UNIVERSITY OF TWENTE.

BERGMAN CLINICS

IMPROVING OPERATING ROOM UTILIZATION AT BERGMAN CLINICS

Evaluation of various surgery scheduling approaches using discrete-event simulation

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Management Summary

Problem description

The operating room (OR) department is one of the most expensive resources and at the same time the greatest source of revenues within the Bergman Clinics. Therefore, available OR resources must be used as efficient as possible. OR planners are responsible for the OR schedule. Together with the patient, they decide on the surgery date of the patient. OR planners are not supported by a uniform surgery scheduling approach, so the extent to which available OR time is used depends on the expertise of the OR planners. Because of the high costs associated with the OR department, management demands that OR utilization is high. OR planners experience a high workload because they are aware of their influence on OR utilization and consequently on the revenues of Bergman Clinics.

To decrease the workload of OR planners and increase OR utilization and revenues, we defined the following research goal:

To develop a uniform surgery scheduling approach which increases OR utilization through increasing scheduled OR utilization, decreases workload of OR planners, and meets access time targets.

Two clinics, A and B, are included in this research, but the outcomes of this research could possibly be useful for other clinics as well.

Approach

We analyse the current performance of the OR department and the efficiency of the OR schedule. We perform a literature study on surgery scheduling approaches and decide about the suitability of our findings with regard to the Bergman Clinics. We assess three surgery scheduling rules. A rule that is based on revenue management (RM) theory, the latest start time rule and the earliest start time rule. These rules can also be combined. Moreover, we assess the influence of the planning horizon and the appointment flexibility on the performance of the OR planning department. The appointment flexibility indicates the number of surgery dates a patient can choose from.

We use discrete event simulation to assess the proposed interventions in terms of various KPIs. We assess the robustness of the best performing intervention by changing the arrival process at the OR planning department.

Results

We created a discrete event simulation model which is a close representation of the real OR planning department. The simulation model measures the performance of an intervention in various KPIs concerning scheduled gross OR utilization, average surgery access time and the percentage of patients that could not be scheduled within the planning horizon.

The current used surgery scheduling rule results in an average scheduled gross OR utilization of 85.5%, an average surgery access time of 33 days and an average percentage of patients that could not be scheduled within the planning horizon of 0.8%.

Table 1 shows per KPI the difference between the current performance and the performance achieved by the proposed scheduling rules.

Applied scheduling rule	Number of used OR sessions	Average scheduled gross OR utilization	Average surgery access time in days	Average percentage of patients that could not be scheduled within the planning horizon
RM-based rule	+1	+0.1%	+1	Same
Earliest start time rule	-3	-3.7%	+29	+4.1%
Latest start time rule	-17	+2.2%	+22	+3.0%
RM based rule + Latest start time rule	-5	+1.7%	+8	+0.6%

Table 1: difference in performance between the current surgery scheduling rule and the proposed surgery scheduling rules

An increase in average scheduled gross OR utilization always comes with an increase in average surgery access time. This relation could be explained by the fact that scheduling a surgery in the most efficient way, does not by definition mean that the surgery is scheduled in the first available OR session. The latest start time rule results in the best average scheduled gross OR utilization but the average surgery access time increases drastically. Combining the latest start time rule with the RM based rule increases the average scheduled gross OR utilization with 1.7%, while the average surgery access time increases with only 8 days.

If the latest start time rule is used in combination with the RM based rule, shortening the planning horizon from 1-10 weeks to 1-6 weeks reduces the average surgery access time with 15 days, but decreases the average scheduled gross OR utilization with 2.7%. The average percentage of patients that could not be scheduled within the planning horizon increases with 3.4%. This indicates that the number of available OR sessions within the planning horizon is not sufficient to treat all patient within 6 weeks.

Offering less appointment flexibility improves the average scheduled gross OR utilization. The difference in average scheduled gross OR utilization between an appointment flexibility of 1 choice and an appointment flexibility of 4 choices is 4.5%. The average surgery access time deviates with only 1 day.

Using a combination of the RM based rule and the latest start time rule, and using a planning horizon of 1-6 weeks and an appointment flexibility of 2 choices, has proven to be robust against changes in the arrival process at the OR planning department. The average surgery access time in days deviates 1 day at most and the average scheduled gross OR utilization deviates 0.2% at most.

Conclusions and recommendations

We conclude that the latest start time rule should be combined with the RM based rule to improve the average scheduled gross OR utilization and to avoid that surgery access times increase drastically. To meet the access time target, the planning horizon should be chosen such that the maximum possible surgery access time is within the access time target. If shortening the planning horizon results in a high percentage of patients that could not be scheduled within the planning horizon, the number of OR sessions within the planning horizon has to be increased. Offering less appointment flexibility increases the average scheduled gross OR utilization but is at the expense of customer service. Therefore, we advise an appointment flexibility of 2 choices, so patients are offered the possibility to choose and the average scheduled gross OR utilization is the second best that can be achieved.

Value for science

We developed a surgery scheduling rule that uses revenue management theory to value available OR time differently. One of the conditions that should be met to apply RM is that customers value a product differently and show different purchase behaviour (Talluri & van Ryzin, 2004). Even though the healthcare industry does not meet this condition, we investigated if RM could be used to distinguish valuable and less valuable OR time. If available OR time is not used, it cannot be inventoried so it is of great importance to use all required OR time. The scheduling rule we introduced distinguishes valuable and less valuable OR time based on a combination of factors. One of these factors is the chance that the unused amount of OR time could be used at a later moment in time. The lower that chance, the more value is assigned to that OR time. To the best of our knowledge, we did not find such a method in literature. Even though the healthcare industry might not seem ideal for applying RM, we find a way to use RM theory successfully.

Value for practice

With this research we have given the company insight in their performance in terms of OR utilization and surgery access times. The company had a lot of assumptions with regard to their performance, but these were never verified. Moreover, using the RM based rule in combination with the latest start time rule contributes to better utilization of OR resources and less workload for OR planners as they can use a surgery scheduling rule that guarantees high OR utilizations.

Preface

Dear reader,

With proud I present you my Master Thesis 'Improving operating room utilization at Bergman Clinics', that I have written in order to obtain my Master's degree in Industrial Engineering and Management, with a specialization in Healthcare Technology and Management.

This graduation project marks the end of my student life, which has been an ongoing process of learning and getting to know myself. During my Bachelor studies in Technical Medicine, I discovered my interest in the processes that take place after the research and development phase towards new healthcare technologies. This has led to the decision to start a Master's programme in Industrial Engineering and Management, a decision that I have never regretted.

Although I have been looking forward to completing my Master's degree and to starting a job for a while, I can look back on a pleasant study period. During both my Bachelor and Master studies I have made a lot of new friends, with whom even the most boring lectures were worth attending. I also want to highlight my exchange to Taiwan with Nina and Marleen. Studying abroad was definitely the most memorable experience during my student days, but it would not have been this great without you.

I would like to thank all the people who have supported me during my student days and during this graduation project in particular. To start with, I thank Ivo Piest and Anne Schrama-Kiers for offering me the chance to do my graduation project at Bergman Clinics, as the first graduate student in the company in this field. I also thank Diana Bukkems, who has been my company supervisor, for helping me structuring the process and to continuously remind me of everything that must be taken into account during the surgery scheduling process.

Furthermore, I would like to thank my supervisors from the University of Twente, Erwin Hans and Gréanne Maan-Leeftink, for guiding me through this graduation project, which has not always been easy. From the beginning Erwin challenged me, but also gave me the trust I needed. I experienced our meetings as very helpful and he always kept me motivated when things didn't go the way I wanted. During the last phase of my graduation project, Gréanne really contributed to putting pieces together and by providing me with useful feedback. I also thank Ipek Seyran Topan for replacing Gréanne during my colloquium, and for making the effort to assess my Master thesis.

Last, but certainly not least, I would like to thank my family for their unconditional support and never putting pressure on me, and Sjoerd for his listening ear and for helping me with putting "problems" into perspective.

All that remains for me is to wish you a pleasant read.

Suzan Kamp
Zwolle, March 2020

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1 Introduction

This thesis presents a research project that has been performed at Bergman Clinics *in order to develop a surgery scheduling approach that increases operating room (OR) utilization*. Two clinics, A and B, are included in the research. The outcomes of this research could possibly be useful for other clinics as well.

Section 1.1 provides a general description of Bergman Clinics. Section 1.2 describes the motivation for this research. In Section 1.3 we define stakeholders and describe the problems perceived by these particular stakeholders. Section 1.4 poses the research objective resulting from the problem descriptions, after which Section 1.5 lists the research questions.

1.1 Context description

Bergman Clinics is a network of 64 healthcare clinics located throughout the Netherlands. Every clinic provides specialized, plannable healthcare and together they have served 114,750 patients and performed 42,950 surgeries in 2018. In contrast to hospitals, Bergman Clinics focusses on high volume, plannable and less complex care. None of the clinics have an intensive care unit and therefore only low risk patients could be treated.

It is the patient's own choice whether to visit a hospital or a specialized healthcare clinic like one of the Bergman Clinics. Patients prefer a specialized clinic mostly because of lower access times, expertise and ambiance. Just like in hospitals, patients are eligible for reimbursement if they have a medical indication and are referred by a general practitioner or a medical specialist. Medically unnecessary treatments always have to be paid by the patients themselves.

1.2 Research motivation

The operating room (OR) department is one of the most expensive resources and at the same time the greatest source of revenues within the Bergman Clinics. Therefore, management aims for maximizing the use of available OR resources. The surgery scheduling process is performed by the OR planners. A uniform surgery scheduling approach does not exist, so the OR utilization depends on the expertise of OR planners. Inefficient schedules result in underutilization, as well as in surgery cancellations due to violation of resource restrictions. Moreover, the lack of a uniform surgery scheduling approach increases the workload of OR planners. The development of a uniform surgery scheduling approach must support OR planners and increase the use of available OR resources.

1.3 Stakeholders

We distinguish the following stakeholders: management of Bergman Clinics, patients, OR planners, OR department personnel, surgeons and nurses. In this paragraph, the problems perceived from each perspective are described.

Management of Bergman Clinics

The management of Bergman Clinics wants to maximize utilization of available OR resources. The problem perceived by them, is that OR planners highly influence the utilization of OR resources, because no uniform surgery scheduling approach exists. Therefore, management is really dependant on the expertise of OR planners, and aims for a uniform surgery scheduling approach that could be used by all OR planners.

Patients

As the majority of the patients want to undergo surgery as soon as possible, the main problem perceived by patients is high access times. However, this does not apply to all patients since the length of the waiting list depends on the specialty and the specialist. Another problem faced by some patients is that their surgery time, and sometimes even their surgery date, is changed last minute. In particular older patients need to arrange transport and subsequent care, so changes in their agreed surgery date are extremely undesirable.

OR planners

The OR planners are responsible for agreeing on the surgery date with the patient. This surgery scheduling process is very complicated since a lot of restrictions and, sometimes conflicting, interests have to be considered. Scheduling procedures exist, in which many planning rules and resource restrictions are described, but these are not always complete. Since the OR planning personnel is not supported by a scheduling tool, they must trust on their own expertise and experience. Together with their awareness of the importance of an efficient OR schedule and the many influences it has on other departments, they often perceive a high workload.

Another problem faced by the OR planning personnel is that they have to deal with many last minute changes and cancellations in the OR schedule, as the OR programme is evaluated only one week in advance. Sometimes a whole OR session must be cancelled because of a sudden surgeon absence or because the OR session is underutilized. OR planners need to call patients to cancel or replace their surgery, which often result in dissatisfaction. Since surgeries are scheduled whether or not patients are already accepted at the preoperative screening (POS), some surgeries have to be cancelled because of last minute rejection at the POS. All these last minute changes result in an increased workload.

OR department personnel

OR personnel is defined as all personnel present at the OR department, including holding and recovery nurses but excluding surgeons. OR personnel need to work 9 hours consecutively each day, so for them it is important to avoid overtime. Surgery durations that are not estimated accurately can take more time than expected. Moreover, the last minute addition of high priority patients to the schedule possibly results in too many scheduled surgeries and consequently increases the risk of overtime. Another problem perceived by OR department personnel is violation of resource restrictions, resulting in an increased workload because everything must be done in order to finish all scheduled surgeries.

Surgeons

The main problem perceived by surgeons is the violation of resource restrictions. Not all OR planners are aware of these restrictions and therefore mistakes in the schedule occur. It is no exception that the OR programme needs to be changed last minute due to violation of restrictions.

Another problem is the reassignment of OR time. OR time that is released due to a sudden surgeon absence or a low utilization is reassigned to surgeons who need more OR time. This is done two weeks in advance. However, at this point in time, most surgeons already have outpatient clinic appointments that could not be cancelled.

Nurses

Nurses are defined as all nursing personnel in the ward. For them, the sequence of surgeries on a day is most important, in order to balance the number of patients during the day. In case not enough nursing personnel is available, it could happen that surgeries are cancelled.

From the problems perceived by the different stakeholders, the major problem that is defined is:

The OR utilization depends too much on the expertise of OR planners, because a uniform surgery scheduling approach does not exist. This increases the workload of many employees. Available OR resources are not always used efficiently which increases access times and decreases OR utilization.

1.4 Research objective

The research objective that we defined in order to address the major problem is:

To design and assess a uniform surgery scheduling approach which supports OR planners to maximize utilization of available OR resources, while meeting access time targets.

The research objective addresses the tactical and operational offline planning. The operational offline planning is responsible for the high workload experienced by OR planners, but regarding OR utilization, decisions made at all levels are of influence. From management perspective, a uniformly applicable approach is favourable, so other clinics could take advantage of this research as well.

1.5 Research questions

Each of the following chapters in this report correspond to a research question.

Chapter 2 provides a system description as well as a performance analysis and a problem overview. It answers the question: *How is the current surgery scheduling process organized and how does it perform?*

Each section of Chapter 2 addresses a couple of sub-questions:

Section 2.1: OR department

- How is the OR department organized?
- Which process does the patient goes through?

  The whole process that the patient goes through, from the first moment the patient enters the system until the patient is discharged from the ward, is described.

Section 2.2: OR planning and control

- Which decisions have to be made at each level of control and who is responsible for making the decisions?

  Based on interviews with involved employees and observations, a complete overview of the current surgery scheduling process is given.

Section 2.3: Performance analysis

- Which performance indicators could be defined?
- What is the current performance of the OR department and the planning and control department?

  Historical data is analysed in order to measure the current performance.

Section 2.4: Problem overview

- Which problems regarding the current surgery scheduling process exist and what are the underlying causes?
- What key problem could be defined for which an intervention will be designed in this research?

  The scope of this research is demarcated by defining the key problem that will be addressed in the remainder of this research.

Chapter 3 contains a literature review and answers the question: *Which surgery scheduling approaches exist in literature and which could be suitable for the surgery scheduling process at Bergman Clinics?*

The following sub-questions are defined:

- Which surgery scheduling approaches exist in literature?

- What are the differences between the situations described in literature and the current situation at Bergman Clinics?

  A broad range of literature is reviewed concerning the surgery scheduling process in different situations and with varying research objectives. The situation of Bergman Clinics possibly differs from those in literature, since Bergman Clinics focusses on plannable and high volume care and does not need to deal with emergency patients.
- Which interventions could be defined for Bergman Clinics in order to achieve the research goal?

In Chapter 4 we introduce the solution design, including the actual modelling of the surgery scheduling process and the assumptions made. We answer the following questions:

- How should the surgery scheduling process at the clinics of Bergman Clinics be modelled?
- Which key performance indicators are used to assess the proposed interventions?
- How does the experimental design look like?

In Chapter 5 we present the results of the experiments. We answer the following questions:

- What are the performances of the proposed interventions in terms of the KPIs?
- How robust are the interventions?

In Chapter 6 we draw conclusions and we answer the question :

- Which intervention performs best in terms of the defined KPIs?

Finally, in Chapter 7 we discuss our research and we give recommendations regarding the surgery scheduling approach and future research.

2 Context analysis

Section 1 provides a system overview of the OR department in clinics A and B of Bergman Clinics. The whole patient process from the first moment the patient enters the clinic until being discharged from the ward is described. The people who are involved in this process and their roll are described too.

Section 2 describes the OR scheduling process on different levels. Many decisions need to be taken regarding the surgery scheduling process. The section describes for each level what needs to be decided, how the decision is made and by who the decision is made.

Section 3 defines performance indicators to measure the performance of the OR department and the efficiency of the OR schedule. Subsequently, the performances of the OR departments are analysed and the clinics are compared to each other.

Section 4 gives a conclusion of the performance analysis and identifies the encountered problems. Finally a description of the demarcated core problem, that will be further elaborated in this research, is given.

2.1 OR department description

2.1.1 Layout OR department

Clinic A is equipped with four ORs (N1,N2,N3,N4) and clinic B is equipped with three ORs (R1,R2,R3). The ORs are available five days per week, from Monday till Friday, resulting in 20 available OR days per week in clinic A and 15 available OR days per week in clinic B. During the execution of this research, the operating theatre in clinic B has changed to four OR's. However, the data that is analysed, contains surgeries performed in the former operating theatre. The ORs in clinic A are available between 8 am and 4.15 pm. The ORs in clinic B are available between 8 am and 4.30 pm. Since there are no breaks during an OR day, an OR day in clinic A consists of 495 minutes and an OR day in clinic B consists of 510 minutes. In clinic A, all ORs are generic, so they could be used for any type of surgery. In theory, each surgeon could perform surgeries in any OR. However, some surgeons are always allocated to the same OR because they need specific instruments or devices. Moving these from one to another OR result in more changeover time and is therefore not efficient. In clinic B, operating room 3 could not be used for all surgery types, since the sterile area is smaller than in the other ORs. Since Bergman Clinics do not need to deal with emergency patients, all surgeries are scheduled in advance and no OR has to be reserved for emergency patients. It can occur that a patient has more priority, paragraph 2 will describe how is dealt with these patients.

Not all available OR days are actually used due to, for example, national holidays, maintenance or low demand. A used OR day is defined as a day on which at least 1 surgery was performed.

Year	Clinic	Number of used OR days
2017	A	867
2017	B	135
2018	A	911
2018	B	491

Table 2: number of used OR days in clinics A and B in 2017 and 2018 (HiX)

The small number of used OR days in clinic B in 2017 could be explained by the fact that this clinic has opened at the end of 2017. The clinic originated from the Haga hospital located in the Hague. Due to the recent opening, the clinic is not very well-known yet. The number of patients visiting the clinic is expected to increase during the next couple of years.

2.1.2 OR department personnel

OR department personnel is defined as all personnel present at the OR department. OR planners and the OR coordinator do not belong to this personnel group since they perform their tasks outside the OR department. The role of the planning personnel is described in Section 2 of this chapter. All OR department personnel start at 7.30 am and end at 4.30 pm. Between 7.30 am and 8 am, the OR is prepared for the first surgery of the day. According to the opening hours of the OR in clinic A, the last patient of the day should leave the OR at 4.15 at the latest. Between 4.15 pm and 4.30 pm the OR personnel have time to finish their work. In clinic B, surgeries could last until 4.30 pm, which, at the same time, is the end of the working day of OR department personnel. The logistics department is responsible for preparing the ORs for the surgeries of the next day, by making sure the right instruments and devices are available.

The OR department personnel is divided into the following subgroups, based on their responsibilities during the surgery process.

1. Floor manager
   One floor manager is available per OR department. The floor manager is responsible for all decisions that have to be made at the OR department during the day, and needs to make sure the OR schedule could be adhered to.

2. Anaesthetists
   One anaesthetist is available per two ORs. After the patient has arrived in the OR, the anaesthetist administers the anaesthetics and monitors the patient. Monitoring of the patient is also done by the anaesthesia assistant, but the anaesthetist has the final responsibility.

3. Anaesthesia assistants
   One anaesthesia assistant is available per OR, and is supervised by the anaesthetist. The anaesthesia assistant is responsible for transporting the patient from the holding to the operating room and from the operating room to the recovery. The anaesthesia assistant prepares the patient for surgery and anaesthetics and monitors the patient during surgery. During the transfer from the holding to the OR and from the OR to the recovery, patient information is passed on from nurses to the anaesthesia assistant and vice versa.

4. Surgeons
   Each surgeon is specialized in one or more surgery types, and is assisted by the surgery assistants. After performing the surgery, the surgeon needs to report the details of the surgery in the patient's medical record.

5. Surgery assistants
   Depending on the type of surgery that is performed, there are two or three surgery assistants per OR. They prepare the OR for surgery by setting up surgical instruments and equipment. One or two surgery assistants are responsible for assisting the surgeon in the sterile field of the OR during the surgical procedures. The other surgery assistant is responsible for passing instruments and supplies to the surgeon or surgery assistant.

6. Holding nurses
   One holding nurse is available per OR department. The holding nurse takes care of the patients before they undergo surgery.

7. Recovery nurses
   One recovery nurse is available per OR. The recovery nurses take care of the patients after they have had surgery.

2.1.3 Patient process

Contact and Service Centre

Once the patient has decided to visit one of the clinics of Bergman, the first contact is with the so called "Contact and Service Centre". The employees of the contact and service centre make a first appointment with one of the specialists that they think is most suitable.

Outpatient clinic

At the outpatient clinic the first contact between the patient and specialist takes place. This first appointment is about determining the medical indication and whether the patient is in the right place. If the patient is eligible for surgery, in most cases he or she could visit the preoperative screening (POS) and OR planning department right after seeing the specialist. It sometimes occurs that the patient has to come back to visit the POS and OR planning department, because no places are available. In some cases, the patient or specialist prefers making another appointment at the outpatient clinic in order to determine if surgery is desirable.

Sometimes it turns out that another specialist might be more suitable. Then the patient is referred. This could take place within the clinic, but when the required specialty is not represented, the patient is referred to another clinic.

Preoperative Screening (POS)

Every patient that undergoes surgery, needs to visit the POS. Since only low risk patients may be treated at Bergman Clinics, the medical history of the patient is reviewed and a couple of medical tests are performed at the POS. This is done by an anaesthesia assistant or a general practitioner, however, the anaesthetist has the final responsibility. Sometimes additional checks like a blood test or an ECG are required. Depending on the schedule, this is done directly or it is scheduled afterwards. In some cases, additional medical information needs to be requested at a third party. If it is likely that the patient will be accepted for surgery, he or she visits the planning department right after the POS and is scheduled, even if the patient is not yet accepted.

OR planning department

The planning department schedules the surgery. The surgery scheduling at Bergman Clinics contains a face to face appointment between the OR planner and the patient. In consultation with the patient, a surgery date is set, taking into account the patient's personal preferences as much as possible. In the exceptional case that the surgery has high priority, which means that postponing the surgery would worsen the results, the surgery needs to be scheduled within 3 days. One week before the surgery date, the hostess or nurse informs the patient via telephone about the time of the surgery.

Day of surgery

A patient is admitted to the ward on the day of surgery. From the moment the OR is ready to receive the patient, several time registrations are made. Figure 1 shows all time registrations. Only the 'Arrival OR' and 'Departure OR' registrations are made automatically. The manual registrations are not always reliable.

Figure 1: time registrations during the surgical process

2.2 Planning and control

A distinction is made between the outpatient clinic agenda and the operating room agenda of a specialist. Obviously, a specialist could not have outpatient clinic appointments and surgeries at the same time. Therefore, a schedule defines for each day or daypart if the specialist is assigned to the outpatient clinic or to the operating room. The ratio of outpatient clinic days and OR days depends on the specialist and specialty. How this assignment is made is described in Section 2.2.2.

In Section 2.2.1 the outpatient clinic planning process is described. Section 2.2.2 describes the operating room planning process.

2.2.1 Outpatient clinic planning

The outpatient clinic planning is made in the electronic health record, by the employees of the Contact & Service Centre. Once a patient calls to make an appointment, the Contact & Service Centre employee has to find an available timeslot in the agenda of the right specialist, that suits the patient's wishes. Sometimes the patient has a preference regarding the specialist to visit. Otherwise, the Contact & Service Centre employee decides, through a number of questions about the patient's symptoms, at which specialist to schedule the patient. In case multiple specialists are eligible, the length of the waiting lists are also kept in mind.

Each day in the specialist's outpatient clinic agenda contains a predefined number of timeslots that are available for new patients, also called NP slots. The other timeslots are used for control appointments. It depends on the specialist and surgery type how many times a patient has to return to the outpatient clinic.

Specialists that perform different types of surgeries divide the number of NP slots over different patient types. For example, a day in the agenda of specialist A contains 6 NP slots for patients with shoulder issues and 8 NP slots for patients with knee issues. The duration of a NP slot depends on the patient type it is intended for.

New patients are assigned to NP slots on a first come first serve basis. If a patient has a preference regarding the appointment day, this could be specified in the search function of the electronic health record. The system searches for the first available NP slot, keeping in mind the specified preferences.

2.2.2 Operating Room planning

The OR planning department makes the OR plan. The OR plan describes which surgeries are scheduled on what day, in which OR and by which surgeon. In healthcare delivery operations, four levels of control and four managerial areas are represented in a framework (Hans, van Houdenhoven, & Hulshof, 2012). In this section, the OR planning and control process at Bergman Clinics is described based on this framework.

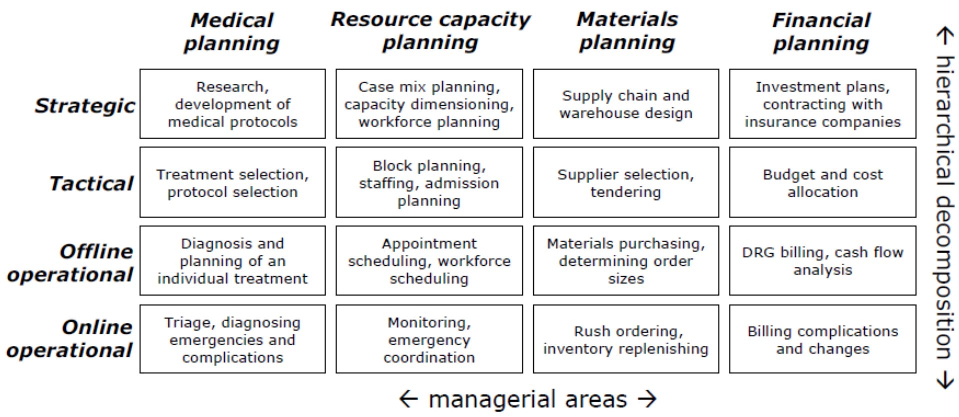


Figure 2: framework for healthcare planning and control (Hans, van Houdenhoven, & Hulshof, 2012)

Strategic level

Decisions made at the strategic level highly influence all other levels of control. Strategic planning concerns long term decisions including the dimensioning of the OR department and the case mix planning. The management of Bergman Clinics decides about the number of available ORs per location, the opening hours of the ORs and whether or not to dedicate the ORs to specific specialties. Regarding the case mix planning, agreements with healthcare insurers are made about the number of treatments per treatment type, that Bergman Clinics may perform each year. The healthcare contracting department is responsible for the negotiations regarding these agreements. If the agreed volumes are expected to be exceeded before the end of the year, new negotiations take place in order to obtain more reimbursement. In most cases this works out since some healthcare providers declare less than agreed, so the healthcare insurer could transfer some volume from one to another healthcare provider. The volumes that are agreed on are based on historic data and expected growth.

Tactical level

The planning horizon of the tactical planning and operational offline planning somewhat overlap with each other at Bergman Clinics. Approximately four months in advance, available OR time is distributed over all present surgeons by the clinic manager and OR coordinator. This differs from hospitals, where OR time is distributed over all specialties. Usually one OR day is assigned to one surgeon, but sometimes OR days are shared between two surgeons. This happens when it is expected that surgeons do not have enough patients to utilize a whole OR day. The time block that is assigned to a surgeon is called an OR session. These OR sessions are filled with surgeries, which is part of the operational offline planning. Since available OR time is distributed over the surgeons approximately 4 months in advance, from then onwards surgeries may be assigned to these OR sessions. This means that the planning horizon of the operational offline planning equals the planning horizon of the tactical planning. However, it does not happen regularly that surgeries are scheduled four months in advance, but it is allowed if it is the patient's wish. Given the planning horizon, surgeons need to announce their absence four months in advance as well. However, it is no exception that assigned OR time has to be cancelled later due to a sudden surgeon absence. Two weeks in advance, released OR time is assigned to surgeons who need more OR time. However, sometimes gaps in the OR schedule remain since surgeons already have outpatient clinic appointments.

The volumes that are negotiated at the strategic level do not play a role in distributing the OR time over the specialists. This means that if, for example, 500 hip replacements may be performed per year, these are not equally distributed over the months because of seasonal fluctuations. Instead, waiting lists are evaluated and the conversion ratio is used. The conversion ratio indicates the percentage of patients that visit the outpatient clinic and eventually undergoes surgery. Depending on the specialty, some specialists need to see more patients at the outpatient clinic in order to fill a whole OR day than others.

On the tactical level no procedures exist that describe how to assign OR time to specialists. The OR schedule is not cyclic, so the clinic manager and OR coordinator evaluate the waiting lists and allocate OR time every two weeks again. The other weeks they should evaluate the already allocated time and make adjustments if necessary. However, as already mentioned in the problem description, this is not done regularly.

Besides the evaluation of waiting lists and the use of the conversion ratio, some decisions are made because it is always done in a certain way. For example in clinic A, part of the surgeons get paid by the number of surgeries they perform. Therefore, surgeons claim a minimum amount of OR time each week in order to prevent a fluctuating salary. This results in a more or less equally distribution of OR time over the surgeons. Obviously, this does not result in the most efficient distribution of OR time.

Operational offline level

The operational offline planning process involves assigning surgeries to OR sessions. The difference between the operational online and offline level, is that decisions made at the offline level are made in advance, while decisions made at the online level are reactive. OR planners are responsible for the operational offline planning. During an appointment with the patient, the OR planer sets the date of the surgery. This method differs from many other healthcare providers, where patients receive their surgery date afterwards. As mentioned previously, surgeries may be scheduled into OR sessions once these are released.

The OR planners receive surgery requests that are submitted by the surgeon. The surgeon has to define which operations have to be performed during the surgical procedure. It is of great importance that they define the right operations, because the electronic health record proposes a surgery duration based on the combination of the surgeon and the operations to be performed. A wrong estimation result in an unrealistic OR schedule. The calculation is based on the last 80 observations. A drawback of the calculation is that outliers are included. Outliers exist because of missing time registrations or incidents, and do not reflect reality. The surgeon is able to accept or adjust the estimated duration. Adjusting this duration could be done in case the surgeon knows from experience that more or less time is needed, given the patient type or other circumstances. The surgery duration estimate includes all OR activities, except changeover time.

As long as all restrictions are met, surgeries may be scheduled on any day and in any session of the surgeon that requested the surgery. Restrictions are described in protocols but OR planners are expected to know them by head. The OR planner has to find an OR session that has enough available time left, while keeping in mind all resource restrictions and the patient's preferences. The electronic health record in which the planning is made, does not warn when restrictions are violated. To what extent an OR session is already filled with surgeries is represented by a percentage of the total available session time. Once a surgery is added to an OR session, the percentage is adjusted. The changeover time is added separately and automatically. The amount of added changeover time depends on the surgeon and is usually 8, 10, 12 or 15 minutes.

Figure 3 shows an example of a week schedule in clinic A. The numbers next to the percentages represent the number of scheduled surgeries.

Week	Monday	Tuesday	Wednesday	Thursday	Friday
OR 1	Specialist 8.00 102 % 7	Specialist 8.00 57 % 3 Specialist 12.30 62 % 5	Specialist 8.00 97 % 6	Specialist 8.00 37 % 2 Specialist 12.30 106 % 4	Specialist 8.00 21 % 1
OR 2	Specialist 8.00 92 % 5	Specialist 8.00 82 % 7	Specialist 8.00 72 % 4	Specialist 8.00 52 % 4	Specialist 8.00 52 % 3
OR 3	Specialist 8.00 88 % 8	Specialist 8.00 105 % 6	Specialist 8.00 94 % 7	Specialist 8.00 81 % 5	Specialist 8.00 101 % 8
OR 4	Specialist 8.00 52 % 4	Specialist 8.00 103 % 8	Specialist 8.00 42 % 3 Specialist 12.30 102 % 6	Specialist 8.00 102 % 7	Specialist 8.00 65 % 3 Specialist 8.00 100 % 4

Figure 3: example of a week schedule in clinic A

Initially, the OR planner schedules the date of the surgery, not the sequence of surgeries on a day. The sequence is determined one week in advance during a weekly meeting of OR department personnel. This meeting is attended by an anaesthetist, the floor manager and an OR planner. The surgery sequence is affected by factors like the age of the patients, the locations they need to come from, but more important it needs to be efficient. For example, if a specialist performs a couple of total knee replacements, first the right knees and subsequently the left knees are planned. This minimizes the changeover times. Next to determining the sequence of surgeries, they also assess the OR day regarding resource restrictions. In case insufficient resources or personnel are available, surgeries have to be cancelled or replaced. Ideally, once the surgery date is set, it is not being adjusted anymore. However, sometimes changes are unavoidable. As long as the schedule is not confirmed during the weekly meeting of OR personnel, OR planners make all necessary changes in the OR programme. The operational online level concerns decisions that have to made after confirmation of the OR programme.

Operational online level

As long as changes do not apply to the current day, OR planners adjust the OR programme in consultation with the OR coordinator and anaesthetist. Examples of changes that occur after confirmation of the schedule are the addition of high priority patients and the cancellation of patients. Cancellations occur as a result of, for example, last minute rejection at the POS or the patient's decision. The gaps in the schedule that arise because of cancellations are used to schedule high priority patients or to move other surgeries forward. During the surgery scheduling appointment between the OR planner and the patient, the OR planner note if the patient is open to a sooner surgery date. The patients who are, could be used to fill up gaps.

Even during the day of execution, things do not always work out the way that was intended. Surgeries could take more time than expected, personnel could suddenly become ill or patients are not sober at the moment the surgery is about to start. The floor manager is responsible for all decisions that have to be made at the day itself. Everything possible is done in order to finish all scheduled surgeries. OR personnel make use of their creativity to find solutions to unforeseen circumstances or events. However, last minute cancellations could not always be prevented. If surgeries could not be switched, the OR programme runs out too much or resource restrictions get violated, cancellations do occur.

To monitor the progress in each OR, the OR department makes use of a screen, the so called 'Schipholbord'. This is a timeline that shows the initial OR day schedule together with the live performance of the OR. Each block in this screen represents a surgery and the length of a block represents the total surgery duration, in other words the total time an OR is occupied by a patient. The gaps between the surgery blocks represent the changeover times, during which no patient is in the OR. The estimated total surgery duration is not divided into different activities, but the realized surgery duration is. A vertical line on the screen indicates the current moment in time. Therefore, the OR personnel could see what is going on in each of the ORs. At a glance, one can see if an OR is on, ahead or behind schedule. Figures 4 and 5 provide a representation of the "Schipholbord".

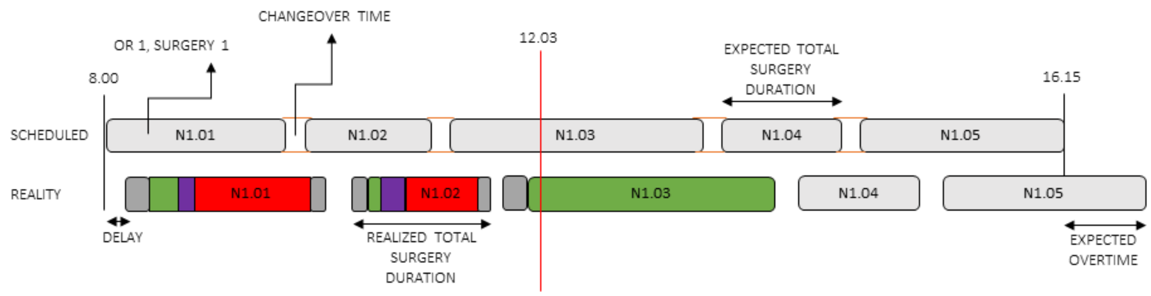


Figure 4: representation of "Schipholbord"

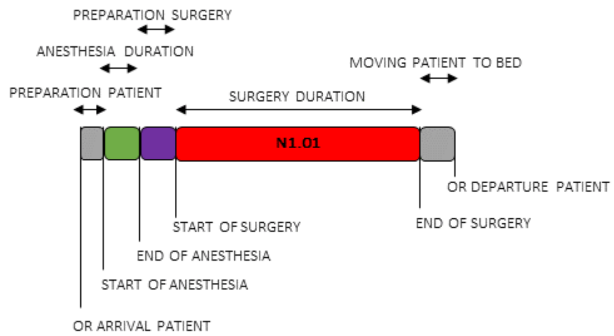


Figure 5: representation of surgical procedure

2.3 Performance analysis

2.3.1 Data collection

The data used to analyse the performance of the OR department contains all surgeries performed in 2017, 2018 and the first half of 2019 in clinics A and B. The total number of registered surgeries equals 19144. For each surgery, several time registrations are made during the patient process at the OR department. The following time registrations are available in the data:

1: OR arrival

2: Start of surgery

3: End of surgery

4: OR departure

The start- and end-times of anaesthetics are registered as well, but not available in the data.

Next to the time registrations, the data shows per surgery the location, surgeon, OR number, date of surgery request, surgery date, scheduled surgery duration, scheduled OR arrival time, scheduled changeover time, whether or not the surgery is the first or last one of the surgeon that day and whether or not the surgery is the first or last one in the OR that day.

Some filters are applied to the data. The following data has been removed because it is expected to be unreliable:

- Surgeries that lack registrations regarding the OR arrival time and/or OR departure time
- Surgeries that have a changeover time of zero minutes, but are not registered as the last surgery of the day
- Surgeries from which the OR arrival time > OR departure time

2.3.2 Key Performance Indicators

We measure the performance of the OR departments and OR planning departments in terms of OR utilization, OR schedule realization, workload and surgery access time. For this purpose we use the following Key Performance Indicators (KPIs):

OR utilization

OR utilization could be expressed in different terms and therefore it is important to make clear which definition of OR utilization is used in this research. We make a distinction between net and gross OR utilization, and between realized and scheduled OR utilization. Net utilization is defined as the percentage of the total available time per OR day that is used to perform surgeries excluding changeover time. Gross utilization includes changeover time as well. To calculate the scheduled OR utilization we use the scheduled surgery and changeover durations. To calculate the realized OR utilization we use the actual surgery and changeover durations. Overtime is included in the calculation of OR utilization, because we want to analyse the difference between the scheduled OR utilization and the realized OR utilization. Excluding overtime influences this difference.

Risk of Overtime

Overtime is defined as the time that is used to perform surgeries or changeovers after the OR's closing time. The risk of overtime is defined as the percentage of OR days on which at least 15 minutes of overtime has occurred.

Surgery access times

The surgery access time is defined as the number of days between the date of the first outpatient clinic appointment and the surgery date.

2.3.3 OR utilization

To calculate the average net and gross utilization of the OR departments in clinics A and B, only days that consist of reliable surgery registrations are included. It should be mentioned that OR days that are included in the calculation are assumed to have resources available for the whole day.

Clinic A	Year	Number of registered surgeries	Number of OR days included	Average net OR utilization	Average gross OR utilization
	2017	5761	728 (of 867)	82.56%	94.58%
	2018	5963	750 (of 911)	78.98%	91.74%
	2019	3112	393 (of 467)	79.64%	93.06%
Clinic B					
	2017	638	115 (of 135)	71.38%	80.74%
	2018	2337	406 (of 491)	73.28%	82.11%
	2019	1333	254 (of 295)	71.04%	76.80%

Table 3: realized utilization rates in clinics A and B in 2017, 2018 and the first half of 2019 (HiX)

Table 3 shows that the OR utilization in clinic B is lower than in clinic A. As mentioned previously, the recent opening of clinic B could be an explanation for this, as the number of patients visiting the clinic is relatively small compared to clinic A. The difference between the gross and net OR utilization indicates how much time is needed for changeovers. This should be minimized to increase revenues.

Since we are interested in the performance of the OR planning department, we analyse the scheduled gross utilization. Figures 6 and 7 show how the scheduled gross utilizations are distributed in clinics A and B respectively.

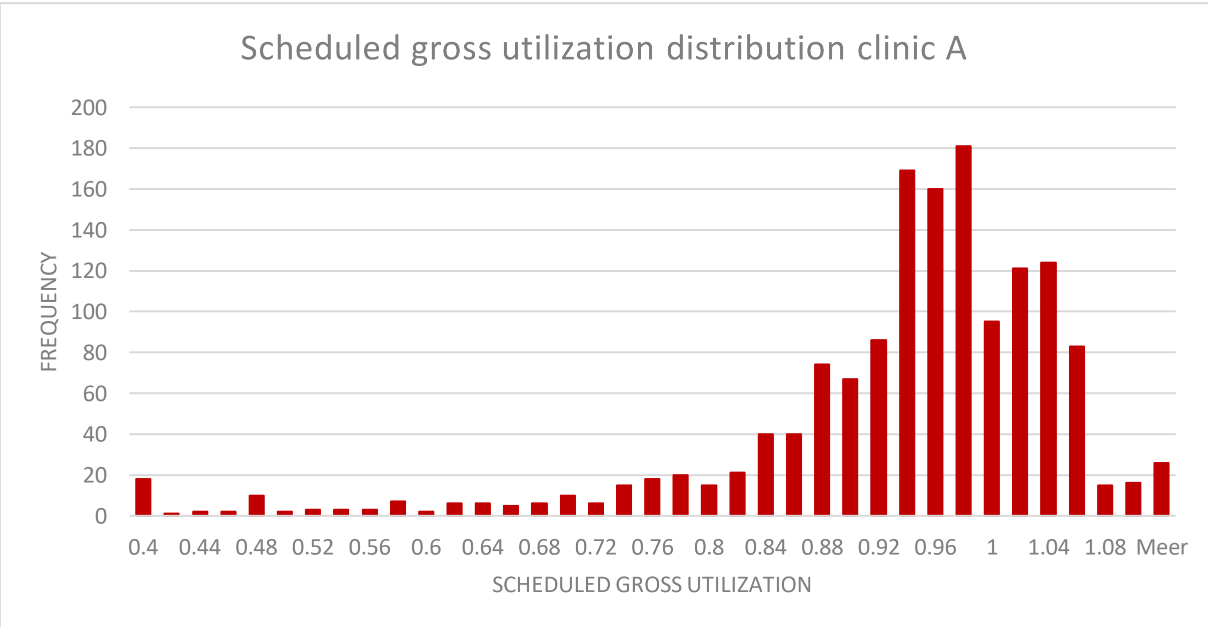


Figure 6: distribution of scheduled gross utilization in 2017 and 2018 in clinic A (HiX)

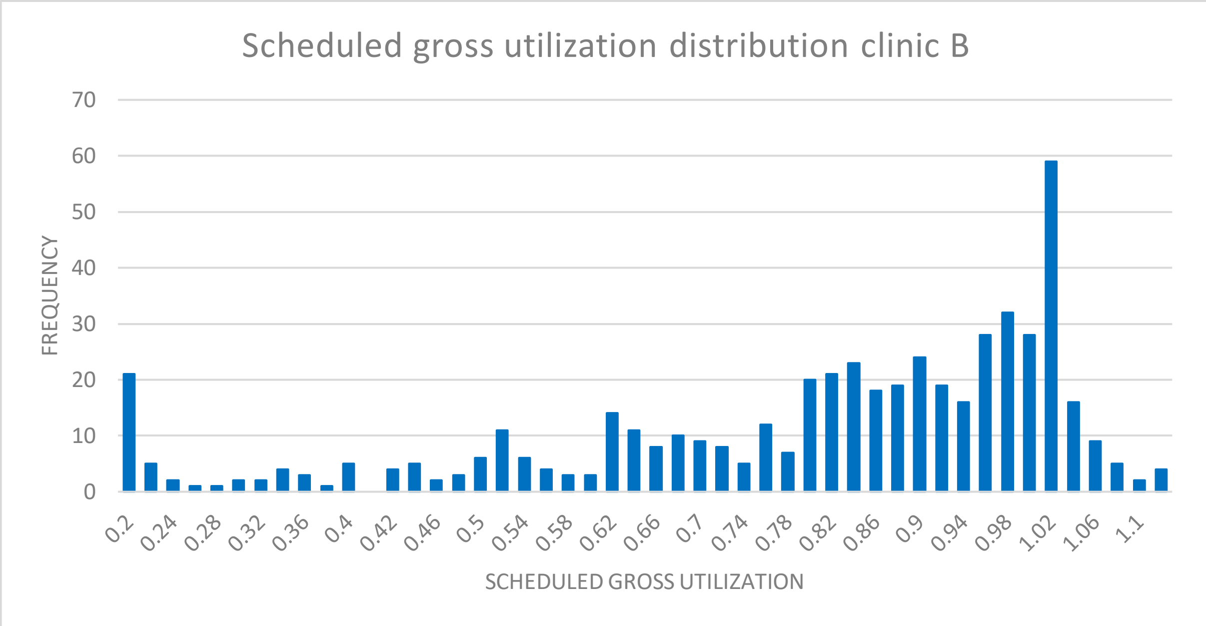


Figure 7: distribution of scheduled gross utilization in 2018 in clinic B (HiX)

In theory the scheduled gross utilization can be 100%, since it includes changeover times. Low scheduled gross utilizations can be the result of an inaccurate assignment of available OR time to specialists, or because surgeries are scheduled inefficiently and an unusable amount of available OR time remains in the schedule. From these figures we conclude that, especially in clinic B, much variation exists in the scheduled gross utilization, and scheduled gross utilizations of less than 80% occur frequently. The variation in scheduled gross utilization results in an unbalanced workload of OR department personnel.

This section showed that OR utilization in clinic A is better than in clinic B. Especially in clinic B low utilized OR days occur frequently and combining these days can increase the average OR utilization.

2.3.4 OR schedule realization

Creating a realistic OR schedule is very important to obtain optimal OR utilizations. If surgery durations are underestimated, subsequent surgeries get postponed or even cancelled, and the risk of overtime increases. However, overestimating surgery durations result in unused OR time and increased surgery access times (Kayis et al., 2012).

We investigate if the OR schedule at Bergman Clinics is realistic by analysing the difference between the scheduled and realized surgery and changeover durations, and between the scheduled and realized gross OR utilizations.

Surgery duration

Figures 8 and 9 show the differences between the scheduled surgery durations and the realized surgery durations of all surgeries performed in 2017 and 2018 in clinics A and B respectively.

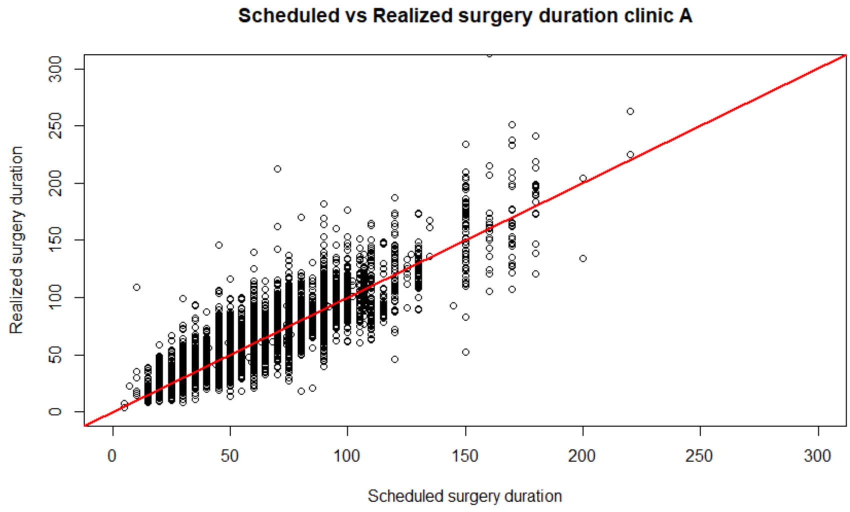


Figure 8: scheduled versus realized surgery duration in clinic A in 2017 and 2018 (HiX)

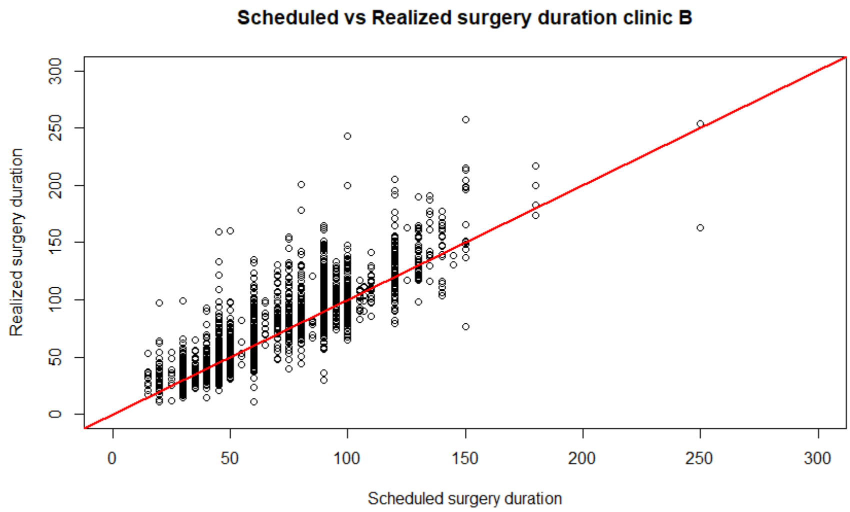


Figure 9: scheduled versus realized surgery duration in clinic B in 2017 and 2018 (HiX)

Points that lie exactly on the red line represent a surgery of which the surgery duration is estimated correctly. The larger the distance from a point to the red line, the less the estimated surgery duration and the realized surgery duration correspond.

In clinic A surgery durations are approximately as often underestimated as they are overestimated. This is a desirable situation. In clinic B more surgery durations are underestimated, which increases the risk of overtime.

Deviation from the planned surgery duration could occur because of unforeseen events or because surgeons have submitted a wrong surgery request and duration. It is of great importance that the request is done correctly since this influences the scheduled surgery duration. Not all surgeons are aware of this impact and surgery details are defined inaccurately. At the moment of performing this research, another project is executed at Bergman Clinics to raise awareness with regard to the importance of correctly submitting a surgery request.

The level of experience of personnel has influence on the surgery duration too. Since more and more freelancers are employed, the experience among personnel differs. At Bergman Clinics, dedicated teams exist that are highly specialized and well-coordinated. However, less experienced employees could be allocated to an OR too. This variation makes it difficult to estimate surgery durations, since it really depends on the OR personnel. Natural variation will always exists, but due to the fact that Bergman Clinics performs many of the same kind of surgeries, we assume this is minimal.

Changeover duration

Figures 10 and 11 show the differences between the scheduled changeover durations and the realized changeover durations of all surgeries performed in 2017 and 2018 in clinics A and B respectively.

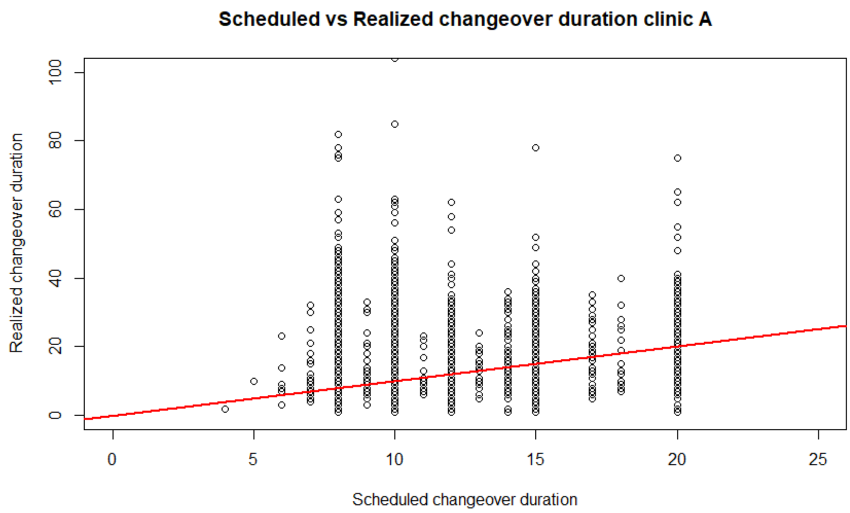


Figure 10: planned versus realized changeover durations in clinic A in 2017 and 2018 (HiX)

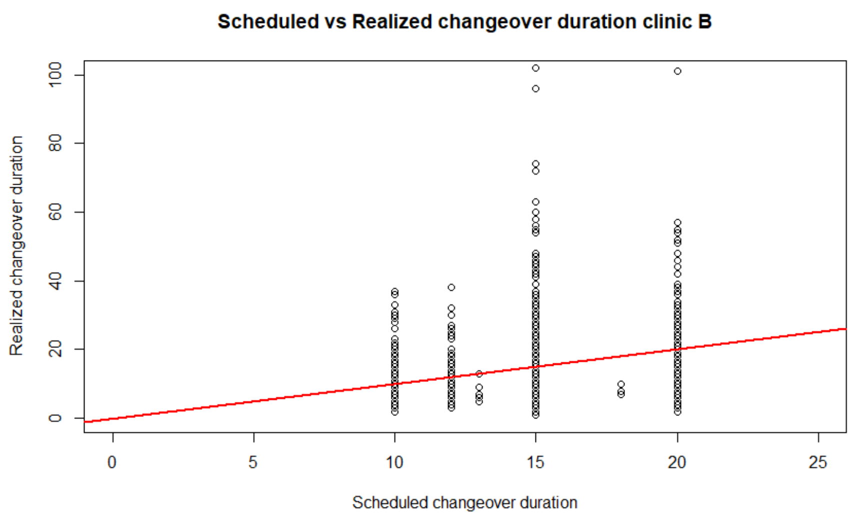


Figure 11: planned versus realized changeover durations in clinic B in 2017 and 2018 (HiX)

The figures show that most of the planned changeover durations are underestimated, since the majority of the points lie above the red line. In other words, more changeover time is needed than scheduled. This applies in particular to planned changeover durations of 15 minutes or less.

One of the possible reasons that changeover durations do not equal the scheduled duration, is that a standard amount of changeover time is added per surgeon. These durations are not evaluated once in a while or adjusted based on the surgery type to be performed. The experience of personnel does also play a role in the amount of changeover time needed. Although changeover durations are most often underestimated, we do not aim for increasing changeover durations as the more changeover time is scheduled, the more time will be used.

Gross OR utilization

To visualize the overall difference between the OR schedule and the realization, Figures 12 and 13 show the realized gross OR utilization and the scheduled gross OR utilization over time during 2018, in clinics A and B respectively.

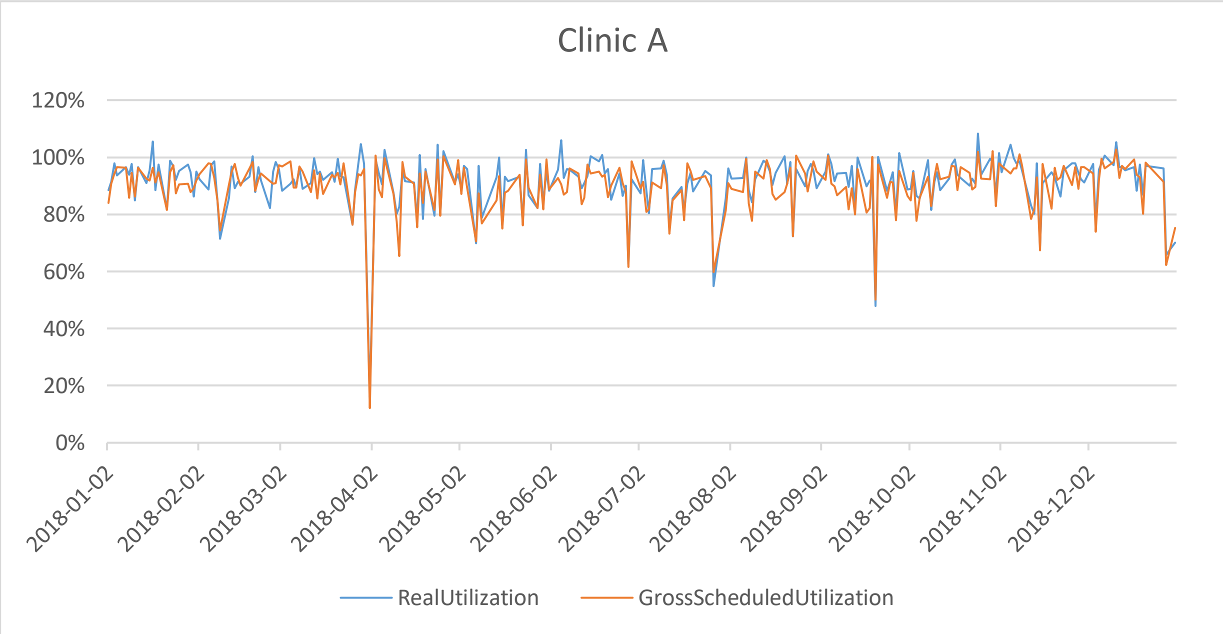


Figure 12: real utilization and scheduled gross utilization during 2018 in clinic A (HiX)

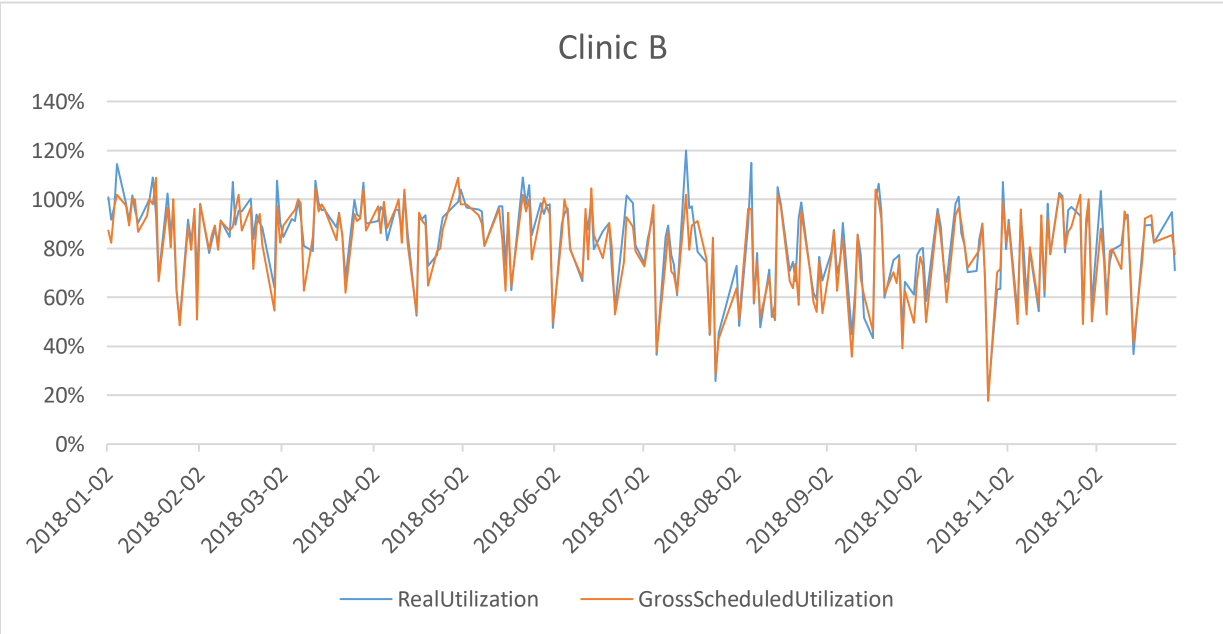


Figure 13: real utilization and scheduled gross utilization during 2018 in clinic B (HiX)

The shape of the realized gross OR utilization and the scheduled gross OR utilization is slightly the same for both locations. Therefore, we conclude that the scheduled gross OR utilization is a good predictor for the actual gross OR utilization, and low OR utilizations are the result of low scheduled OR utilizations. As labor costs do not change according to the number of patients cared for, low scheduled OR utilizations should be prevented to decrease costs (Dexter, Hopwood, Macario, Traub, & Lubarsky, 1999).

This section demonstrated that the scheduled gross OR utilization is a good predictor for the actual gross OR utilization and that low OR utilizations are the result of low scheduled OR utilizations.

2.3.5 Workload

Overtime

The workload of OR personnel is influenced by the risk of overtime. The last surgery of the day should end before 4:15 pm in clinic A and before 4:30 pm in clinic B to avoid overtime. Figures 14 and 15 show how the last patient departure times in 2017 and 2018 are distributed in clinics A and B respectively. The black line indicates the OR closure time, which differ for the locations.

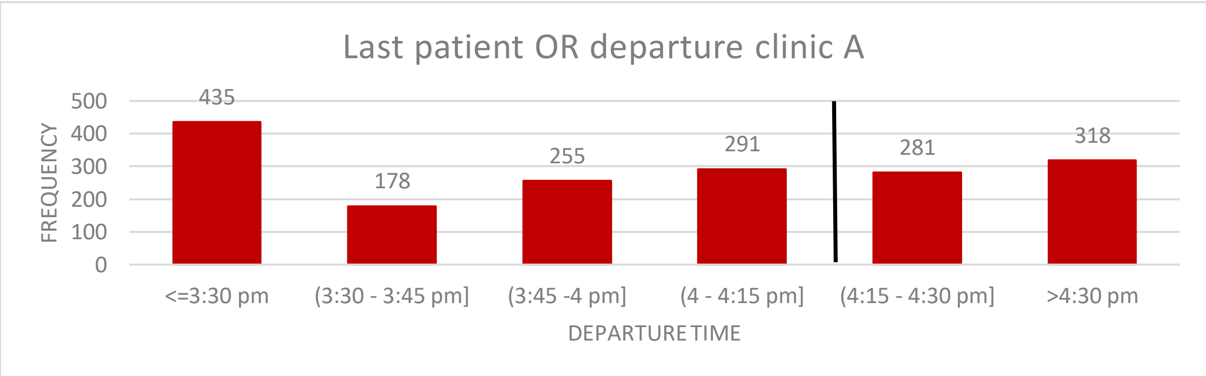


Figure 14: last patient OR departures in clinic A in 2017 and 2018 (HiX)

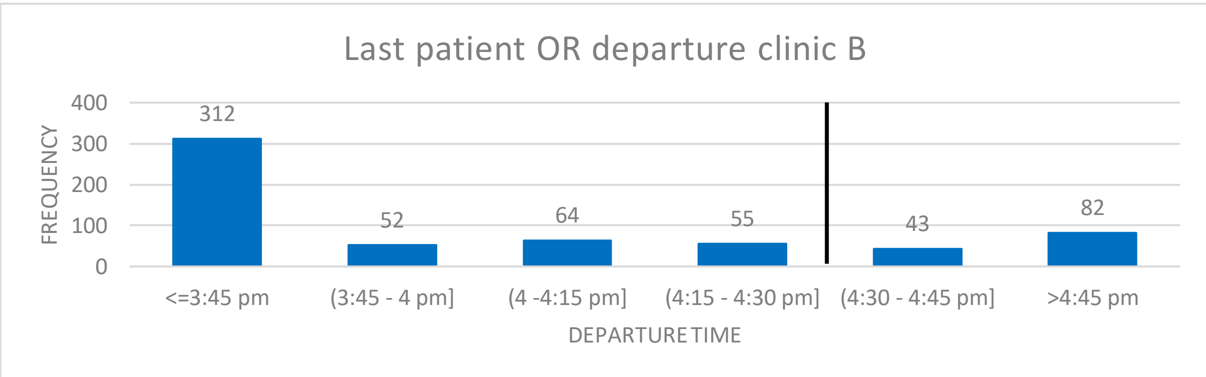


Figure 15: last patient OR departures in clinic B in 2017 and 2018 (HiX)

In clinic A, a 18.1% chance exists that more than 15 minutes of overtime occur. In clinic B this chance equals 13.5%. However, the chance that an OR day ends at least 45 minutes before closing time is 24.7% in clinic A and 51.3% in clinic B. This confirms that much variation in OR utilization exists.

2.3.6 Surgery scheduling process

The workload of OR planners is influenced by the surgery scheduling process. As we could not measure the workload of OR planners quantitative, we have interviewed OR planners about their perceived workload. Based on these interviews and our own observations we concluded that the current surgery scheduling process increases the workload of OR planners in different ways:

- Patients immediately get their surgery date when they visit the OR planning department. The OR planner decides together with the patient about the surgery date, and has to take the patient's preferences into account. This face to face appointment is highly appreciated by patients and therefore the management of Bergman Clinics wants to retain this procedure. However, this way of scheduling surgeries complicates efficient use of OR resources.

- Many resource restrictions have to be taken into account and OR planners need to know them by head since these are not integrated in a scheduling tool. The experience among OR planners differs, so resource restrictions are sometimes violated and OR planning personnel is busy with correcting mistakes.

- The evaluation and confirmation of the OR schedule takes place one week before execution, so violation of resource restrictions is identified lately. This results in last minute surgery cancellations or changes in the OR schedule. Both have to be performed by the OR planners.

- Patients are scheduled before being accepted at the preoperative screening. When these patients are rejected later, the already scheduled surgery must be cancelled. This results in unused OR time and OR planners must try to replace other surgeries to use the released OR time.

- Late evaluation of the OR schedule results in late detection of underutilization. It is the task of OR planners to search for surgeries that could be scheduled last minute, or to replace other surgeries in order to use the remaining OR time. In some cases, underutilization results in cancellation of the whole OR session. OR planners must cancel or replace the surgeries that were already scheduled in this OR session last minute. This often results in patient dissatisfaction, which OR planners have to deal with.

- OR planners are aware of the importance of the OR schedule and its consequences on other departments.

2.3.7 Surgery access times

Figure 16 presents the average surgery access time in days per specialist. Each point in the figure represents a specialist employed in clinic A or B. Since some patients choose to postpone their surgery or need to visit the outpatient clinic again before their surgery is scheduled, the average surgery access time for patients that are eligible for surgery directly, is actually lower.

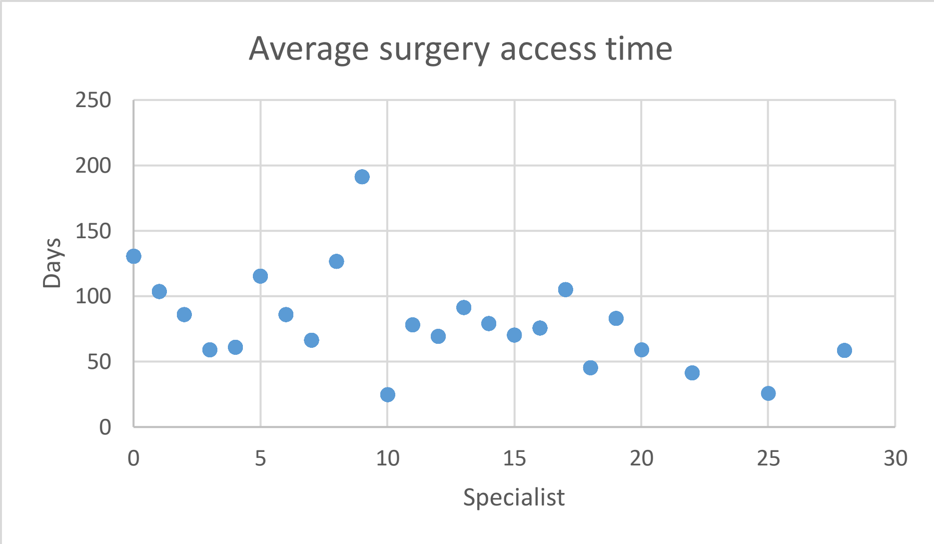


Figure 16: mean patient throughput time in days per specialist (HiX)

Unfortunately no data is available about the date the surgery has been scheduled. This date could differ from the outpatient clinic appointment date. Therefore we could not calculate the average time between the day the surgery has been scheduled and the surgery date. Although patients exist that increase the average surgery access time, the majority of patients is scheduled directly. The figure makes clear that surgery access times are high for most specialists.

2.4 Conclusion performance analysis

Section 2.4.1 summarizes the most important findings of the performance analysis, after which Section 2.4.2 describes our research goal.

2.4.1 Summary performance analysis

The performance analysis has shown that surgery access times are high and available OR time is not always used efficiently, especially in clinic B. Low utilized OR days are mostly the result of low scheduled OR utilizations. Combining low utilized OR days can increase the average OR utilization. Management demands that OR utilization is high and OR planners are aware of this. Therefore, they experience a high workload.

2.4.2 Research goal

We conclude that Bergman Clinics is in need of a uniform surgery scheduling approach in order to increase OR utilization and decrease workload of OR planners. We define the following research goal:

To develop a uniform surgery scheduling approach which increases OR utilization through increasing scheduled OR utilization, decreases workload of OR planners, and meets access time targets.

An important aspect of the research goal is that the surgery scheduling approach could be used by all OR planners, so their level of expertise does not influence OR utilization anymore. The research goal addresses the operational offline planning as well as the tactical planning.

3 Literature review

In this chapter we present a literature study about increasing OR utilization, decreasing OR utilization variation and different scheduling strategies. We do not focus on healthcare related literature only, because scheduling approaches used in other sectors could be useful in the healthcare sector as well. Section 3.1 summarizes our findings. Section 3.2 describes to what extent our findings could be useful for Bergman Clinics. Finally, Section 3.3 describes our proposed interventions.

3.1 Relevant literature

A lot of literature is available about increasing OR utilization. The common definition of OR utilization in literature, is the total time it takes to perform each surgical procedure plus the total changeover time, divided by the total available time. The OR utilization could never be known in advance, because the actual surgery and changeover durations are required to make the calculation. However, the scheduled OR utilization is a prediction of the OR utilization. (Tyler, Pasquariello, & Chen, 2003). A high scheduled OR utilization does not result in a high OR utilization by definition. Many factors exist that have influence on the OR utilization. However, according to Arcidiacono et al., if the scheduled utilization is high, a good chance exists that the OR utilization will be high (Arcidiacono et al., 2016).

Although we focus on increasing scheduled OR utilization, we investigate the effect of scheduled OR utilization on real OR utilization.. Tyler et al. performed a simulation study, to assess the effect of different factors as case durations and the variability of case durations, on actual OR utilization. It turned out that to achieve maximum OR utilization, the variability of surgery durations is an important factor to consider. The situation they simulated differs from real world situations, because they only used small surgery durations with a small coefficient of variation. For that situation, they determined the optimum scheduled OR utilization, in terms of achieving maximum OR utilization without running late for more than 15 minutes and a maximum average patient delay of 15 minutes. It turned out that the optimal scheduled OR utilization lies between 85% and 90%. However, the optimal scheduled OR utilization strongly depends on the variability of surgery durations, and is probably less in more complex OR suites. (Tyler et al., 2003).

Dexter et al. performed a study which is more related to our research goal. They introduced the term underutilized OR time, referring to the time that OR staff is scheduled to work, during which no surgeries are scheduled. This underutilized OR time should be minimized to increase labour productivity. The higher the labour productivity, the less OR staff is needed to care for all patients, and the lower the labour costs, as these do not depend on the number of patients cared for. In their study, they proposed a statistical method, that could be used in order to assess the effect of management strategies, on decreasing variability in OR utilization. For the OR suites they analysed, it turned out that to decrease day to day variations in underutilized OR time, management should focus on improving predictions of elective surgery durations, and on improving methods that are used for assigning surgeries to OR days in a way that available OR time is best filled. The latter seems to have the greatest impact on decreasing underutilized time (Dexter, Macario, Lubarsky, & Burns, 1999).

In another study performed by Dexter and Traub, they assess two different patient-scheduling rules. They investigate their effect on OR efficiency and under what conditions one might be more preferable than the other in maximizing OR efficiency and balancing workload. Maximizing OR efficiency is defined as minimizing the sum of underutilized OR hours multiplied with the cost per hour of underutilized OR time, and overutilized OR hours multiplied with the cost per hour of overutilized OR time. The rules they used to schedule an elective surgery were the earliest start time rule and the latest start time rule. Using the earliest start time rule, the surgery is scheduled in the OR that has most available time left. Using the latest start time rule, the surgery is scheduled in the OR that has least available, but sufficient time left, to complete the surgery during regularly scheduled OR time. They concluded that the latest start time rule performs better at balancing workload and the earliest start time rule performs better at maximizing OR efficiency (Dexter & Traub, 2002).

One of the methods we found in literature, that results in higher utilization rates, is making use of the master surgical schedule (MSS). This cyclic planning approach is frequently used in environments in which production is repetitive. Since elective procedures tend to be identical during consecutive weeks of the year, Van Oostrum et al. proposed a model for a cyclic scheduling approach of elective surgical procedures, which they call a master surgical schedule. Such a schedule reduces planning efforts and demand fluctuations, and results in higher utilization rates. For each OR day of the planning cycle, the MSS describes which recurring surgical procedure types have to be performed. Only elective procedures that occur quite frequent, can be incorporated in the MSS. The frequency must be such that the procedure occurs at least once during the planning cycle. Therefore, the planning cycle determines which surgical procedures could be implemented. Capacity for other procedures will be reserved in the MSS. How capacity is divided is the choice of managers or clinicians (Van Oostrum et al., 2008).

In other industries, revenue management is applied successfully, when decisions must be made with regard to selling a product or service. It has originated in the airline industry, but is recently used by many industries. RM concerns a number of fundamental decisions, that every seller of a product or service faces, in which uncertainty is involved. For example, a seller has to decide about when to sell, how much to ask and which offer to accept. A right price is important, since you do not want to put off potential buyers, however, you do not want to lose out on potential revenues either. RM deals with these demand-management decisions, as well as with the methodology and systems that are required to make them (Talluri & van Ryzin, 2004).

Heterogeneity is required to apply RM. Customers need to value a product differently and show different purchase behaviour. The more heterogeneity, the more potential to improve revenues. In the airline industry, customers vary with regard to the moment they purchase a ticket, their flexibility and their need to travel. Moreover, demand variations and uncertainty about future demand complicate demand-management decisions. Bad decisions could be made easily and sophisticated tools to evaluate complex trade-offs become important (Talluri & van Ryzin, 2004) .

The less variations in demand could be dealt with by varying supply, the more complicated the demand-management problem becomes. Once an airline committed to a flight, the level of its output, the number of seats, and the total cost of the output, is fixed. This does not depend on the number of customers that actually fly on the flight. Like all services, output cannot not be inventoried. Therefore, RM is from great importance in inflexible industries (Talluri & van Ryzin, 2004).

Industries in which revenue management is used, have the characteristic that if the product is not sold out in a certain period, it will bring no revenues. This characteristic applies to the healthcare industry too. Although RM is not particularly known for its use in the healthcare industry, some articles exist in which revenue management is applied to healthcare related problems.

Zhou and Zhao performed a study in which they used revenue management to establish a hospital outpatient appointment scheduling optimization model. In their model they assume that the total revenue of the hospital is generated by any treatment of each department, and that the working time of a doctor is divided into different slots which are assigned to different patients. The doctors are divided into expert doctors and general doctors, and revenues generated by expert doctors are higher than of general doctors. Therefore, during scheduling, the expert doctors are expected to be the priority choice. Part-time doctors can be hired in case full-time doctors are unavailable. The salary of a doctor is divided into basic wage and performance wage. The latter is determined by the number of treatments given. The objective of the model is to maximize total revenues (Zhou & Zhao, 2015).

Gupta and Wang applied RM at a primary care clinic, in which patients are allowed to choose a same-day appointment or a scheduled future appointment. Due to this allowance, the clinic must balance the number of available future appointments and same-day appointments, so the patients' wishes could be satisfied. Scheduling too many future appointments could result in capacity shortages for patients that need a same-day appointment. However, scheduling too few appointments could result in unused timeslots and increased access times. They used RM techniques to define the optimal booking policy (Gupta & Wang, 2008).

3.2 Interventions

In this section we define potential interventions, based on our findings in literature. These interventions possibly contribute towards achieving our research goal. In Chapter 4 we define appropriate KPIs, that are used to assess the interventions.

3.2.1 Master Surgical Schedule

The MSS seems to be suitable in situations in which production is repetitive. Although Bergman Clinics performs recurring surgical procedures, the operation theatre of the clinics consists of four ORs at most, which is probably too little to apply a MSS.

3.2.2 Adjust the surgery scheduling rule

Several surgery scheduling approaches could be applied. Revenue management does not seem suitable since in the healthcare sector, every patient has to be scheduled. It is not possible to neglect patients that contribute less to revenues, or to differ prices based on the moment of selling the service. However, it is possible to distinguish between valuable OR time and less valuable OR time. Valuable OR time could be defined as OR time that likely remains unused. Using this OR time can increase revenues the most. For example, an OR session next week has 80 minutes of OR time left and an OR session in 2 weeks has 50 minutes of OR time left. If a surgery of 50 minutes has to be scheduled right now, assigning this surgery to next week's OR session likely result in 30 minutes of unused OR time. It seems to be a better option to wait until another surgery, with a higher surgery duration, has to be scheduled. However, there is no guarantee that a patient with the desired surgery duration arrives before next week's OR session.

To deal with this dilemma, we propose a scheduling rule that prioritizes suitable OR sessions based on week number and the chance that available OR time could be used in the future. An OR session is suitable if it lies within a predefined planning horizon, belongs to the right specialist, has sufficient time available and will not violate resource restrictions.

Three different priority values must be assigned to the suitable OR sessions. Priority value 1 is based on week number. The chance to use available OR time decreases as the week number decreases. Therefore, the OR session that takes place in the furthest week gets assigned a priority value of 1. The priority value increases by one when the week number decreases by one. As a result, the highest priority value is given to the OR session in the nearest week. All assigned priority values are weighted, so the sum of the priority values equals 1.

Priority value 2 depends on how likely the available time in the OR session could be used in the future. Suppose one of the suitable OR sessions has 50 minutes of available OR time left. A surgery of 30 minutes must be scheduled, but we know that a surgery of 45 minutes does exist. It could be better to wait until the surgery of 45 minutes must be planned, instead of scheduling the surgery of 30 minutes in this OR session, as the latter results in 20 minutes of unusable OR time. Whether or not it is the best choice to wait, highly depends on how frequently the surgery of 45 minutes occurs, and when the OR session takes place. To deal with this dilemma, we introduce priority value 2, that must be combined with priority value 1, in order to take into account when the OR session takes place. To assign value 2, intervals must be defined that contain frequently occurring surgery durations. These intervals are used to check whether or not a surgery duration exists that fits in the OR session, in a way that results in at most 5 minutes of unused OR time. We define an OR session that has at most 5 minutes of unused OR time as an optimal solution. All suitable OR sessions must be evaluated and prioritized. If an OR session could result in an optimal solution, the assigned priority value is negative, since it is better to wait for a surgery that results in an optimal solution. The more frequently the surgery duration in an interval occurs, the more chance to obtain an optimal solution in the future, and so the more negative the associated priority value must be.

Priority value 3 is used to prevent OR sessions from having an unusable amount of available OR time left. The amount of available OR time that will be left after the surgery is scheduled into the OR session must be concerned. To prioritize the OR sessions, the same intervals as for priority value 2 are used. However, the priorities associated with the intervals are positive. The highest priority value is assigned to the OR session that most likely results in an optimal solution after the surgery is scheduled in that OR session. If the surgery to be scheduled could be planned in an OR session in an optimal way, so at most 5 minutes of unused OR time will remain, the surgery is planned in that OR session in any case.

The sum of priority values 1, 2 and 3 is the overall priority value of the OR session. The OR session that has the highest overall priority value is the first choice. We want to investigate what influence this RM based scheduling rule has on our KPIs. Moreover, we want to assess the earliest and latest start time rule.

Intervention 1: adjust the surgery scheduling rule

3.2.3 Adjust the planning horizon

Akin et al. performed a study in which they analysed the influence of using different appointment windows for scheduling outpatient clinic appointments, on capacity utilization and patient access times. They concluded that the appointment window has influence on the KPIs (Akin, Ivy, Huschka, Rohleder, & Marmor, 2013). We want to investigate if the planning horizon used during surgery scheduling, effects capacity utilization and patient access times at the OR department as well.

Intervention 2: adjust the planning horizon

3.2.4 Adjust the appointment flexibility

In literature, a lot of attention is paid to dealing with patients' preferences when arranging appointments at outpatient clinics. Patients prefer to have flexibility of appointment times (Cheraghi-Sohi et al., 2008), and access times are of minor importance compared to choice of appointment time (Rubin, Bate, George, Shackley, & Hall, 2006). The extent to which patients' preferences are considered, influences patient satisfaction, the number of no-shows and the number of patients that choose to go to another clinic. On the other hand, appointment flexibility for patients could result in capacity utilization variations (Feldman, Liu, Topaloglu, & Ziya, 2014).

As Bergman Clinics performs elective surgeries only, patients may want to choose their surgery date. Moreover, at Bergman Clinics, patient satisfaction is of great importance. Therefore, we want to investigate if offering the patient a number of appointment possibilities, influences the defined KPIs.

Intervention 3: adjust the appointment flexibility

3.3 Proposed interventions

The interventions we defined in Section 3.2 are:

1: adjust the surgery scheduling rule

2: adjust the planning horizon

3: adjust the appointment flexibility

For each of the defined interventions, we propose a number of sub interventions. Tables 4, 5 and 6 list these sub interventions.

Intervention	Surgery scheduling rule
1.1	Use RM based rule
1.2	Use latest start time rule
1.3	Use earliest start time rule

Table 4: possible scenarios with regard to intervention 1: adjust the surgery scheduling rule

Intervention	Planning horizon
2.1	1-4 weeks
2.2	1-6 weeks
2.3	1-8 weeks

Table 5: possible scenarios with regard to intervention 2: adjust the planning horizon

Intervention	Appointment Flexibility
3.1	1 choice
3.2	2 choices
3.3	4 choices

Table 6: possible scenarios with regard to intervention 3: adjust the appointment flexibility

We assume that the current planning horizon equals 1-10 weeks and the current appointment flexibility equals 3 choices. Therefore, the proposed interventions do not contain these possibilities.

In Chapter 4 we elaborate on the experimental design, i.e. the sequence in which the interventions will be assessed, and we define appropriate KPIs that are used to assess the interventions.

4 Solution design

In Chapter 3 we defined several interventions. To test whether these interventions contribute towards achieving our research goal, we use a discrete event simulation (DES) model. The conceptual design of this model is described in Section 4.1. Section 4.2 addresses the realization of the model. In Section 4.3 we determine required simulation settings and we validate the model. Section 4.4 describes the experimental design.

4.1 Conceptual design

4.1.1 General description of the model

To assess different surgery scheduling approaches, the simulation model must be a realistic representation of the current OR planning department and should mimic the current procedure concerning operational offline planning. In terms of our defined performance indicators, the performance of the modelled OR planning department must be the same as the performance of the current OR planning department. Once these performances are equal, we could use the simulation model to assess the interventions.

Although we focus on the performance of the OR planning department, the model should contain other departments as well. Patients visit several departments before their surgery is scheduled and what happens at these departments has influence on what happens at the OR planning department. For example, the number of patients a specialist sees at the outpatient clinic, influences the number of patients that visit the OR planning department. Figure 17 shows the departments that should be integrated in the simulation model.

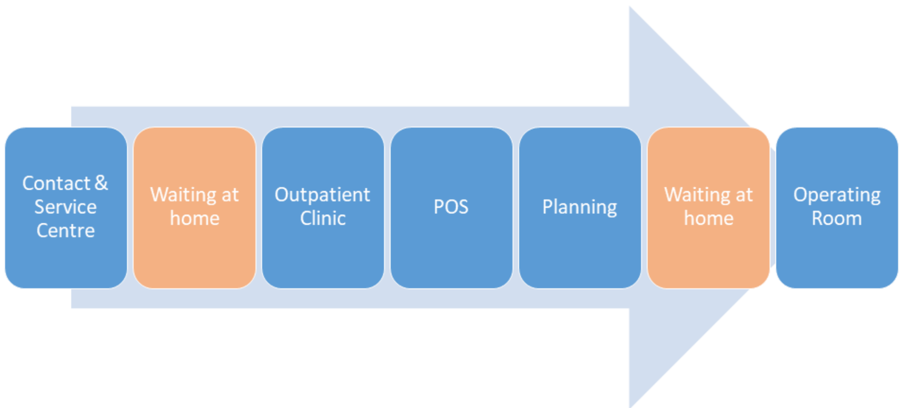


Figure 17: overview of departments that should be integrated in the simulation model

To mimic the function of the current OR planning department, we have to make sure that what happens at the OR planning department in the model, is realistic. If, for example, we compare the performance of our model with the realized performance and the number of scheduled surgeries in our model is much bigger than in reality, the results are unreliable. To avoid unrealistic events at the OR planning department, we define the following model objectives:

- The arrival process of patients at the OR planning department in the model, equals the arrival process of patients at the current OR planning department. The arrival process follows the same seasonal pattern as in reality.
- Patients that visit the OR planning department, are assigned to an OR session according to the current operational offline planning procedure.

- The number of available OR sessions per specialist and the distribution of these OR sessions over the year, equals reality.
- The surgeries that must be scheduled are from the same type and frequency as in reality.
- The same resource restrictions are taken into account as in reality.
- The behaviour of patients, i.e. their wishes regarding the surgery date, peer with the real patients' behaviour. For example, a part of the patients would like to postpone their surgery.

For experimenting purposes, we defined the following additional model objectives:

- The simulation model could be used to assess the proposed interventions.
- The simulation model stores performance statistics.

4.1.2 Model scope

Almost 30 specialists are employed by clinics A and B together. All specialists perform different surgery types, have individual outpatient clinic and OR agendas, and have different resource restrictions to be taken into account. To model all of this in an accurate way, we need a lot of data. Therefore, we have decided to include 2 specialists employed by clinic A and 2 specialists employed by clinic B, instead of including all specialists. This also have a positive influence on the runtimes of the simulation. The included specialists have different properties with regard to access times, conversion, and the types of surgeries they perform. This makes it possible to investigate if the performance of different surgery scheduling approaches, depend on specialist specific properties.

Together with one of the project owners at Bergman Clinics, we defined the following conditions to be met by the specialists, in order to be eligible to be included in the simulation model:

- The specialist has to perform at least 5 different surgery types so that it is possible to make different combinations of surgeries on a day
- The specialist must have performed surgeries on at least 52 days per year, so on average at least one day per week.

Table 7 shows the properties of the included specialists.

	High surgery access time	**Low surgery access time**
High OR utilization	Specialist 1	Specialist 2
Low OR utilization	Specialist 3	Specialist 4

Table 7: properties of specialists included in the simulation model

4.1.3 Performance measures

The research goal we defined is:

To develop a uniform surgery scheduling approach which increases OR utilization through increasing scheduled OR utilization, decreases workload of OR planners, and meets access time targets.

To assess the performance of the proposed interventions, we use the following performance indicators.

- Average scheduled gross OR utilization
- Percentage of OR sessions with a scheduled gross OR utilization > 90%
- Percentage of OR sessions with a scheduled gross OR utilization < 60%
- Number of used OR sessions
- Average surgery access times in days
- Percentage of patients that could not be scheduled within the defined planning horizon

The average scheduled gross OR utilization depends on the number of surgeries that has to be scheduled and the timeframe within these surgeries have to be scheduled. Since the number of surgeries to be scheduled and the timeframe within these surgeries have to be scheduled must be the same in the simulation model as in reality, a difference in scheduled gross OR utilization can only be made by minimizing the number of required OR sessions.

The percentage of OR sessions with a scheduled gross OR utilization of more than 90% or less than 60% indicates the variation in scheduled gross OR utilization. This variation should be minimized.

The number of required OR sessions indicates the number of OR sessions in which at least 1 surgery has been performed and should be minimized to improve the average scheduled gross OR utilization.

To calculate the average surgery access times in days, only patients that request a surgery date as soon as possible are included.

The percentage of patients that could not be scheduled within the defined planning horizon, equals the percentage of patients from who their wish with regard to the surgery date could not be met. For example, if only 1 OR session is available within the planning horizon and the appointment flexibility equals 3 choices, the patient could refuse the surgery date and should be offered another date. If this is not possible, the patient could not be scheduled within the planning horizon because the wish of the patient could not be met.

Since we included 4 specialists, we measure the performance of the OR planning department with regard to the specialists separately, as well as the overall performance.

4.2 Model realization

To convert the conceptual model into a real simulation model, we need input data or we need to make assumptions in case the required data is not available. In this section we describe how, and to what extent, we realized the model objectives. For each defined model objective, we describe what challenges we face, which input data we use, which assumptions we make and, if applicable, how patients move through the modelled system. According to the objectives that have been defined for experimental purposes, we describe what we have modelled to realize the objectives. The data that we used as input for our model includes all performed surgeries between July 2018 and July 2019, and it includes specialist specific statistics, i.e. the number of performed outpatient clinic appointments per day.

- *The arrival process of patients at the OR planning department in the model, equals the arrival process of patients at the current OR planning department. The arrival process follows the same seasonal pattern as in reality.*

The varying number of patients to schedule due to demand fluctuations, is the challenge that OR planners face. Therefore, it is important that the arrival process of patients at the OR planning department equals reality. No data is available about the number of patient arrivals per day at the OR planning department. We use the outpatient clinic agendas of the specialists as input for the outpatient clinic agendas in the simulation model. The number of available outpatient clinic timeslots per day per specialist in the model, equals the number of performed outpatient clinic appointments by that specialist on that day. The source generates a sufficient number of new patients, so that all available outpatient clinic appointment slots are used. Once a new patient has been generated by the source, the patient gets assigned a specialist based on how patients are distributed over the specialists. This is calculated by dividing the number of new patients per specialist by the total number of new patients. The patient is then assigned to the first available timeslot in the outpatient clinic agenda of the right specialist, and is forwarded to the outpatient clinic at the beginning of the day of appointment. At the outpatient clinic, patients are served in a random sequence and their processing time is a constant.

After visiting the outpatient clinic, the patient has to visit the screening and OR planning department with a certain probability. This chance equals the conversion of the corresponding specialist, i.e. the percentage of new patients that have visited the outpatient clinic and eventually undergoes surgery. We extracted this from the data by dividing the total number of scheduled surgeries by the total number of performed first outpatient clinic appointments. We assume that the outpatient clinic/OR ratio is constant for each specialist and that the conversion is the same during the year. Appendix A shows the conversions of the specialists. To make sure the arrival process at the OR planning department equals the real arrival process, we need to know how the time between the outpatient clinic appointment and the OR planning department appointment is distributed. The data does not show on what date the surgery has been scheduled, so we need to model this process based on observations and interviews. We assume that the screening and OR planning are on the same day, since this applies to 99% of the patients. In most cases, patients visit the screening and OR planning department right after the outpatient clinic. However, if surgery access times of a specialist are high, patients get a return appointment for the screening and planning. If patients must return, this usually takes place within 2 and 4 weeks from the outpatient clinic appointment. In our model we update the average number of weeks between surgery scheduling and surgery every 4 weeks and for each specialist separately. Only patients that want a surgery date as soon as possible are used to calculate this average, because patients that want to postpone their surgery are not representative. If the average number of weeks between surgery scheduling and surgery exceeds 5, 80% of the patients get assigned a return appointment on a random day within 2 and 4 weeks. The other 20% does continue to the screening and OR planning department, because some patients are not asked to return to the clinic, for example old patients of patients who live far away from the clinic. If the average number of surgery access weeks is 5 or less than 5, 90% of the patients continue directly to the screening and OR planning department. The other 10% gets a return appointment because it is the patient's wish.

- *Patients that visit the OR planning department, are assigned to an OR session according to the current operational offline planning procedure.*

To be able to validate our created simulation model, we must schedule patients according to the current surgery scheduling procedure. However, no clear procedure exists and OR planners schedule surgeries based on their own expertise. Therefore it is very difficult to model the current surgery scheduling process accurately. The data does not show on what date a surgery has been scheduled, but it does show the corresponding screening date. Since we assume that the screening and planning appointment are on the same day, we can estimate how the time between surgery scheduling and surgery is distributed. It turned out that this distribution is very specialist specific, and since the time between surgery scheduling and surgery depends on the availability of the specialist's agenda, it would be unrealistic to schedule surgeries based on this distribution.

To imitate the OR planners as much as possible, we base our surgery scheduling procedure on observations and interviews. Most patients are scheduled as soon as possible, and all patients are scheduled within 1 and 10 weeks from the moment of scheduling. In general, surgeries are not scheduled during overtime and OR planners do not use slack time either. We assume that 85% of the patients requests a surgery date as soon as possible. The other 15% has another wish with regard to the surgery date, and is scheduled in a random available OR session within 1 and 10 weeks from the moment of scheduling. Each patient gets assigned a surgery time that equals the beginning of the OR session the patient is assigned to. All patients are forwarded to the OR waitingroom 15 minutes before the assigned surgery time, and processed by the OR in a random sequence. The processing time of a patient at the OR equals the scheduled surgery duration. Once the processing time has exceeded, the patient leaves the OR and the next patient enters the OR.

- *The number of available OR sessions per specialist and the distribution of these OR sessions over the year, equals reality.*

The data shows per specialist per day the number of performed surgeries and the number of performed outpatient clinic appointments. On days that a specialist has performed surgeries only, we assume that a whole OR session was assigned to the specialist on that day. On days that a specialist has performed surgeries and outpatient clinic appointments, we assume that a half OR session was assigned to the specialist on that day. On days that a specialist has performed outpatient clinic appointments only, we assume no OR session was assigned to the specialist on that day. We used this as input for the assignment of OR sessions to specialists in the simulation model.

- *The surgeries that must be scheduled are from the same type and frequency as in reality.*

A surgery consists of one or a couple of operations to be performed. For each unique combination of operations, an activity code exists to register the surgery. Surgeries that do not share the same activity code could be almost homogenous in terms of required resources, surgery duration and surgery description. Therefore, we created specialist specific surgery clusters. Each cluster contains a set of activity codes that correspond to surgeries that are homogenous in terms of surgery duration, required resources and surgery description. The clusters have been defined with one of the OR planners. In the simulation model the patient gets assigned a cluster type and its corresponding properties, such as surgery duration. The total number of surgeries in a cluster is divided by the total number of surgeries in all clusters, to determine the probability for each cluster that it should be assigned to a patient.

- *The same resource restrictions are taken into account as in reality.*

We have collected the resource restrictions that must be taken into account for each surgery cluster type. The resource restrictions are checked by a method and updated after a surgery has been scheduled.

- *The behaviour of patients, i.e. their wishes regarding the surgery date, peer with the real patients' behaviour. For example, a part of the patients would like to postpone their surgery.*

Based on observations, we know that not every patient accepts the proposed surgery date. Therefore we made an assumption with regard to the patients' surgery date preferences. The part of the patients that do not want a surgery date as soon as possible is scheduled in a random available OR session within 1 and 10 weeks from the moment of scheduling. The other part of the patients is assigned to one of the first 3 available OR sessions. For each of the three proposed surgery dates, the probability that the patient chooses the surgery date is the same. In this way we deal with the patients' own agendas as well.

- *The simulation model could be used to assess the proposed interventions.*

To be able to assess the proposed interventions, we created a method that is called every time a surgery has to be scheduled. In this method, several input variables are used. The input variables MinWeek and Maxweek define the planning horizon, and the input variable NrProposedSurgeryDates defines the appointment flexibility.

The method lists all suitable OR sessions and checks if OR sessions in the list violate resource restrictions. If so, these OR sessions are removed from the list. The method continues with assigning 5 priority values, to each of the OR sessions that are still in the list. Priority values 1, 2 and 3 are used for the RM based scheduling approach.

To assign priority 1, the OR sessions are sorted down, based on week number. The OR session in row 1 has the highest week number and gets assigned a priority value of 1, since much time is left to use the remaining OR session time. If the OR session in the next row has the same week number as the OR session in the previous row, the same priority value is assigned. If the week number has decreased, the priority value increases by one.

To assign priority value 2, we created a table for each specialist, that contains specialist specific intervals. These intervals cover surgery durations of the specialist. Priority 2 values are negative, and the more frequently a surgery duration in an interval occurs, the more negative the associated priority value. This is because there is a high chance that we need to plan a surgery in the future, which uses all the remaining OR session time.

Priority value 3 is associated with the available OR session time *after* the surgery is planned in the OR session. In contrast to priority value 2, the interval which contains a surgery duration that frequently occurs, is associated with a high priority value 3. This is because we expect that another surgery could be planned in the future, that uses all remaining OR session time.

If a surgery duration barely occurs, no interval exists that contains the surgery duration. If scheduling a surgery in an OR session results in 0 to 5 minutes of available time left, the surgery fits best in that OR session. Therefore, the highest priority 3 value is associated with the interval that contains 0 to 5 available minutes left *after* the surgery is planned in the OR session. Table 8 is an example of how the intervals are prioritized.

Interval Lower bound (min)	**Interval Upper bound (min)**	**Frequency surgery duration**	**Priority 2**	**Priority 3**
0	5	-	0	5
47	52	301	-4	4
56	61	201	-3	3
73	78	37	-1	1
88	93	52	-2	2

Table 8: example of defined intervals and associated priority values

Appendix B shows the defined intervals and the associated priority values for all specialists. Again, the priority 2 values and the priority 3 values are weighted, so the sum of the priority values equals 1.

Priority values 4 and 5 are associated with the latest start time and earliest start time rule respectively. The OR sessions are sorted, based on available OR session time left. The OR session that has the most available OR session time left gets assigned the lowest priority 4 value and the highest priority 5 value. All OR sessions in the list are evaluated until they all have been prioritized.

All priority values are multiplied with a weight, before they are summed up. These weights are input variables, so they could be adjusted as wished. Making use of these weights, allows us to assess the performance of all surgery scheduling approaches separately, because if we use a weight of zero, the priority value is not used. This also enables us to combine surgery scheduling approaches and to use different weights.

The defined appointment flexibility determines the number of surgery dates that the patient can choose from. In the usual surgery scheduling procedure, this equals 3. We draw a random number from a uniform distribution on the interval (0,1), and use this number to determine which surgery date the patient chooses. We assume that each surgery has the same chance to be chosen by the patient. The part of the patients that want to postpone their surgery, is always planned in a random suitable OR session. Therefore, the appointment flexibility does not have an effect on this part of the patients as they are not offered a choice.

- *The simulation model stores performance statistics.*

Different statistics tables are added to the model. The patient table stores all patient associated information, as the number of days between surgery scheduling and surgery. The operating room table stores all OR department related information, as the total number of performed surgery minutes per OR day. Each column of the table holds a different key performance indicator and each row correspond to a simulation run. After a whole experiment, the averages of the key performance indicators over all performed runs are calculated and stored in the experiment statistics table. We also use two tables that store the performances per specialist per run and per specialist per experiment respectively.

Appendix C displays the control panel of the simulation model.

4.3 Simulation settings and model validation

The model we created must be validated in order to make sure the model is a reliable representation of reality. First we determine the simulation settings that are required to achieve a sufficient accuracy of the outcomes. These simulation settings are the warmup period, the number of runs per experiment and the run length. After this, we validate our simulation model by comparing the simulation model with reality.

4.3.1 Warmup period

The period during which the initial state of the system influences the output values is called the warmup period (Law, 2013). As long as the initial state of the system has influence on the output values, for example on the surgery access times, we could not start measuring the performance of the system. The initial state of our system does not reflect reality, since the operating room agendas are empty. Therefore, we must determine the length of the warmup period, after which the values of the output parameters could be used to assess the performance of the system.

We determine the length of the required warmup period using Welch's graphical procedure (Law, 2013). The output value we concern is the surgery access time, i.e. the number of days between the surgery scheduling date and the surgery date. This is the output value that is most affected by the initial state of the system. According to Welch's procedure, at least 5 replications of the simulation must be performed. We perform 7 replications, with a run length of 1500 days. We calculate for each observation, i.e. each scheduled patient, an average of the surgery access time over all replications. The average values are used to calculate a moving average for a specified range of values. Once the moving average flattens out, the system has reached a steady state and we can assume that the initial state of the system does not influence the performance of the system anymore. Figure 18 shows the moving average over time.

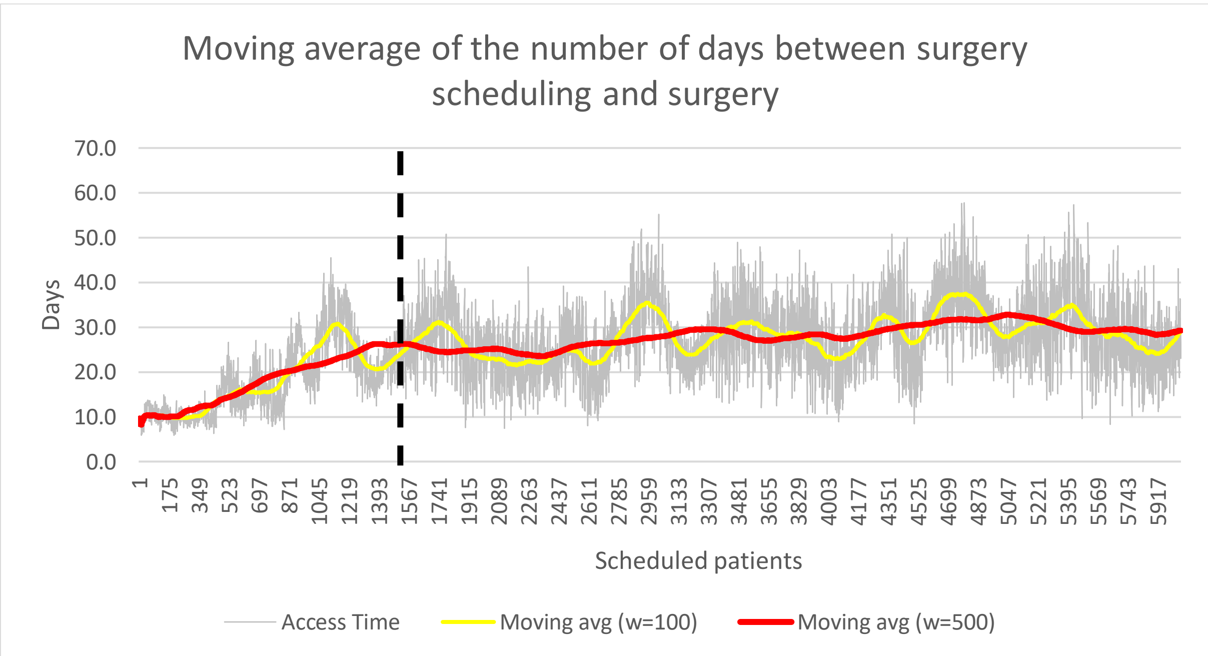


Figure 18: determination of warmup period

The moving average never flattens out completely, due to seasonal fluctuations. However, a clear warmup period is visible in the figure. After approximately scheduling 1500 patients, the system reaches a steady state. The 1500th patient was scheduled on day 309. To be sure our system has warmed up, we decide to use a warmup period of one year.

4.3.2 Number of runs

We need to determine the number of runs per experiment, because several statistical distributions are used in the model, and therefore the output values depend on random numbers. A run is one repetition of the simulation with a previously defined run length. To increase the accuracy of our results, we need to perform multiple runs per experiment. Because we have a warmup period of 1 year, we investigate if the number of runs per experiment that is required to achieve a predefined accuracy of our results, decreases if the run length increases. Therefore we determine the number of required runs per experiment if we use a run length of 2 years and if we use a run length of 3 years. In both cases, a warmup period of 1 year is included.

To determine the required number of runs per experiment, in order to achieve a predefined accuracy of our output variables, we use the sequential procedure described by Law (Law, 2013). With this procedure it is possible to determine the exact number of runs that is needed to estimate the mean of an output value, with a specified required relative error γ and a confidence level of $100(1-\alpha)$ percent. Data that is generated during the warmup period is excluded when estimating the mean of an output value, because this data is unreliable and will also not be used to calculate the mean of the output values during the experiments. We concern the same output value as we did to determine the length of the warmup period. This output value is the surgery access time.

The relative error γ of the observed mean over a number of replications, is the difference between the observed mean and the actual mean, divided by the actual mean. However, we do not know the actual mean so we must estimate the relative error γ. The relative error γ could be estimated by dividing the confidence interval half-width of the observed mean, by the observed mean (Law, 2013).

During the sequential procedure, we perform as many runs as needed to obtain an estimated relative error of the mean, that is smaller than the required relative error. We use a run length of 2 and 3 years to investigate how this influences the number of required runs per experiment. Since we estimate the relative error of the mean, we need to use the adjusted relative error $\gamma' = \gamma/(1-\gamma)$ as a threshold to obtain the required relative error γ. Figures 19 and 20 show the adjusted relative error and the estimated relative error per number of runs, if we use a run length of respectively 2 and 3 years. We perform as many replications as needed until the estimated relative error is smaller than the adjusted relative error. We use a required relative error of $\gamma= 0.05$ ($\gamma' = 0.04762$) and a confidence level of 95% ($\alpha=0.05$).

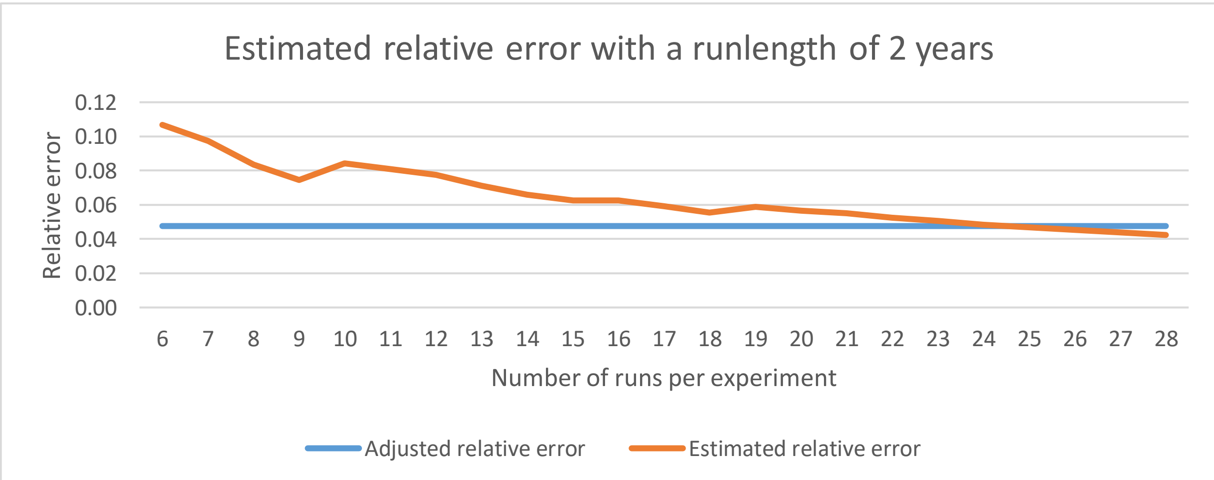


Figure 19: estimated relative error per number of runs per experiment ($\alpha=0.05$, $\gamma= 0.05$, output value=average OR access time in seconds, runlength = 2 years)

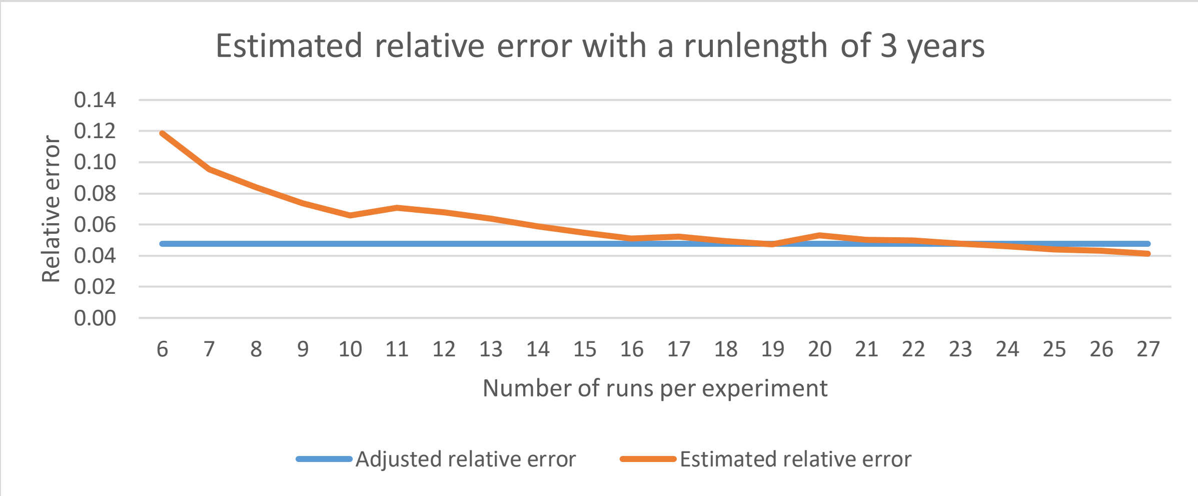


Figure 20: estimated relative error per number of runs per experiment (α=0.05, y= 0.05, output value=average OR access time in seconds, runlength = 3 years)

4.3.3 Run length

If we use a run length of 2 years including a warmup period of 1 year, we must perform at least 26 runs per experiment to obtain statistically significant results. If we use a run length of 3 years including a warmup period of 1 year, we must perform at least 23 runs per experiment. We must perform 26 runs of 2 years or 23 runs of 3 years. Given the time it takes to perform a run, we choose to use a run length of 2 years and we perform 30 runs per experiment, to guarantee that we obtain statistically significant results.

4.3.4 Comparison simulation and reality

To evaluate if the simulation model represents reality, we compare several simulation outcomes with reality. Table 9 shows the outcomes with regard to the whole system. Tables 10 and 11 show the outcomes with regard to the specialists separately.

Outcomes	Reality	Simulation
Number of outpatient clinic visits	5698	5698
Number of performed surgeries	1842	1801
Number of performed surgery minutes	125678	122802

Table 9: comparison of outcomes simulation model and reality with regard to the overall system

Outcomes	Reality Specialist 1	Simulation Specialist 1	Reality Specialist 2	Simulation Specialist 2
Number of outpatient clinic visits	1426	1426	2058	2058
Number of performed surgeries	568	555	602	596
Number of performed surgery minutes	37447	36612	32833	32434

Table 10: comparison of outcomes simulation model and reality with regard to specialist 1 and 2 (clinic A)

Outcomes	Reality Specialist 3	Simulation Specialist 3	Reality Specialist 4	Simulation Specialist 4
Number of outpatient clinic visits	996	996	1218	1218
Number of performed surgeries	424	416	248	232
Number of performed surgery minutes	38440	37680	16958	16076

Table 11: comparison of outcomes simulation model and reality with regard to specialist 3 and 4 (clinic B)

The outcome values approximately correspond to each other. Slightly less surgeries and surgery minutes were scheduled in the simulation model than in reality. According to specialist 2 and 4, the number of used OR days is smaller than in reality. Because patients are scheduled in one of the first three available OR sessions, we expect that some OR days were not used because demand was insufficient.

Table 12 shows the values of the defined KPIs according to our model and according to reality.

Key Performance Indicator	Reality	Simulation
Average scheduled gross OR utilization	79.2%	85.5%
Percentage of OR sessions with a scheduled gross OR utilization > 90%	48.9%	53.3%
Percentage of OR sessions with a scheduled gross OR utilization < 60%	22.4%	7.6%
Average surgery access times in days	39	33
Number of OR sessions	362	359

Table 12: comparison of KPI values simulation model and reality with regard to the overall system

The differences in scheduled gross OR utilization could be explained by the fact that we were not able to correct for half OR sessions in the calculation of the real scheduled gross OR utilizations. From the data that we used we could not extract if a specialist was assigned a half or a whole OR session. This means that in order to calculate the real scheduled gross OR utilizations, we assumed that on days that a specialist has performed at least one surgery, a whole OR session was assigned to that specialist on that day. This results in underestimated OR utilizations. The difference in surgery access time possibly exists because the patients' preferences with regard to their surgery date differs from what we expected. If more patients want to postpone their surgery than expected, the real surgery access time in days is overestimated. In our simulation, we assumed that only 15% of the patients want to postpone their surgery date and this has influence on the average surgery access time.

We conclude that we can use the simulation model to assess and compare the performances of the proposed interventions in terms of the defined KPIs. Since we made assumptions about the current surgery scheduling procedure, we are not able to accurately predict the performance of an intervention in reality, but we could use the simulation model to determine which intervention performs best in terms of the defined KPIs.

4.4 Experimental design

The proposed interventions we defined in Section 3.3 could be combined, resulting in many possible experiments. To minimize the number of experiments, we will first evaluate the optimal surgery scheduling rule. During these experiments, the same planning horizon and the same appointment flexibility are used. Once we know which surgery scheduling rule performs best, we perform experiments in which we vary the planning horizon. Last, we perform experiments to evaluate the effect of the appointment flexibility on the defined KPIs.

4.4.1 Surgery scheduling rule

To investigate which of the proposed surgery scheduling rules performs best in terms of the defined KPIs, we use the following input variables during the first set of experiments.

Experiment	Weight priority 1	Weight priority 2	Weight priority 3	Weight priority 4	Weight priority 5	MinWeek	MaxWeek	NrProposed SurgeryDates
1.1	1	1	1	0	0	1	10	3
1.2	0	0	0	1	0	1	10	3
1.3	0	0	0	0	1	1	10	3

Table 13: experiment settings to assess different surgery scheduling approaches

The outcomes of these experiment are possibly used to define one or more new experiments. These are defined in Chapter 5.

4.4.2 Planning horizon

To determine which of the proposed planning horizons results in the best performance in terms of the defined KPIs, we perform 3 experiments in which we vary the planning horizon. During these experiments we use the best performing surgery scheduling approach and the current appointment flexibility. We could not use the current surgery scheduling approach during these experiments, as patients are scheduled as soon as possible so the planning horizon does not have any influence on the scheduled gross utilization. Table 14 shows the experiment settings during these set of experiments.

Experiment	Surgery scheduling rule	MinWeek	MaxWeek	NrProposedSurgeryDates
2.1	Best performing	1	4	3
2.2	Best performing	1	6	3
2.3	Best performing	1	8	3

Table 14: experiment settings to assess different planning horizons

4.4.3 Appointment flexibility

In the last set of experiments, we vary the appointment flexibility. Again we use the best performing surgery scheduling rule in combination with the best performing planning horizon. Table 15 shows the experiment settings during these set of experiments.

Experiment	Surgery scheduling rule	NrProposedSurgeryDates	Planning Horizon
3.1	Best performing	1	Best performing
3.2	Best performing	2	Best performing
3.3	Best performing	4	Best performing

Table 15: experiment settings to assess different appointment flexibilities

4.4.4 Sensitivity analysis

After we defined which intervention performs best, we test the robustness of the intervention, because a change in the arrival process at the OR planning department could have influence on the performance of the intervention. For example, if patients are equally distributed over the year, it is easier to keep access times low and have a constant OR utilization.

During the experiments, patients are forwarded from the outpatient clinic department to the OR planning department in different ways. If the surgery access time in weeks exceeds 5, 80% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment. If the surgery access time in weeks is 5 or less, only 10% of the patients get a return appointment. We adjust this procedure in order to change the arrival process at the OR planning department.

The defined scenarios are realistic according to the OR planners. Table 16 lists the possible scenarios.

Scenario	Applied procedure to forward patients to OR planning department
A	Regardless of the surgery access time, 80% of the patients proceed to the OR planning department directly after visiting the outpatient clinic. The other 20% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.
B	Regardless of the surgery access time, 60% of the patients proceed to the OR planning department directly after visiting the outpatient clinic. The other 40% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.
C	If the surgery access time in weeks exceeds 5, 70% of the patients get a return appointment. Otherwise, 20% get a return appointment. The return appointments are between 2 weeks and 4 weeks from the outpatient clinic appointment.
D	If the surgery access time in weeks exceeds 6, 60% of the patients get a return appointment. Otherwise, 30% get a return appointment. The return appointments are between 2 weeks and 4 weeks from the outpatient clinic appointment.

Table 16: possible scenarios with regard to the arrival process at the OR planning department

5 Results

In this chapter we present the results of the performed experiments. Section 5.1 presents the influence of different surgery scheduling rules on the KPIs. In Section 5.2 and 5.3 we present the influence of the planning horizon and appointment flexibility on the KPIs respectively. Section 5.4 presents the robustness of the best performing intervention.

5.1 Surgery scheduling approach

The interventions we proposed with regard to the surgery scheduling rule are shown in Table 17.

Intervention	Surgery scheduling rule
1.1	Use RM based rule
1.2	Use latest start time rule
1.3	Use earliest start time rule

Table 17: proposed interventions with regard to the surgery scheduling approach

Table 18 presents the average performance according to the simulation model, of each of the proposed interventions. With average we mean that the performances of all specialists are included in the calculation.

KPI → Surgery scheduling rule ↓	Average scheduled gross OR utilization	Average percentage OR sessions > 90% scheduled gross utilization	Average percentage OR sessions < 60% scheduled gross utilization	Number of used OR sessions	Average surgery access time in days	Average percentage of patients not scheduled within planning horizon
Current used rule	85.5%	53.3%	7.6%	359	33	0.8%
Use RM based rule	85.4%	48.5%	6.4%	360	34	0.8%
Use latest start time rule	88.7%	62.4%	3.6%	342	55	3.8%
Use earliest start time rule	81.8%	36.6%	8.6%	356	62	4.9%

Table 18: performances of different interventions with regard to the surgery scheduling approach in terms of KPIs, according to the simulation model

The current surgery scheduling approach results in the best surgery access time. This is not surprising, as the OR planners schedule surgeries as soon as possible. However, this way of scheduling does not result in the best average scheduled gross OR utilization.

The earliest start time rule performs worst in terms of all KPIs. This rule does not take into account the surgery access time and since a surgery is assigned to an OR session that has most available time left, probably more OR sessions are used than needed. The percentage of patients that could not be scheduled within the planning horizon confirms that OR sessions are not used efficiently. It is remarkable that the number of used OR sessions when using the earliest start time rule is less than when using the current or latest start time rule. An explanation for this is that an OR session could last a half or a whole day, so probably most of the used OR sessions when using the earliest start time rule are whole day OR sessions whereas for the other approaches more OR sessions of half a day are used.

The latest start time rule results in the highest scheduled gross OR utilization. We already expected this because the number of used OR sessions is minimized by this rule. However, the latest start time rule performs worse on average surgery access time, as it does not take this into account. Therefore, many patients are not assigned to one of the first available OR session and the average surgery access time increases drastically. The average percentage of patients that could not be scheduled within the planning horizon increases with 3% compared to the current performance. We expect that this is caused by the fact that available OR time in the near future sometimes remain unused, because OR sessions that take place later could get more priority. Specialists with high demand need all OR time in order to treat all their patients within the planning horizon. Therefore, using the latest start time rule increases the percentage of patients that could not be scheduled within the planning horizon.

The RM based rule achieves an acceptable average surgery access time, probably because the first priority value is based on surgery access time. Priority values 2 and 3 contribute to an efficient use of available OR time, which also decreases the average surgery access time. The average scheduled gross OR utilization is disappointing. This could be explained by the fact that many OR sessions are used. Surgeries are not always scheduled as soon as possible because of priority values 2 and 3. If for example a surgery has to be scheduled that fits in an OR session perfectly, that OR session gets a higher priority than an OR session that has enough available time left and takes place earlier. Therefore, the use of priority value 2 and 3 could result in unused OR time and a lower average gross OR utilization.

Given these results, we want to investigate if it is possible to lower the surgery access time when using the latest start time rule, or to increase the scheduled gross utilization when using the RM based rule. Therefore, we define a new intervention, in which we combine the RM based rule and the latest start time rule.

Intervention	**Surgery scheduling rule**
1.4	Use combination of RM based rule and latest start time rule

Table 19: new proposed intervention

We use the following experiment settings:

Experiment	**Weight priority 1**	**Weight priority 2**	**Weight priority 3**	**Weight priority 4**	**Weight priority 5**	**MinWeek**	**MaxWeek**	**NrProposed SurgeryDates**
1.4	1	1	1	1	0	1	10	3

Table 20: experiment settings of new proposed intervention

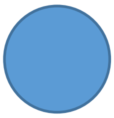
Table 21 shows the average performance of the new intervention.

KPI → **Surgery scheduling rule ↓**	**Average scheduled gross OR utilization**	**Average percentage days > 90% scheduled gross utilization**	**Average percentage days < 60% scheduled gross utilization**	**Number of used OR sessions**	**Average surgery access time in days**	**Average percentage of patients not scheduled within planning horizon**
Current used rule	85.5%	53.3%	7.6%	359	33	0.8%
RM based rule + latest start time rule	87.2%	57.4%	5.1%	354	41	1.4%

Table 21: performance of new intervention in terms of KPIs, according to the simulation model

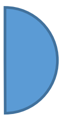
Combining the RM based approach with the latest start time rule results in an increase in scheduled gross OR utilization compared to using the RM based rule only. It also results in a decrease in average surgery access time in days compared to using the latest start time rule only, which we already expected. Compared to the current approach, all KPIs concerning OR utilization are improved, but the average surgery access time in days has increased.

To investigate if the performance of a surgery scheduling approach depends on the type of specialist it is used for, we assess the performance per proposed intervention per specialist. For this purpose we use a scoring system to visualize the performance of the interventions. For each KPI we defined value ranges, which are associated with the following circles:



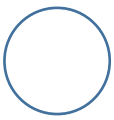
Average scheduled gross utilization > 90
Average surgery access time in days < 15
Average percentage of days > 90% scheduled gross utilization > 80
Average percentage of days < 60% scheduled gross utilization < 5

Average scheduled gross utilization > 85
Average surgery access time in days >= 15 < 30
Average percentage of days > 90% scheduled gross utilization > 70
Average percentage of days < 60% scheduled gross utilization >= 5 < 10



Average scheduled gross utilization > 80
Average surgery access time in days >= 30 < 45
Average percentage of days > 90% scheduled gross utilization > 60
Average percentage of days < 60% scheduled gross utilization >= 10 < 15

Average scheduled gross utilization > 70
Average surgery access time in days >= 45 < 60
Average percentage of days > 90% scheduled gross utilization > 50
Average percentage of days < 60% scheduled gross utilization >=15 < 20



Average scheduled gross utilization <= 70
Average surgery access time in days >= 60
Average percentage of days > 90% scheduled gross utilization <= 50
Average percentage of days < 60% scheduled gross utilization >= 20

In addition to the KPIs we score with the circles, we mention some other performance indicators. The average number of used OR sessions could not be scored since this depends on the specialist. Therefore, we also mention the number of used OR sessions per intervention per specialist.

To relate the performance of the interventions to the properties of the specialists, we categorized the included specialists according to Table 22.

	High surgery access time	**Low surgery access time**
High OR utilization	Specialist 1	Specialist 2
Low OR utilization	Specialist 3	Specialist 4

Table 22: properties of specialists included in the simulation model

Figure 21 shows the scores per intervention with regard to specialist 1.

SPECIALIST 1	Current	RM	Latest start time	Earliest start time	RM + Latest start time
Average scheduled gross utilization	●	●	●	◕	●
Average surgery access time in days	◔	◑	◔	○	◔
Average percentage of days > 90% scheduled gross utilization	●	●	●	◔	●
Average percentage of days < gross 60% scheduled gross utilization	●	●	●	●	●
Average number of used OR sessions	99	99	97	99	98
Average percentage of patients not scheduled	1.5%	1.5%	5.3%	6.5%	2.6%
Variance	3.9%	2.4%	3.2%	0.9%	4.3%
Standard deviation	13.7%	11.5%	10.8%	8.1%	13.6%

Figure 21: assigned scores per KPI with regard to specialist 1

The best performance with regard to the average surgery access time in days is achieved when applying the RM based rule. Given the high access times of specialist 1 it is of great importance to use the available OR time efficiently in order to keep access times low. Therefore, it is not a surprise that specialist 1 benefits most from the RM based rule in terms of surgery access times. The average scheduled gross OR utilization is not very sensitive to a change in the surgery scheduling approach. A high percentage of patients that could not be scheduled within the planning horizon indicates that the number of assigned OR sessions is not sufficient to treat all patients within the planning horizon. The current used surgery scheduling rule and the RM based rule minimize the percentage of patients that could not be scheduled within the planning horizon.

Figure 22 shows the scores per intervention with regard to specialist 2.

SPECIALIST 2	Current	RM	Latest start time	Earliest start time	RM + Latest start time
Average scheduled gross utilization	◕	◕	●	◕	◕
Average surgery access time in days	◕	◕	◔	○	◑
Average percentage of days > 90% scheduled gross utilization	◑	◔	●	○	◕
Average percentage of days < 60% scheduled gross utilization	◕	◕	●	●	◕
Average number of used OR sessions	92	93	88	93	90
Average percentage of patients not scheduled	0.0%	0.0%	1,0%	2,0%	0.0%
Variance	1.1%	1.2%	2.3%	1.7%	0.9%
Standard deviation	10.0%	10.5%	9.3%	12.3%	8.8%

Figure 22: assigned scores per KPI with regard to specialist 2

The current used surgery scheduling rule as well as the RM based rule result in an acceptable average surgery access time and 0 patients that could not be scheduled within the planning horizon. From this we conclude that the number of assigned OR sessions is sufficient to treat all patients within the planning horizon. To improve the scheduled gross OR utilization, the latest start time rule should be used. However, this results in worse surgery access times as this is not taken into account by the latest start time rule. Applying the RM based rule in combination with the latest start time rule increases the number of days with an average scheduled gross utilization of more than 90%, resulting in less used OR sessions.

Figure 23 shows the scores per intervention with regard to specialist 3.

SPECIALIST 3	Current	RM	Latest start time	Earliest start time	RM + Latest start time
Average scheduled gross utilization	◑	◑	◑	◑	◑
Average surgery access time in days	◑	◑	◔	○	◔
Average percentage of days > 90% scheduled gross utilization	○	○	○	○	○
Average percentage of days < 60% scheduled gross utilization	●	●	●	◕	●
Average number of used OR sessions	104	103	99	103	103
Average percentage of patients not scheduled	1.5%	1.2%	7.5%	8.7%	2.5%
Variance	0.3%	0.6%	0.6%	0.5%	0.5%
Standard deviation	5.1%	6.1%	7.4%	4.8%	6.6%

Figure 23: assigned scores per KPI with regard to specialist 3

Specialist 3 scores very bad on average percentage of days with a scheduled gross utilization of more than 90%. Also the average scheduled gross OR utilization could be improved. Given the high surgery access times, we assume that demand is sufficient to increase the average scheduled gross OR utilization. The worse performance on average scheduled gross OR utilization could be explained by the fact that specialist 3 performs many surgeries with high surgery durations. We expect that remaining OR time is often just not sufficient to schedule another surgery. Allowing overtime or expanding the opening hours of the OR probably has much influence on the scheduled gross utilization and consequently on surgery access times. The current surgery scheduling approach and the RM based approach perform best, but differences are small. Concerning specialists that perform surgeries with high surgery durations, it is of importance to evaluate the opening hours of the OR in order to improve scheduled gross utilizations and surgery access times.

Figure 24 shows the scores per intervention with regard to specialist 4.

SPECIALIST 4	Current	RM	Latest start time	Earliest start time	RM + Latest start time
Average scheduled gross utilization	○	○	◑	○	◔
Average surgery access time in days	◕	◕	◔	◔	◑
Average percentage of days > 90% scheduled gross utilization	○	○	○	○	○
Average percentage of days < 60% scheduled gross utilization	○	○	◑	○	◔
Average number of used OR sessions	63	64	56	60	61
Average percentage of patients not scheduled	0.0%	0.0%	0.5%	1.0%	0.0%
Variance	1.3%	0.8%	0.5%	0.8%	2.5%
Standard deviation	9.9%	7.7%	6.6%	7.0%	11.3%

Figure 24: assigned scores per KPI with regard to specialist 4

Specialist 4 performs worst on average scheduled gross OR utilization compared to the other specialists. This could be explained by the fact that demand of specialist 4 is insufficient to use all available OR sessions. The intervention that performs best on average scheduled gross utilization, uses less OR sessions. Using less OR sessions increases the average scheduled gross OR utilization, but also increases the average surgery access time. Concerning specialists with low demand, it is of importance to minimize the number of used OR sessions in order to increase scheduled gross OR utilizations. However, a decrease in the number of used OR sessions also results in an increase in average surgery access time.

It very much depends on the specialist which surgery scheduling rule performs best in terms of the KPIs, and none of the surgery scheduling rules improves all KPIs. Increasing the average scheduled gross OR utilization is always at the expense of surgery access times. Specialists that have low surgery access times should minimize the number of used OR sessions. The latest start time rule performs best in minimizing the number of OR sessions, but this rule increases the average surgery access time too much. Therefore it is better to use the latest start time rule in combination with the RM based rule. Specialists that have high surgery access times should evaluate if the number of OR sessions within the planning horizon is sufficient to treat all patients within the planning horizon. In order to minimize surgery access times, the RM based rule should be used.

Appendix D contains all simulation outcomes with regard to the surgery scheduling rule.

5.2 Planning horizon

We proposed the following interventions with regard to the planning horizon:

Intervention	Planning horizon
2.1	1-4 weeks
2.2	1-6 weeks
2.3	1-8 weeks

Table 233: proposed interventions with regard to the planning horizon

The best performing surgery scheduling rule in terms of scheduled gross OR utilization is the latest start time rule. However, the latest start time rule results in high surgery access times. The planning horizon probably has a positive influence on the surgery access times. Therefore, we use the latest start time rule to assess the effect of the planning horizon on the KPIs.

Table 24 shows the performances of interventions 2.1, 2.2 and 2.3 in terms of the KPIs.

KPI → Planning horizon ↓	Average scheduled gross OR utilization	Average percentage days > 90% scheduled gross utilization	Average percentage days < 60% scheduled gross utilization	Number of used OR sessions	Average surgery access time in days	Average percentage of patients not scheduled within planning horizon
Current planning horizon: 1 – 10 weeks	88.7%	62.4%	3.6%	342	55	3.8%
1 – 4 weeks	82.8%	48.1%	10.7%	330	22	13.5%
1 – 6 weeks	86.3%	55.9%	6.2%	334	32	8.4%
1 – 8 weeks	87.8%	60.5%	4.6%	336	42	6.4%

Table 24: performances of different interventions with regard to the planning horizon, in terms of KPIs, according to the simulation model

The simulation outcomes show that shortening the planning horizon decreases the average surgery access time, but it also decreases the average scheduled gross OR utilization. It is not surprising that the average surgery access time in days decreases when a shorter planning horizon is used, because surgeries can only be scheduled within the planning horizon. The decrease in average scheduled gross OR utilization is probably caused by the fact that less OR sessions are available to choose from. If none of the OR sessions within the planning horizon is available, the patient could not be scheduled. The shorter the planning horizon, the less OR sessions are available and the higher the chance that none of the OR sessions within the planning horizon is available. Therefore, a shorter planning horizon results in more OR time that remains unused. The use of the latest start time rule also increases the risk that available OR time remains unused. This rule does not take surgery access time into account, so available OR sessions in the near future could get a lower priority value than available OR sessions that take place later. This increases the chance that available OR time in the near future remains unused. If a lot of available OR time remains unused, the average surgery access time increases and the percentage of patients that could not be scheduled within the planning horizon possibly increases as well. The latter applies in particular to specialists who need all OR sessions to treat their patients within the planning horizon.

Figure 25 shows a trade-off per specialist between the average scheduled gross OR utilization and the average surgery access time in days.

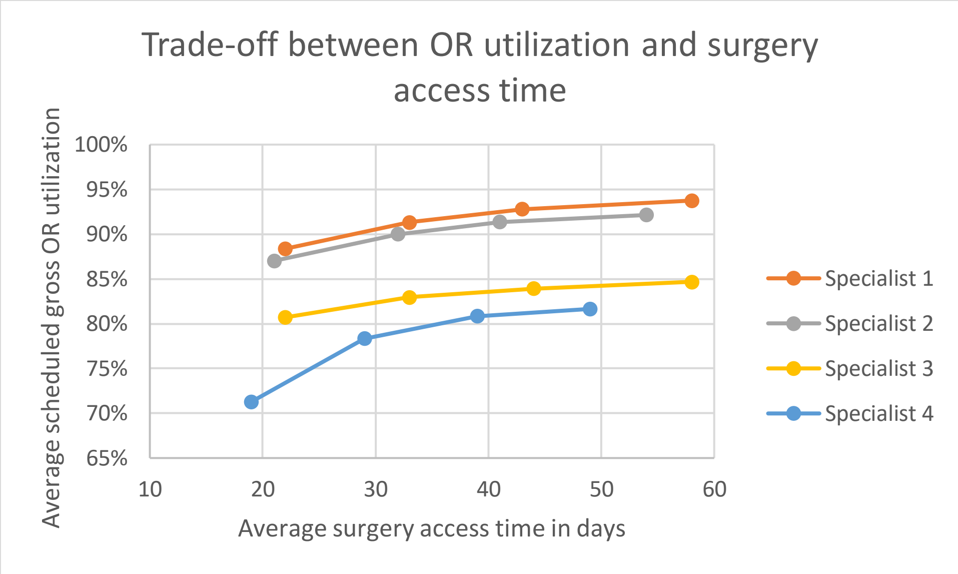


Figure 25: trade-off per specialist between the average scheduled gross OR utilization and the average surgery access time in days

The biggest improvement in average scheduled gross OR utilization by broadening the planning horizon is achieved by specialist 4. This specialist is characterized by low surgery access times and low OR utilizations. The other specialists achieve only small improvements in average scheduled gross OR utilization, while the average surgery access time in days increases a lot. Therefore, concerning specialists with a low average scheduled gross OR utilization and a low average surgery access time, broadening the planning horizon is useful to increase the average scheduled gross OR utilization but it is always at the expense of the average surgery access time.

Using the latest start time rule increases the chance that available OR time remains unused. To compensate for this effect, we should take the surgery access time into account. Therefore, we will use the latest start time rule in combination with the RM based rule to assess the influence of the appointment flexibility on the KPIs. Furthermore, we will use a planning horizon of 1 – 6 weeks because we expect that combining the latest start time rule with the RM based rule decreases the amount of unused OR time and therefore increases the number of patients that could be scheduled within the planning horizon.

Appendix E contains all simulation outcomes with regard to the planning horizon.

5.3 Appointment flexibility

We proposed the following interventions with regard to the appointment flexibility:

Intervention	**Appointment Flexibility**
3.1	1 choice
3.2	2 choices
3.3	4 choices

Table 25: proposed interventions with regard to the appointment flexibility

The current approach uses an appointment flexibility of 3 choices, which means that if a patient rejects the surgery date, the patient should be offered 2 more possibilities. If it is not possible to offer the patient 1 or 2 more possibilities, the patient could not be scheduled within the planning horizon.

We will use the latest start time rule in combination with the RM based rule and a planning horizon of 1-6 weeks to assess the influence of the appointment flexibility on the KPIs.

Table 26 shows the performances of intervention 3.1, 3.2 and 3.3 in combination with the latest start time rule and RM bused rule, in terms of the KPIs.

KPI → Appointment flexibility ↓	Average scheduled gross OR utilization	Average percentage days > 90% scheduled gross utilization	Average percentage days < 60% scheduled gross utilization	Number of used OR sessions	Average surgery access time in days	Average percentage of patients not scheduled during planning horizon
Current appointment flexibility: 3 choices	84.5%	50.4%	8.2%	354	26	4.8%
1 choice	87.4%	56.5%	4.0%	346	27	3.9%
2 choices	86.0%	53.4%	6.2%	351	26	4.1%
4 choices	82.9%	45.2%	10.3%	356	26	6.1%

Table 26: performances of different interventions with regard to the appointment flexibility, in terms of KPIs, according to the simulation model

With regard to the appointment flexibility, the more choices you offer the patient, the more is lost on average scheduled gross OR utilization and the more patients could not be scheduled within the planning horizon. If less choices are offered, patients are scheduled more efficiently because the scheduling rules determine in which OR session a surgery is scheduled. If more choices are offered, the patient can decide in which OR session the surgery is scheduled and this is at the expense of efficiency and therefore it is also at the expense of the average scheduled gross OR utilization. Again, a decrease in average scheduled gross OR utilization comes with an increase in the percentage of patients that could not be scheduled within the planning horizon. The average surgery access time decreases minimally when more choices are offered. A possible reason for this is that OR sessions are not prioritized on surgery access time only, but also on the amount of available time left. Therefore the OR session that gets the highest priority is not by definition the OR session with the lowest surgery access time.

With regard to the appointment flexibility, the relation between the KPIs is the same for all specialists. Therefore, we conclude that increasing the appointment flexibility is at the expense of the average scheduled gross OR utilization and therefore also at the expense of the percentage of patients that could not be scheduled within the planning horizon. The difference in surgery access time between an appointment flexibility of 1 choice and 4 choices is only 1 day, but the difference in average scheduled gross OR utilization is 4.5%.

5.4 Sensitivity analysis

None of the interventions performs best in terms of all KPIs but in the previous sections we determined that the latest start time rule should be used in combination with the RM based rule to improve the average scheduled gross OR utilization and to keep access times acceptable. Using this surgery scheduling approach in combination with a planning horizon of 1-6 weeks and an appointment flexibility of 2 choices results in an increased average scheduled gross OR utilization and a decreased average surgery access time, compared to the current performance. To determine if this intervention is robust to changes in the arrival process at the OR planning department, we assess this intervention in different scenarios. These scenarios have effect on the arrival process at the OR planning department.

Table 27 lists the defined scenarios.

Scenario	Applied procedure to forward patients to OR planning department
A	Regardless of the surgery access time, 80% of the patients proceed to the OR planning department directly after visiting the outpatient clinic. The other 20% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.
B	Regardless of the surgery access time, 60% of the patients proceed to the OR planning department directly after visiting the outpatient clinic. The other 40% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.
C	If the surgery access time in weeks exceeds 5, 70% of the patients get a return appointment. Otherwise, 20% get a return appointment. The return appointments are between 2 weeks and 4 weeks from the outpatient clinic appointment.
D	If the surgery access time in weeks exceeds 6, 60% of the patients get a return appointment. Otherwise, 30% get a return appointment. The return appointments are between 2 weeks and 4 weeks from the outpatient clinic appointment.

Table 27: possible scenarios with regard to the arrival process at the OR planning department

Table 28 shows the values of 3 important KPIs when using the defined scenarios. The right column contains the results when using the standard scenario, in which 80% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment if the surgery access time in weeks exceeds 5, and if the surgery access time in weeks is 5 or less only 10% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.

Scenario → KPI ↓	A	B	C	D	Standard
Average scheduled gross OR utilization	86.1%	86.2%	86.1%	86.1%	86.0%
Average surgery access time	26	27	26	27	26
Percentage of patients not scheduled within planning horizon	4.1%	3.7%	4.2%	3.9%	4.1%

Table 28: performance of best performing intervention in different scenarios, in terms of KPIs

The KPIs are almost not sensitive to a change in the arrival process at the OR planning department. It is possible that the defined scenarios do not differ enough from the standard scenario. Therefore, we perform another experiment in which we adjust the forwarding procedure to the OR planning department drastically. We use the following scenario:

Scenario	Applied procedure to forward patients to OR planning department
E	Regardless of the surgery access time, only 30% of the patients proceed to the OR planning department directly after visiting the outpatient clinic. The other 70% of the patients get a return appointment between 2 weeks and 4 weeks from the outpatient clinic appointment.

Table 29: additional scenario with regard to the arrival process at the OR planning department

Table 30 shows the values of the KPIs when using scenario E.

Scenario → KPI ↓	E
Average scheduled gross utilization	86.0%
Average surgery access time	27
Percentage not scheduled within planning horizon	3.7%

Table 30: performance of best performing intervention in scenario E

Even though scenario E is very different than the other defined scenarios, the values of the KPIs are almost equal. Therefore, we conclude that the best performing intervention is robust to changes in the arrival process at the OR planning department.

6 Conclusions

In Chapter 2 we concluded that the current surgery scheduling process results in an unacceptable workload for OR planners. The data analysis has shown that low OR utilization is the result of low scheduled OR utilization. Especially in clinic B, OR utilization could be improved by reducing the number of low utilized OR sessions. The research goal resulting from the analysis is:

To develop a uniform surgery scheduling approach, which increases OR utilization through increasing scheduled OR utilization, decreases workload of OR planners, and meets access time target.

We created a discrete event simulation model, which closely represents the OR planning department, in order to assess different interventions in terms of several KPIs.

Section 6.1 contains the conclusion with regard to the proposed interventions. Section 6.2 contains the conclusion with regard to the robustness of the best performing intervention.

6.1 Proposed interventions

In order to achieve the research goal, we defined several interventions with regard to the surgery scheduling approach. We proposed a revenue management (RM) based rule, an earliest start time rule and a latest start time rule. These rules can be used separately, but can also be combined. Furthermore, we proposed to assess the influence of the planning horizon and the appointment flexibility on the KPIs.

Table 31 categorizes the surgery scheduling rules based on their performance in terms of average surgery access time and average scheduled gross OR utilization.

	Improved average scheduled gross OR utilization compared to current performance	**Worsened average scheduled gross OR utilization compared to current performance**
Acceptable average surgery access time	None of the interventions	RM based rule
Unacceptable average surgery access time	Latest start time rule	Earliest start time rule

Table 31: performance of interventions in terms of average surgery access time and average scheduled gross OR utilization

None of the proposed surgery scheduling rules result in both an improved average scheduled gross OR utilization and an acceptable average surgery access time. This relation could be explained by the fact that scheduling a surgery in the most efficient way, does not by definition mean that the surgery is scheduled in the first available OR session.

Compared to the current used surgery scheduling rule, the latest start time rule increases the average scheduled gross OR utilization with 2.2%. However, it also increases the average surgery access time with 22 days. Using the latest start time rule in combination with a shorter planning horizon decreases the average surgery access time. However, a shorter planning horizon contains less OR sessions, and using the latest start time rule increases the chance that available OR time in the near future remains unused. Less available OR sessions and more unused OR time, increase the risk that patients could not be scheduled within the planning horizon. Therefore the latest start time rule should be combined with a scheduling rule that takes the surgery access time into account, in order to avoid that OR time remains unused.

Combining the latest start time rule with the RM based rule results in an average surgery access time of 41 days and an average scheduled gross OR utilization of 87.2%. Compared to the current performance, the surgery access time increases with 8 days and the average scheduled gross OR utilization increases with 1.7%.

Table 32 shows the performance of the RM based rule in combination with the latest start time rule, when two different planning horizons are used.

Planning horizon	Average scheduled gross OR utilization	Average surgery access time in days	Average percentage of patients that could not be scheduled within the planning horizon
1-6 weeks	84.5%	26	4.8%
1-10 weeks	87.2%	41	1.4%

Table 24: performance of RM based rule in combination with latest start time rule, when using different planning horizons.

Using a shorter planning horizon significantly decreases the average surgery access time in days, but this is at the expense of the average scheduled gross OR utilization. The percentage of patients that could not be scheduled within the planning horizon increases as well, which indicates that a planning horizon of 1-6 weeks does not contain a sufficient amount of OR sessions. This applies in particular to specialists with high surgery access times. To make sure that each specialist meets the access time target, the planning horizon should be chosen such that the maximum possible surgery access time is within the access time target.

To increase the average scheduled gross OR utilization, less appointment flexibility could be offered to the patient. The difference in average scheduled gross OR utilization between an appointment flexibility of 1 choice and an appointment flexibility of 4 choices is 4.5%. The difference in average surgery access time is only 1 day. Adjusting the appointment flexibility has the same influence on all specialists.

We conclude that combining the latest start time rule and the RM based rule results in an improved average scheduled gross OR utilization, compared to the current performance. To make sure that all specialists meet the access time target, the planning horizon should be chosen such that the maximum possible surgery access time is within the access time target. A high percentage of patients that could not be scheduled within the planning horizon indicates that the number of OR sessions within the planning horizon has to be increased. Offering less appointment flexibility increases the average scheduled gross OR utilization, but is at the expense of customer service.

6.2 Robustness of intervention

Using a combination of the RM based rule and the latest start time rule, and using a planning horizon of 1-6 weeks and an appointment flexibility of 2 choices, has proven to be robust against changes in the arrival process at the OR planning department. The average surgery access time in days deviates 1 day at most and the average scheduled gross OR utilization deviates 0.2% at most.

7 Discussion and recommendations

In this chapter we discuss the results and we describe our recommendations to the management of Bergman Clinics. We also do some recommendations on future research. Section 7.1 discusses the results and Section 7.2 contains the recommendations.

7.1 Discussion

Patient preferences

In our simulation model, patients get a choice with regard to their surgery date. Since the real patient preferences are unknown, we did assumptions on this. In our model, 85% of the patients request a surgery date as soon as possible. The other 15% is scheduled on a random day within the planning horizon. In reality, it is possible that patients want, or need, to wait longer than the planning horizon. The part of the patients that request a surgery date as soon as possible, are offered 3 surgery dates, and all are chosen with the same chance. It could be that in reality, the majority of the patients want the first possible surgery date. These patient preferences influence the average surgery access time and the percentage of patients that could not be scheduled within the planning horizon. If more patients want to postpone their surgery, and/or part of the patients want to postpone their surgery outside the planning horizon, the surgery access time for patients that want a surgery date as soon as possible decreases.

Surgery access time

The KPI we used to assess the surgery access time, calculates the difference between the date that the surgery is scheduled and the actual surgery date. However, some patients need to return to the screening and OR planning department, after they have visited the outpatient clinic. The time between the outpatient clinic appointment and the appointment at the OR planning department is waiting time as well, but is not taken into account by this KPI. Therefore, the surgery access time could be slightly underestimated. We expect that this only applies to specialists with high surgery access times, i.e. specialist 1 and specialist 3, as patients of these specialists are asked to return for the screening and planning appointment. Patients that request a return appointment choose to wait longer for their surgery, so the extra waiting time should not be taken into account anyway.

Resource restrictions

Some specialists that are not included in the model, have influence on the resource restrictions that have to be taken into account. This applies in particular to clinic A, as more general resource restrictions exist in clinic A. Therefore, it is possible that our model schedules more surgeries on a day than what is possible in reality.

Appointment flexibility

The appointment flexibility determines the number of surgery dates the patient can choose from. We assumed that each of the offered surgery dates is chosen with the same chance. It could be that in reality, the majority of the patients choose the first available surgery date, so the simulation model overestimates the average surgery access time.

Average scheduled gross OR utilization

In our simulation model, we did not take into account the occurrence of cancellations requested by patients, as this barely happens. However, utilization rates are possibly a little lower due to cancellations. However, the patients who could not be scheduled within the planning horizon are never scheduled again, so this possibly decreases the average scheduled gross OR utilization unjustly.

7.2 Recommendations

Surgery scheduling approach

It is a strategic choice whether to choose for increasing the average scheduled gross OR utilization or decreasing the average surgery access time.

To increase the average scheduled gross OR utilization, the planning horizon has to be broadened. However, this is at the expense of the average surgery access time. We expect that Bergman Clinics wants to achieve their access time target, as they are promoting with their low access times. Therefore, a planning horizon should be used in which the highest possible surgery access time is within the access time target. As the access time target defined by the management of Bergman Clinics is 6 weeks, a planning horizon of 1-6 weeks should be used. Close attention should be payed to the percentage of patients that could not be scheduled within the planning horizon. A high percentage indicates that the number of OR sessions within the planning horizon is not sufficient to treat all patients within the planning horizon. To lower this percentage, the number of OR sessions within the planning horizon has to be increased.

To increase the average scheduled gross OR utilization, a scheduling rule that improves the efficiency of the OR schedule must be used. The latest start time rule has proven that it uses available OR time efficiently as it minimizes the number of required OR sessions. However, only using the latest start time rule has the consequence that the average surgery access time increases, the amount of unused OR time increases and therefore the percentage of patients that could not be scheduled within the planning horizon increases. To avoid that available OR time is not used and surgery access times remain acceptable, the latest start time rule should be used in combination with another rule that prioritizes OR sessions based on surgery access time. The RM based rule is the only rule that takes the surgery access time into account. Therefore, the latest start time rule should be combined with the RM based rule.

A decrease in appointment flexibility can increase the average scheduled gross OR utilization, but the customer service that is offered to the patients will be worse. It is a strategic choice whether to choose for high customer service but lower OR utilization, or to choose for less customer service but higher OR utilization. We expect that Bergman Clinics value OR utilization and customer service equally, so we advise an appointment flexibility of 2 choices as this gives patients the possibility to choose but it also achieves high average scheduled gross OR utilizations.

Patient process

We recommend to structure the patient process from the outpatient clinic to the screening and OR planning department. This process is unclear which makes it hard to predict when patients arrive at the OR planning department. Structuring this process could improve the quality of conclusions with regard to the optimal surgery scheduling approach. Moreover, the process could be structured in a way that improves the performance of the OR planning department.

Future research

During this research we have focused on scheduled OR utilization. The data analysis has shown that the scheduled OR utilization and the realized OR utilization are quite similar. However, differences always exist and every increase in OR utilization have impact on the revenues. Therefore, further research could address minimizing the difference between scheduled OR utilization and realized OR utilization. To efficiently use OR time, the sequence of surgeries is also of importance. Therefore it might be interesting to investigate how to optimize the sequence of surgeries.

Another research that might be interesting, is to investigate to what extent patients value the face to face appointment with OR planners to plan their surgery. The current process of scheduling surgeries, involves sequentially adding surgeries to OR sessions. Batching surgeries before assigning them to an OR session probably increases the average scheduled gross utilization.

To increase the average scheduled gross utilization and decrease surgery access times, it is possibly beneficial to adjust the opening hours of the OR. Especially for specialists that perform many surgeries with a high surgery duration, a lot of available OR time remains unused as the remaining OR time is just not sufficient to schedule another surgery. Future research could investigate if adjusting the opening hours of the OR has a positive influence on the scheduled OR utilization and the surgery access times.

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Appendix A – Conversions

Specialist	Outpatient clinic visits	Number of surgeries	Conversion
1	1426	568	0.40
2	2058	602	0.29
3	996	424	0.43
4	1218	248	0.20

Table 1: number of performed outpatient clinic visits and number of performed surgeries and resulting conversion per specialist (HiX)

Appendix B – Remaining time intervals

Interval Lower bound (min)	Interval Upper bound (min)	Frequency surgery duration	Priority
0	5	-	4
37	42	216	3
76	79	159	2
101	105	125	1

Table 1: defined remaining time intervals with regard to specialist 1

Interval Lower bound (min)	Interval Upper bound (min)	Frequency surgery duration	Priority
0	5	-	5
47	52	301	4
56	61	201	3
73	78	37	1
88	93	52	2

Table 2: defined remaining time intervals with regard to specialist 2

Interval Lower bound (min)	Interval Upper bound (min)	Frequency surgery duration	Priority
0	5	-	3
92	97	301	2
98	103	82	1

Table 3: defined remaining time intervals with regard to specialist 3

Interval Lower bound (min)	Interval Upper bound (min)	Frequency surgery duration	Priority
0	5	-	4
43	50	93	2
53	58	27	1
86	91	110	3

Table 4: defined remaining time intervals with regard to specialist 4

Appendix C: Control panel simulation model

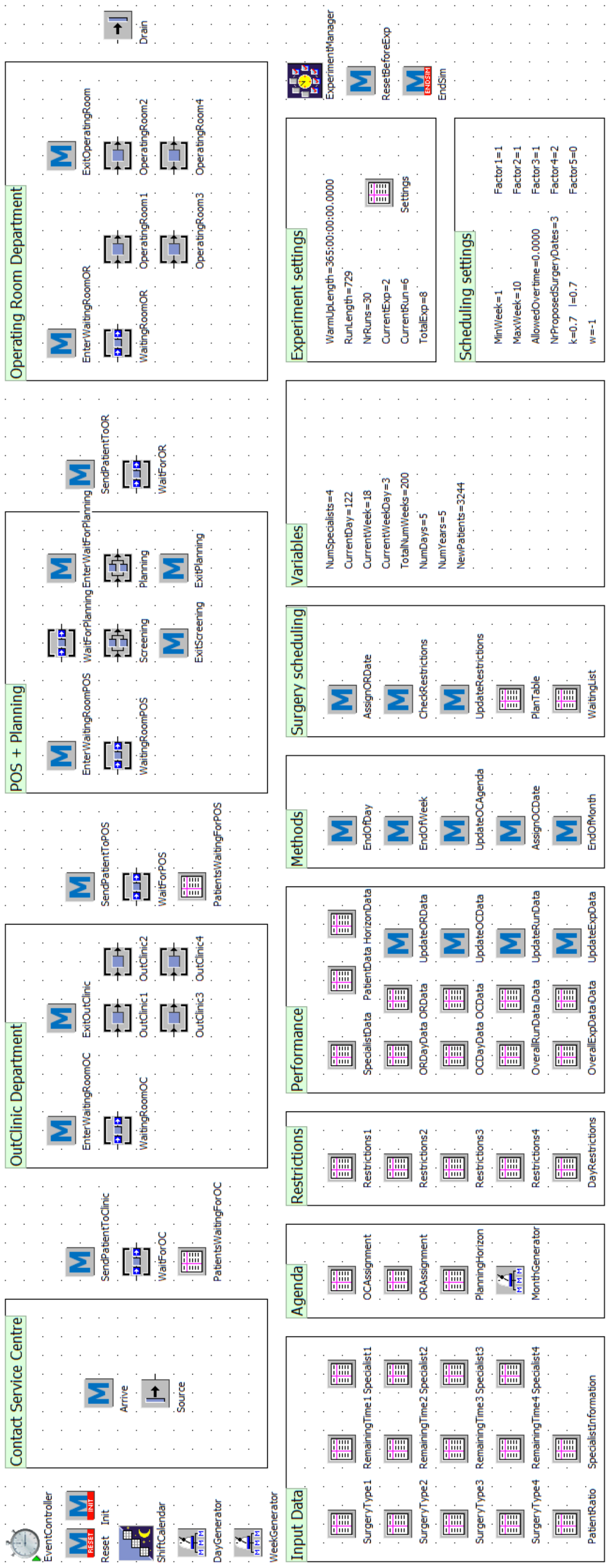

Figure 1: control panel of simulation model

Appendix D: Simulation outcomes surgery scheduling approach

ExpNr	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	PerformedSurgeries	PerformedSurgerySeconds	NrUsedORSessions
Current	85.47%	2.70%	16.38%	53.30%	7.56%	33:07:50:43.0778	0.84%	1801	7368101	359
1.1	85.39%	2.38%	15.37%	48.45%	6.42%	34:01:25:23.6075	0.75%	1808	7383910	360
1.2	88.68%	2.02%	14.09%	62.42%	3.61%	55:09:51:26.5098	3.84%	1777	7212604	342
1.3	81.80%	2.35%	15.31%	36.62%	8.64%	62:00:40:49.9582	4.89%	1754	7091598	356
1.4	87.20%	2.28%	15.06%	57.40%	5.14%	41:06:09:50.0740	1.43%	1805	7368983	354

ExpNr	Specialist	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	NrUsedORSessions	PerformedSurgeries	PerformedSurgerySeconds
Current	1	94.44%	3.91%	13.67%	89.66%	0.57%	45:01:24:49.0333	1.54%	99	555	2196692
Current	2	87.52%	1.10%	9.99%	66.09%	8.11%	20:22:40:02.8000	0.00%	92	596	1946058
Current	3	84.78%	0.31%	5.06%	25.19%	0.32%	42:08:41:28.7000	1.48%	104	416	2260793
Current	4	69.75%	1.31%	9.89%	24.09%	29.32%	19:22:05:13.7000	0.00%	63	232	964556
1.1	1	94.66%	2.38%	11.52%	90.51%	0.67%	43:12:39:03.2667	1.50%	99	558	2198016
1.1	2	87.51%	1.18%	10.48%	50.72%	5.38%	24:10:38:47.8333	0.00%	93	597	1954341
1.1	3	84.80%	0.60%	6.08%	25.55%	0.45%	41:16:46:03.3333	1.18%	103	416	2260386
1.1	4	68.96%	0.80%	7.65%	17.33%	26.51%	21:19:18:49.8000	0.00%	64	236	971165
1.2	1	93.75%	3.24%	10.80%	89.83%	1.65%	58:11:41:43.0667	5.32%	97	545	2130065
1.2	2	92.14%	2.28%	9.35%	82.72%	2.84%	53:12:34:05.7333	1.02%	88	598	1951991
1.2	3	84.68%	0.62%	7.35%	28.49%	1.51%	57:15:32:35.2000	7.47%	99	398	2159544
1.2	4	81.65%	0.53%	6.56%	43.38%	11.82%	49:05:59:57.8333	0.52%	56	235	971003
1.3	1	89.13%	0.90%	8.13%	59.46%	1.92%	63:09:32:46.4333	6.54%	99	537	2074755
1.3	2	85.28%	1.72%	12.31%	45.34%	3.48%	63:01:51:11.1667	1.97%	93	585	1906557
1.3	3	80.31%	0.50%	4.80%	20.27%	6.98%	61:20:05:37.5667	8.69%	103	397	2150843
1.3	4	67.10%	0.80%	7.04%	14.04%	30.33%	56:14:25:26.6667	0.96%	60	234	959442
1.4	1	94.68%	4.32%	13.75%	91.10%	0.68%	50:10:31:52.2333	2.57%	98	559	2195085
1.4	2	89.21%	0.87%	8.80%	72.74%	6.91%	33:11:50:01.3667	0.01%	90	591	1926218
1.4	3	84.94%	0.49%	6.56%	26.68%	0.35%	46:04:17:58.1333	2.52%	103	417	2263186
1.4	4	75.94%	2.50%	11.31%	32.37%	17.93%	30:02:31:13.9667	0.00%	61	238	984493

Appendix E: Simulation outcomes planning horizon

ExpNr	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	PerformedSurgeries	PerformedSurgerySeconds	NrUsedORSessions
2.1	82.80%	4.00%	19.95%	48.09%	10.68%	21:12:01:50.7305	13.46%	1596	6460958	330
2.2	86.32%	2.76%	16.58%	55.88%	6.18%	32:09:21:15.8933	8.44%	1685	6833168	334
2.3	87.83%	2.31%	15.16%	60.51%	4.62%	42:03:29:45.3632	6.35%	1728	7012153	336

ExpNr	Specialist	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	NrUsedORSessions	PerformedSurgeries	PerformedSurgerySeconds
2.1	1	88.37%	3.96%	15.35%	74.72%	7.83%	22:02:41:35.5333	18.05%	90	473	1836559
2.1	2	87.01%	1.52%	11.81%	69.46%	9.01%	21:06:45:51.4667	7.97%	86	551	1795078
2.1	3	80.71%	0.58%	5.52%	18.33%	5.93%	22:09:39:21.0667	15.92%	96	364	1983160
2.1	4	71.28%	1.33%	10.75%	24.13%	25.56%	19:01:34:38.9667	11.40%	57	206	846160
2.2	1	91.32%	0.85%	8.61%	83.38%	4.04%	33:08:57:25.2667	13.27%	92	501	1954669
2.2	2	90.00%	0.94%	9.24%	77.11%	5.36%	32:08:06:17.0667	3.55%	87	576	1874192
2.2	3	82.96%	1.01%	7.47%	23.54%	3.23%	33:08:01:26.0667	10.46%	98	386	2093605
2.2	4	78.33%	3.15%	11.39%	34.70%	16.15%	28:14:12:05.0667	5.04%	56	221	910701
2.3	1	92.80%	4.06%	12.15%	87.27%	2.63%	43:00:06:59.7667	9.57%	95	527	2057202
2.3	2	91.34%	0.71%	7.91%	80.30%	3.72%	41:10:57:56.7000	3.03%	86	580	1892648
2.3	3	83.90%	0.54%	6.97%	27.34%	2.62%	43:17:35:27.7000	8.88%	99	391	2121374
2.3	4	80.83%	4.65%	13.57%	42.88%	12.98%	39:04:53:11.8333	1.84%	55	228	940928

Appendix F: Simulation outcomes appointment flexibility

ExpNr	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	PerformedSurgeries	PerformedSurgerySecon	NrUsedORSessions
Current	84.54%	3.03%	17.38%	50.36%	8.18%	26:02:08:27.3325	4.78%	1758	7151061	354
3.1	87.45%	2.20%	14.78%	56.53%	4.02%	26:10:24:39.0220	3.87%	1775	7230442	346
3.2	85.98%	2.64%	16.21%	53.38%	6.25%	26:04:55:25.2265	4.07%	1771	7208034	351
3.3	82.86%	3.43%	18.50%	45.18%	10.28%	26:01:21:46.1988	6.12%	1734	7050246	356

ExpNr	Specialist	AverageGrossUtilization	Variance	Stdv	AvgPercentageDaysUtilization90	AvgPercentageDaysUtilization60	AverageORAccessTime	PercentageNotScheduled	NrUsedORSessions	PerformedSurgeries	PerformedSurgerySeconds
Current	1	90.87%	2.41%	11.53%	80.06%	4.87%	27:22:52:58.8000	8.66%	97	527	2060086
Current	2	88.11%	1.43%	11.68%	67.30%	7.46%	24:09:16:11.0000	1.01%	92	595	1939742
Current	3	83.48%	0.56%	6.42%	22.68%	2.20%	28:12:42:00.9667	5.96%	103	407	2212462
Current	4	71.15%	2.38%	12.31%	24.90%	24.39%	21:20:14:40.1333	2.47%	62	227	938770
3.1	1	92.99%	1.60%	9.43%	88.84%	2.78%	29:04:04:57.4000	8.06%	95	530	2077268
3.1	2	91.37%	0.74%	8.08%	72.08%	3.49%	25:04:47:00.7667	0.45%	89	600	1955507
3.1	3	85.14%	0.53%	6.95%	28.70%	0.56%	28:09:42:05.8333	4.57%	102	413	2239008
3.1	4	76.47%	0.89%	8.81%	28.81%	12.92%	19:16:57:16.7667	0.78%	58	232	958657
3.2	1	92.11%	2.89%	11.07%	84.63%	3.31%	28:11:25:59.5333	8.05%	96	531	2079068
3.2	2	89.38%	1.06%	9.74%	68.80%	6.11%	24:11:37:15.0333	0.59%	91	598	1949115
3.2	3	84.51%	0.59%	6.76%	26.39%	1.17%	28:14:40:21.2333	4.93%	103	411	2230801
3.2	4	73.59%	1.64%	10.30%	26.19%	19.78%	21:01:37:02.1000	1.34%	60	230	949049
3.3	1	89.23%	2.90%	14.22%	73.98%	6.20%	27:10:42:12.0333	9.70%	97	521	2035580
3.3	2	86.88%	1.70%	12.64%	63.22%	8.94%	24:15:58:27.6333	1.78%	92	591	1922515
3.3	3	82.09%	0.38%	4.24%	17.39%	3.71%	28:03:17:04.4667	7.87%	103	399	2178756
3.3	4	68.32%	4.02%	16.67%	19.61%	29.42%	22:17:23:56.9333	4.91%	62	222	913393