.2	54.4
110	FALSE	FALSE	30%	12.5%	92%	66.0%	5332	234.2	0.6	41.9
111	TRUE	TRUE	30%	12.5%	87%	62.3%	4780	219.2	0	50.8
112	FALSE	TRUE	30%	12.5%	93%	66.4%	5637	241.2	0.6	38.3
113	TRUE	FALSE	40%	12.5%	87%	62.4%	4516	232	0.2	54.3
114	FALSE	FALSE	40%	12.5%	92%	66.5%	5297	241.8	0.4	41.7
115	TRUE	TRUE	40%	12.5%	88%	62.7%	4654	225	0.2	50.5
116	FALSE	TRUE	40%	12.5%	93%	66.7%	5525	255.2	0.4	38.3
117	TRUE	FALSE	50%	12.5%	87%	62.7%	4908	232	0.2	54.2
118	FALSE	FALSE	50%	12.5%	92%	66.7%	5699	257.6	0.2	42.1
119	TRUE	TRUE	50%	12.5%	88%	62.9%	4587	243.8	0	51.1
120	FALSE	TRUE	50%	12.5%	93%	67.0%	5708	247.4	0.6	38.3
121	TRUE	FALSE	0%	15.0%	84%	60.1%	3843	182.6	0	59.5
122	FALSE	FALSE	0%	15.0%	89%	63.9%	4085	200.2	0	48.3
123	TRUE	TRUE	0%	15.0%	85%	60.7%	3866	190.2	0	55.3

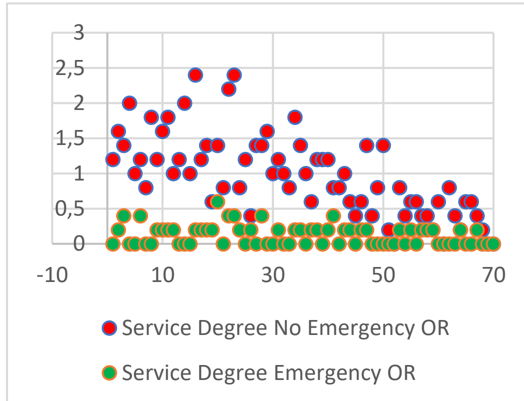
124	FALSE	TRUE	0%	15.0%	91%	64.8%	4934	182.6	0.8	43.8
125	TRUE	FALSE	20%	15.0%	85%	60.5%	3489	185.8	0	58.4
126	FALSE	FALSE	20%	15.0%	90%	64.6%	4679	202	0.4	46.6
127	TRUE	TRUE	20%	15.0%	86%	60.9%	3785	185.2	0.2	55.1
128	FALSE	TRUE	20%	15.0%	91%	65.0%	4797	197.8	0.2	43.0
129	TRUE	FALSE	30%	15.0%	85%	60.9%	3578	180.6	0	58.1
130	FALSE	FALSE	30%	15.0%	90%	64.9%	4396	204.8	0.6	46.0
131	TRUE	TRUE	30%	15.0%	86%	61.2%	3913	195.2	0	54.9
132	FALSE	TRUE	30%	15.0%	91%	65.3%	5001	202.4	0.6	43.0
133	TRUE	FALSE	40%	15.0%	85%	61.2%	3598	186.6	0.2	58.2
134	FALSE	FALSE	40%	15.0%	91%	65.3%	4515	200.2	0.4	46.1
135	TRUE	TRUE	40%	15.0%	86%	61.5%	3841	194.4	0	54.8
136	FALSE	TRUE	40%	15.0%	91%	65.6%	4636	205.4	0.2	42.7
137	TRUE	FALSE	50%	15.0%	85%	61.5%	3655	182.2	0	58.3
138	FALSE	FALSE	50%	15.0%	91%	65.7%	4712	195.6	0	45.8
139	TRUE	TRUE	50%	15.0%	86%	61.5%	4187	187.4	0	55.2
140	FALSE	TRUE	50%	15.0%	92%	65.9%	4949	208.4	0	42.9

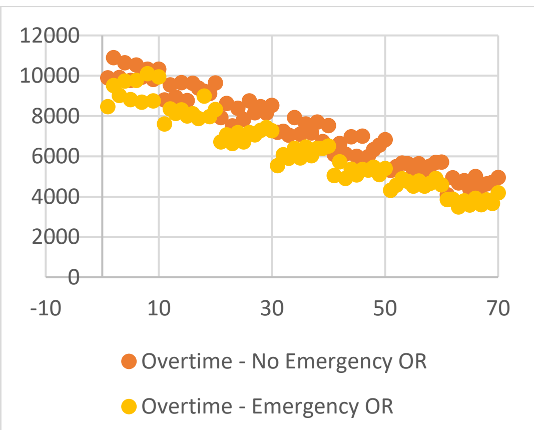
Appendix F: Input – Output Relations

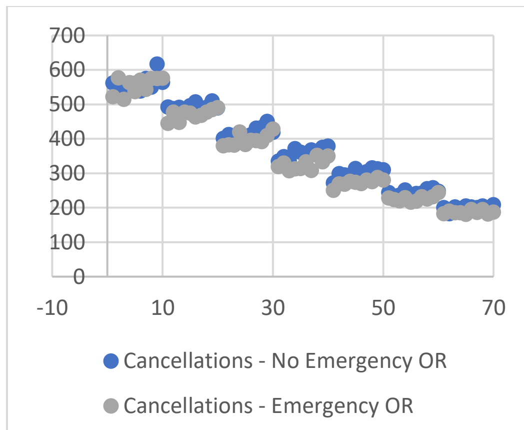
In this appendix, we show the effect of the input variables on the output variables. Per input variable we show five figures, one for every KPI, and compare in these figures the results of the minimum and maximum value of the input variable.

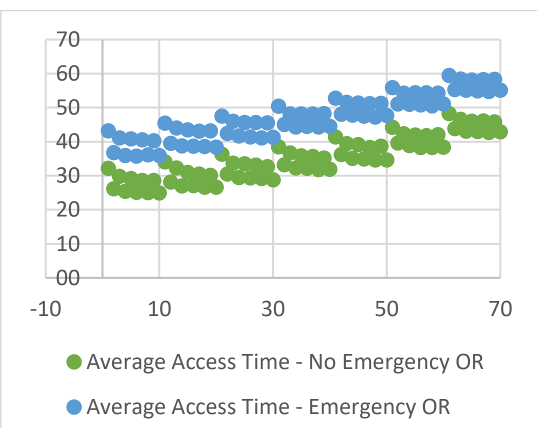
Emergency OR



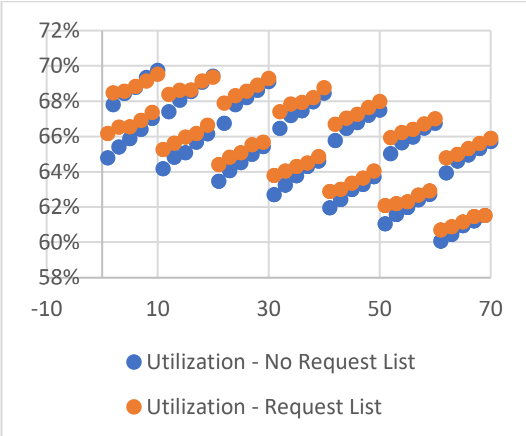


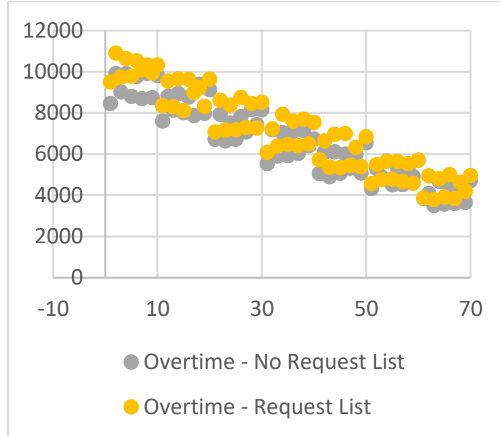


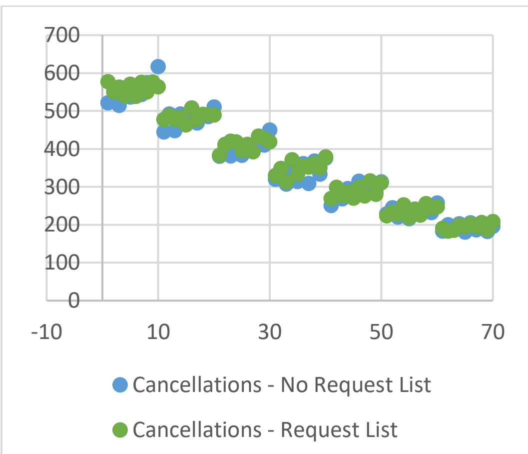


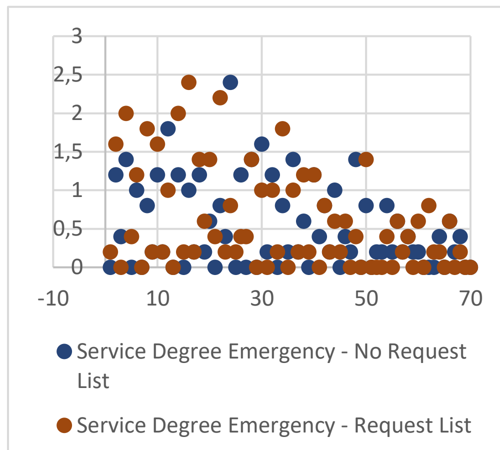


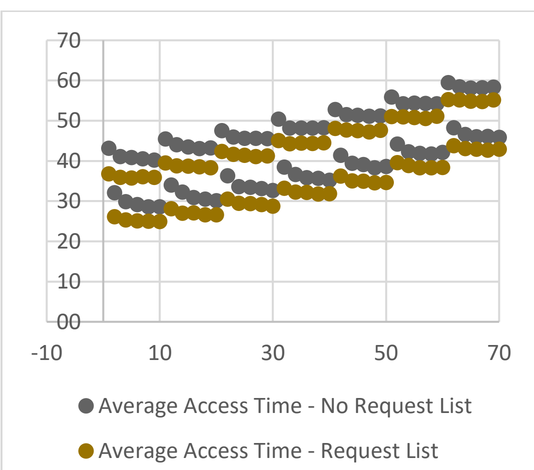
Request List



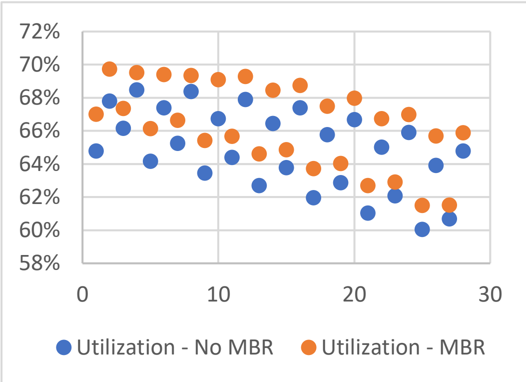


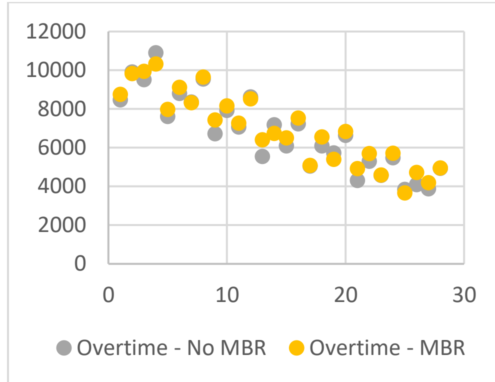


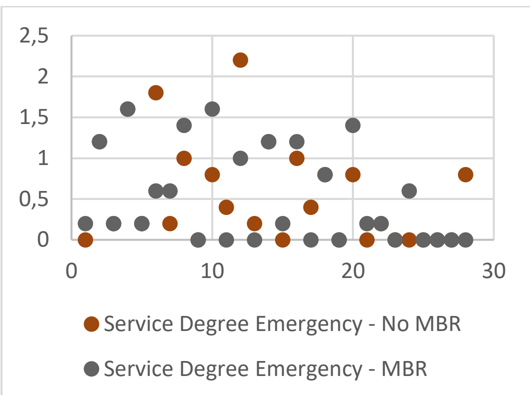


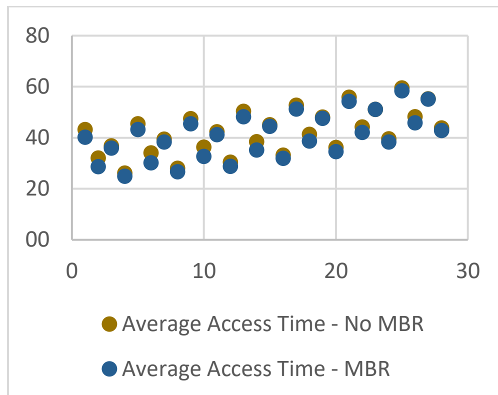


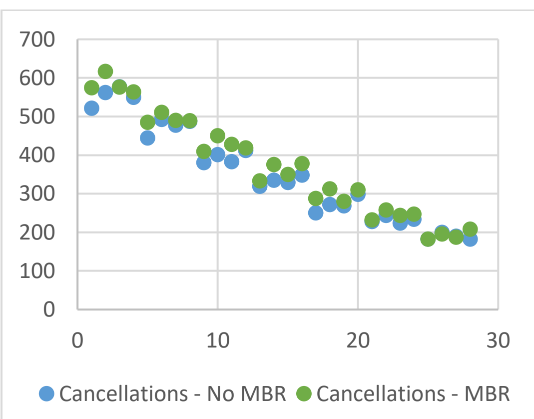
Minimum Booking Rate



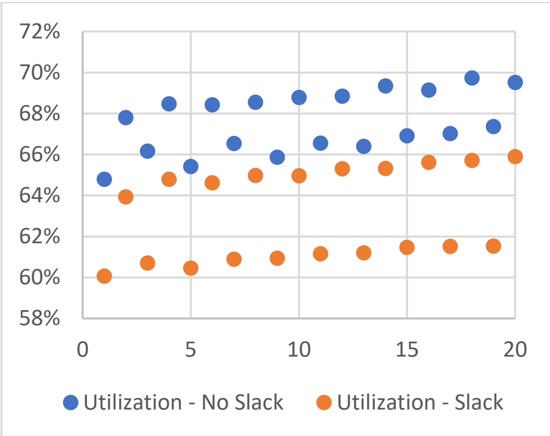








Slack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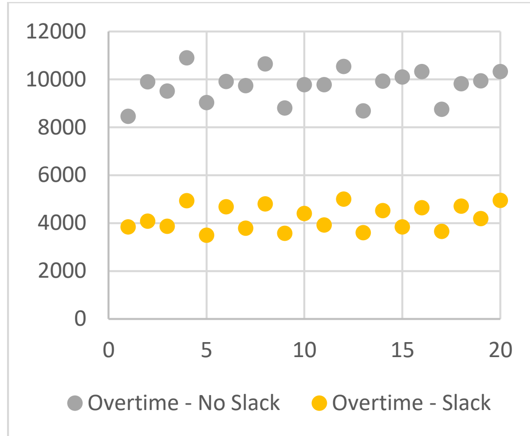
68%
66%
64%
62%
60%
58%
0
5
10
15
20
Utilization - No Slack
Utilization - Slack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8000
6000
4000
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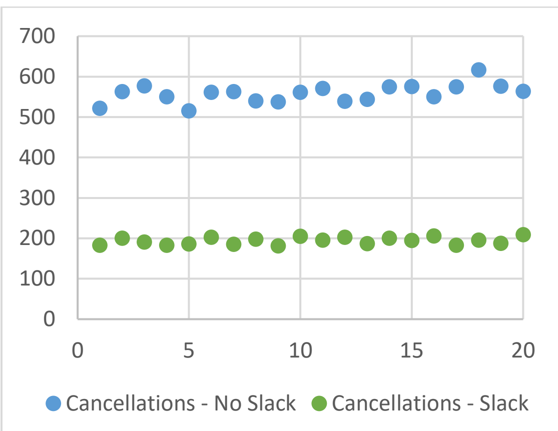
0
5
10
15
20
Overtime - No Slack
Overtime - Slack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500
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300
200
100
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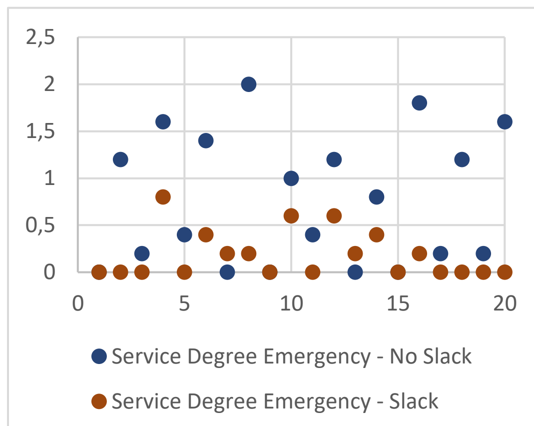
0
5
10
15
20
Cancellations - No Slack
Cancellations - Slack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1
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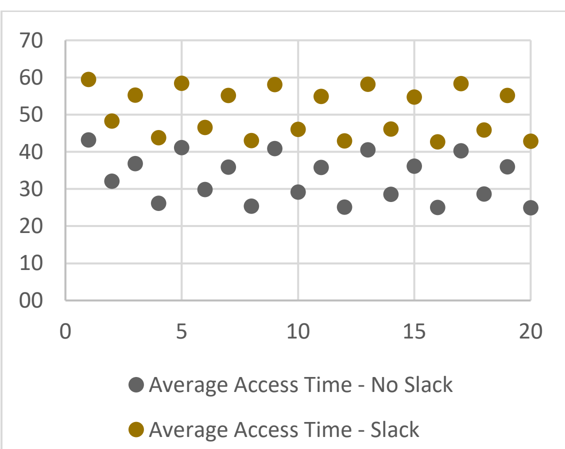
0
5
10
15
20
Service Degree Emergency - No Slack
Service Degree Emergency - Slack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15
20
Average Access Time - No Slack
Average Access Time - Slack