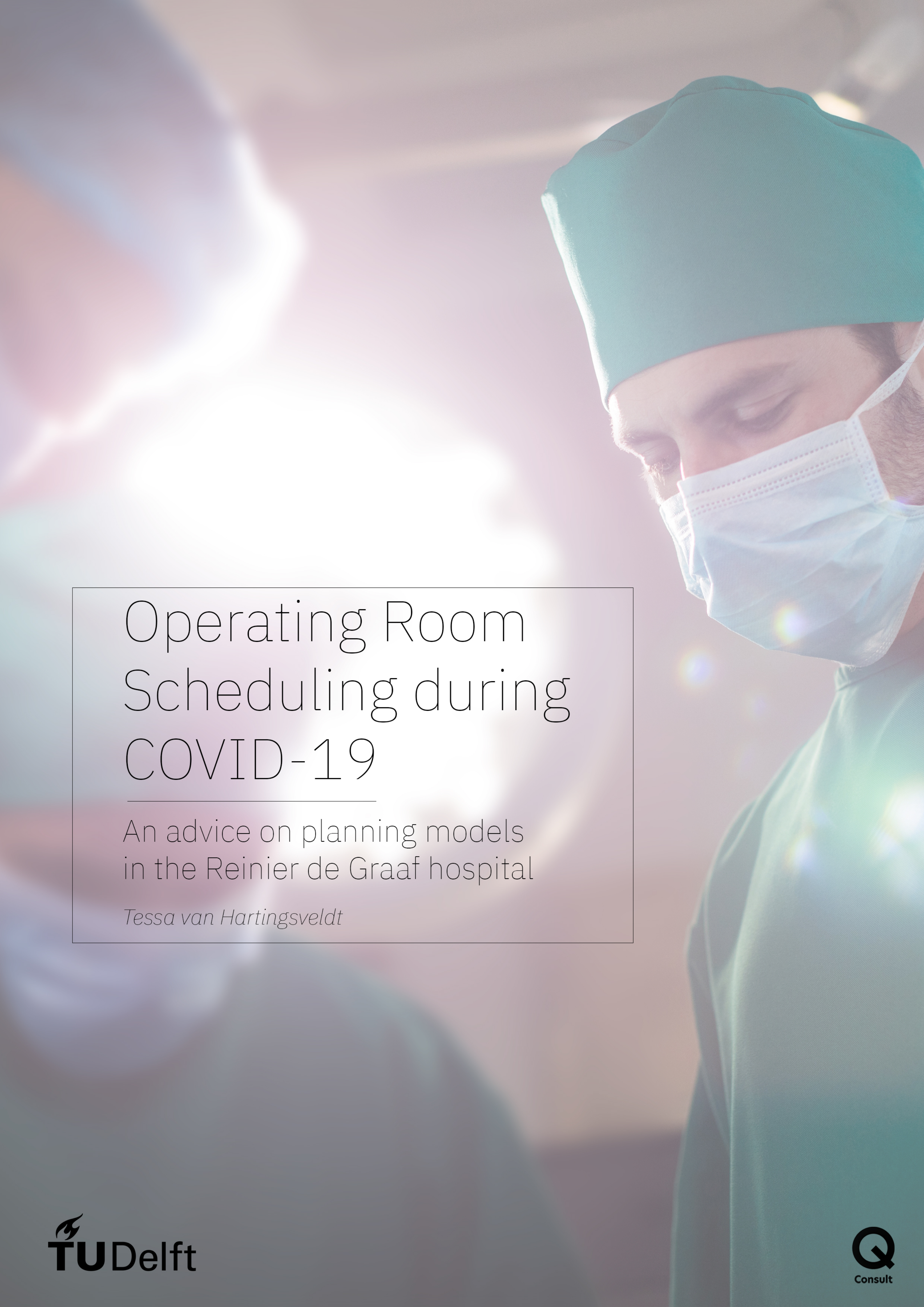

# Operating Room Scheduling during COVID-19

## An advice on planning models in the Reinier de Graaf hospital

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Q Consult

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday January 12, 2021 at 11:00 AM.

| | | |
|---|---|---|
| Student number: | 4279905 | |
| Project duration: | April 23, 2020 – December 18, 2020 | |
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# Summary


This thesis report is written to obtain the masters degree of Biomedical Engineering from the Delft University of Technology. The presented research was conducted in the Reinier de Graaf Gasthuis in Delft, under guidance of Q-Consult.

To make room for COVID-19 patients, hospitals had to scale down their elective care all over the hospital, including in the operating room (OR). The same happened in the Reinier de Graaf hospital during the first COVID-19 wave. During this first wave, they scaled their surgeries down to only acute and semi-acute. In future downscaling, it might not be necessary to scale down as much. However, it is hard to define how much the OR should downscale. Also, there are no national plans on how hospitals should downscale and prioritize their waiting lists. When the COVID-19 situation suddenly changes, there is only a little time to change the OR schedule. Making a new OR schedule with only a little time and lots of extra COVID-19 related variables can be challenging. Plannings are made for only one day ahead because making the new schedule is so time consuming, making it hard for certain specialisms to find patients willing to undergo surgery. A planning model can help the planning department in making an OR planning while keeping the COVID-19 related variables into account and while planning further than one day ahead. The goal of this research is to give an advice to the Reinier de Graaf hospital on what type of planning models are best suited for last minute COVID-19 planning.

To give this advice, first the OR planning during the first COVID-19 wave is analyzed with the help of data-analysis and interviews. The OR planning during the COVID-19 crisis of the first half of 2020 performed well. Acute and semi-acute surgeries were still performed, the outflow towards the ICU and ward was lower than normal, and the number of occupied beds in the ICU and wards by surgical patients was lower. However, there were also some points of improvement, the outflow towards the ICU and ward and the number of occupied beds by surgical patients in the two was not kept constant, also the utilization was lower during the COVID-19 wave, compared to the year before.

To help the Reinier de Graaf hospital in making an even better OR planning during COVID-19, in an easier manner, different existing OR planning models were analyzed. Those were checked to see if they contained parts that complied with COVID-19 demands for an OR planning. Those parts are humanitarian goals, leveling, patient deferral, utilization, waiting time, and constraints. Also the patient levels used, solution techniques and incorporated uncertainty were checked. Next an interview with the Reinier de Graaf hospital was held to see which aspects were most applicable to the Reinier de Graaf. This resulted in an advice of what aspects the Reinier de Graaf should incorporate in their OR planning during COVID-19:

The RdGG should make a planning model in which they plan patients without the use of a MSS. The optimization should be done with weighted goal optimization to plan elective and semi-acute patients. The outflow towards the ICU and the ward should not exceed a certain threshold and might have to be leveled more. Over- and undertime should be minimized. And lastly, multiple constraints should be added, including the availability of ORs, OR time, surgeons, patients, and equipment. There were no patient priority methods found in the articles that would apply to the Reinier de Graaf, therefore a new one was made.

In the Reinier de Graaf hospital patient priority is not included in regular planning. Patients from the top of the waiting list are planned first and new patients enter the bottom of the waiting list. During the first COVID-19 wave all specialists got together to prioritize all urgent patients. This was possible because the specialists had to cancel all their elective care. During new COVID-19 waves, elective care will not be canceled as much, so specialists will not have time to do this. Therefore a new method of prioritizing patients in with a model has been developed. This method prioritizes patients based on their urgency (based on the NZA priority list [16]) and on their waiting time. This article's method is compared to the existing method found in the article of Ozkarahan [18]. The article's method of prioritizing patients outperforms the existing method in terms of planning patients that are more urgent and in utilization.

To conclude, using a OR planning model can be helpful for the RdGG to assist their planning process. The model can help plan patients based on their priority, while keeping the outflow below the threshold and leveled, and while keeping a high utilization of the OR. This will give the planning staff more time to plan patients further ahead and give them a better overview of how many ORs to open, if the maximum outflow is reached, and on the usage of appliances.

# Contents

# Acknowledgments

Before you lies the report of my thesis, "Operation Room Scheduling during COVID-19: An advice on planning models in the Reinier de Graaf hospital." This thesis is the final element required to obtain my master's degree in Biomedical Engineering at the Delft University of Technology. The presented research was conducted in the Reinier de Graaf Gasthuis in Delft, under the guidance of Q-Consult. I was engaged in researching and writing this dissertation from the end of April 2019 to mid-January 2020.

Foremost I would like to thank my supervisors at Q-Consult, Lotte Wang and Kim Rietjens, who have helped me throughout the research. On a weekly basis, we discussed the problems I came across or had brainstorm sessions on what to do next. I am grateful for their enthusiasm, motivation, and understanding, which helped me enormously throughout this project, and for their patience while proof-reading this report. Besides Lotte and Kim, I would also like to thank my other colleagues of Q-Consult. They helped me find a thesis project on such short notice and assisted when needed.

Next, I would like to thank John van den Dobbelsteen for his help on the academic matter. He helped me shape this research into a thesis worthy of graduating the TU Delft and made sure this research stayed focused instead of becoming too broad.

Lastly, I would like to thank the Reinier de Graaf hospital for all their help. Without the time spent by many to perform the interviews and without their surgical data, this research would not have been possible. Especially I would like to thank Karin Trommelen for introducing me to everyone, for thinking along, and for freeing up so much time while being buried in work due to COVID-19.

Thank you all!

*T. van Hartingsveldt*
*Amsterdam, December 18, 2020*

# Nomenclature

ICU - Intensive Care Unit
MSS - Master Surgical Schedule
OR - Operating Room
PACU - Post Anesthetic Care Unit
RdGG - Reinier de Graaf Gasthuis
WHO - World Health Organization

# 1
# Introduction

## 1.1. The spread of COVID-19

In September 2019, the Global Preparedness Monitoring Board - an independent group of 15 experts gathered by the World Health Organization (WHO) and the World Bank after the first Ebola crisis - presented their first annual report. In this report, they described that a pandemic spreading around the world, taking the lives of tens of millions of people, was a real threat. The climate crisis, urbanization, and a lack of adequate sanitation and water, all contribute to the increased chances of fast-spreading, catastrophic outbreaks. However, governments' preparations were "grossly insufficient."[12]

Unfortunately, at the end of 2019, part of this prediction became a reality. In December 2019, in Wuhan, there was an epidemic of cases with unexplained low respiratory functions. This disease was quickly identified as a novel coronavirus and therefore called SARS-CoV-2 or coronavirus disease 2019 (COVID-19). On the 11th of March, this disease was officially called a pandemic by the World Health Organization.

Since the start of COVID-19, there have been over 75 million cases and nearly 1.7 million deaths (situation on 18/12/2020 [31]), with more infections happening daily. Even though the case-fatality rate (proportion of people that die of people diagnosed with the disease) is ≤3%, which is relatively low compared to Severe Acute Respiratory Syndrome (SARS) (30%), the transmission rate (number of newly infected people per infected person) of 2.5 – 3 is high, and this is what causes the danger of this pandemic. For comparison, a regular cold transmission rate is less than 1.4 Dömling and Gao [9].

The symptoms of COVID-19 vary from asymptomatic to respiratory failure that necessitates mechanical ventilation and support in an intensive care unit (ICU) to multiorgan failure or death. Common symptoms are fever, malaise, a dry cough, and dyspnea. Some patients also present gastrointestinal, cardiovascular, or neurological manifestations [4].

## 1.2. COVID-19 in Dutch hospitals

During the COVID-19 wave in spring 2020, many patients presented themselves at the hospital with severe symptoms. Isolated rooms and special COVID-19 departments were created to care for those patients [8, 28, 30]. As many severe COVID-19 patients present lung failure, lots of respiration equipment had to be located. The respiration equipment from the ICU department could not handle the demand, and therefore respirators were taken out of the operating room (OR), among other places. Those OR respirators are different from the ones in the ICU and therefore have to be operated by anesthetic personnel [17]. Because the upcoming dimension and effect of the COVID-19 was not yet know, the hospitals made their plans assuming the worst. They canceled nearly all their elective care to free up their resources like personnel, beds, medicine, and equipment for potentially infected patients [19].

## 1.3. COVID-19 in the operating room

As the hospital scaled down their elective care, they also scaled-down elective surgeries in the operating room (OR). Those elective surgeries were also canceled to transfer respirators and anesthetic personnel to the ICU, as explained in Section 1.2. Only acute and oncological surgeries were performed, which lead to a significant reduction of ORs in use.

Looking back at this moment, the downscaling was done because the disease's extent was yet unknown. However, in the next wave of COVID-19, it might not be necessary to scale down all elective care. It might be possible to perform more surgeries without opposing a higher risk on those patients or COVID-19 patients. Performing more surgeries is better for the patients on the waiting list, as their symptoms might worsen while waiting for surgery and because they experience the discomfort of their symptoms. For the hospital, it is also good to perform surgery as high usage of the OR is extremely important in meeting the increasing demand for health care services and reducing the costs to improve quality of care [18]. However, it is hard to decide how much the hospital should downscale to provide proper care for COVID-19 patients without downscaling too much.

While there was a national plan on upscaling the elective care after the last COVID-19 wave [15], there are no national plans on downscaling the elective care in a new COVID-19 wave. Hospitals have made agreements to spread the COVID-19 patients around the hospitals, but even that seems to happen only a little [24]. When a new COVID-19 wave hits, there is little time to make choices about downscaling elective surgeries, so the planning of the OR has to happen last minute. Making a satisfactory new OR planning while taking all COVID-19 related variables into account can be challenging. During a COVID-19 wave, the hospital's planning can change quickly. If planners have to focus on filling the next day with patients, it is hard for them to plan slightly ahead. This can result in open spaces for specific specialisms. For example, in jaw surgery, patients like to plan ahead and are less likely to agree to surgery the next day. Planning slightly ahead might solve this problem. A planning model can help assist in this process.

## 1.4. COVID-19 in the Reinier de Graaf hospital

This research focuses on the Reinier de Graaf hospital (RdGG) in Delft. The hospital has around 500 beds, which makes it a medium-sized hospital in the Netherlands. The RdGG is a top clinical hospital, focusing on the elderly, oncology, and mother and child care. The hospital is situated in the province of South Holland; therefore, it was not in the Dutch hotspot of the COVID-19 wave of spring 2020. Shortly before COVID-19, the hospital had bought new respiratory devices for the OR, and the old ones had not yet been disposed of. Therefore when the COVID-19 infections started to rise, there was more capacity for respiratory spots. The RdGG quickly downscaled its elective care and made room for lots of COVID-19 patients. However, as the hospital was not situated in the COVID-19 hotspot, the surrounding hospitals had only a small number of COVID-19 patients, as most of them were in the RdGG.

## 1.5. The current situation of COVID-19

Due to an intelligent lockdown in summer, the number of COVID-19 patients had dropped significantly, and only small and local infections were seen. After the summer, the number of infected people started to rise. Currently, the Netherlands is in a second COVID-19 wave. The number of hospital admissions for COVID-19 patients is not as high as in March (maximum of 382 and 557, respectively)[3]. Although hospitals have been preparing for a second COVID-19 wave by locating additional respiratory devices, the elective care still had to be downscaled [24].

## 1.6. Operating room planning in the Reinier de Graaf hospital

The RdGG sees a patient for the first time when it comes to the specialist. The specialist then decides if the patient should undergo surgery; if so, the patient is added to the waiting list. The planning department then checks the schedule for availability and calls the patient to schedule a surgery. The planning department of the RdGG starts planning the patients that are on the waiting list for the most extended period and does not take their urgency into account. The goal is to plan this patient within five weeks; however, this is rarely feasible in reality.

Acute care, care that should be given within 24 hours, skips the planning department and is planned by the OR. Semi-acute care, care that should be given within one week, is planned by the scheduling department. To fit in such patients, they see if there is already room; if not, they will postpone patients that were already planned. If a specialist sees a patient who has to undergo surgery quickly but not within one week, they will call the planning department to ensure that this patient is planned first. Patients are planned based on a master surgical schedule (MSS), a block schedule with the different specialisms in which the surgeries are fitted.

Twice a week, there is a meeting with the planning department and the OR to see if there are enough resources to perform the planned surgeries. Based on this meeting, additional changes can be made to the planning.

During the first COVID-19 wave, all elective care was downscaled, and only acute and semi-acute surgeries were performed. During this period, the specialists worked together to make one list in which the patients were sorted based on their urgency. The planning department then planned the patients starting from the top of the list and working their way down. When elective care was upscaled, elective patients were added to this list to ensure that the most urgent patients were planned first.

## 1.7. Existing planning models for the operating room

Throughout this research, the words OR planning and OR scheduling are used interchangeably; sometimes, they are also referred to as just planning or scheduling.

When making an OR planning model, different aspects have to be taken into account. Gur and Eren [13] summarize the different aspects as follows:

- Patient characteristics
  *Which patients to include: e.g., elective or non-elective patient, inpatient or outpatient, urgency, emergency.*
- Performance measures
  *What measures to use in the evaluation of the planning.*
- Decision delineation
  *What type of decision has to be made (date, time, room, and capacity), and does it apply to a medical discipline surgeon or patient.*
- Up- and downstream facilities
  *Whether or not to include other units (e.g., PACU, WARD, and ICU).*
- Uncertainty
  *How to incorporate uncertainty, stochastic, or deterministic.*
- Operations research methodology
  *What program or algorithm to use.*

The planning level can also be added to this list. The planning level is about how the OR planning will be made. For example, it can be an MSS, an allocation of surgical procedures within this MSS, a schedule of surgical procedures without an MSS, or an adjustment to an existing OR schedule. Before making an OR planning model, choices have to be made on the aspects stated above.

### 1.7.1. Performance measures for operating room planning models during COVID-19

Prior to this research, literature research has been done to find which performance measures should be used for operating room planning models during COVID-19. This literature research also yielded a list of model inputs and rules that should apply to an OR planning model during COVID-19. A summary of the literature research can be found in Appendix A.1, and the research will be referred to as Van Hartingsveldt [26].

The performance measures that are important for an OR planning model during COVID-19 are:

- Humanitarian goals
- Leveling
- Patient deferral
- Utilization
- Waiting time
- Other
  - Medicinal stock

  - Personal protective equipment (PPE) stock

**Humanitarian goals** is about saving as many lives as possible. When planning, starting with the most urgent surgery and postponing less urgent ones can save lives. This choice in who should undergo treatment first is called triage. If the OR has to be downscaled, there is less capacity for surgeries. Therefore it might be necessary to use triage. Prioritizing patients can be done based on the priority list by the NZA [16] in cooperation with specialists. Acute care should still be performed, even if the OR is downscaled. The RdGG chose to make oncological surgeries a high priority as well. If a patient belongs to the risk group and has to undergo elective surgery, the doctor can decide to postpone it.

**Leveling** is about keeping the outflow of the OR constant. During COVID-19, more capacity is needed in the ICU and new COVID-19 departments are created. Therefore there is less capacity for regular ICU patients. There is also less capacity in the wards as both beds and nurses might be redistributed to the COVID-19 departments and the ICU. Therefore the number of patients going from the OR to both the ICU and ward should be lower than usual.

**Patient deferral** usually happens when an urgent patient arrives, and an elective patient has to make room for this patient. If the OR is downscaled, there is less flexibility to do emergency surgeries in between as there are fewer rooms available. Therefore an emergency OR can be necessary when the OR is downscaled.

**Utilization** refers to the utilization of the OR, so how efficiently the OR is being used. In this way, as many patients as possible can undergo surgery. For example, this can be done by including streets of surgeries like groin ruptures in the planning.

**Waiting time** also refers to which patient should undergo surgery first, the so-called triage. Because certain patients should undergo surgery within a specific time frame, optimizing the waiting time, based on priority, is one way to add triage to the model.

**Other** performance measures are also essential to keep in mind, focusing on the stock of both medicine and PPE. In the ICU, propofol is used to keep infected patients that are on mechanical ventilation asleep. Propofol is also used in the OR to keep patients asleep. Therefore, the amount of propofol should be monitored to see if there might arise problems in the stock amount.
PPE is used to protect both the workforce and the patients. When working with infected patients, extra PPE is needed. Without PPE, surgeries cannot be performed safely. Therefore, the amount of PPE should be monitored to see if there might arise problems in the stock amount.

In the literature research, there were also model inputs and rules derived that should be taken into account when making an OR planning model to be used during COVID-19. Those are described below:

- Isolation
  - Isolate infected patients
  - Prevent possible spread
- Treatment
  - Keep a minimum level of ventilation devices
  - Keep a minimum level of medicinal stock
- Decontamination
  - Plan extra time for cleaning and removing appliances
- Scheduling
  - Keep a maximum outflow
  - Plan extra time for surgery of infected patients
  - Realize fewer patients available for surgery
- Staff protection
  - Keep a minimum level of PPE stock

**Isolation** of infected patients is essential. Suspected patients are treated as isolated patients and therefore need to be isolated as well. Preventing the possible spread of the virus is also very important. To do this, one can use a separate COVID-19 OR, which is only used for (suspected) cases. This separate OR also needs its own surgical team. Instead of using a separate OR, one can also decide to thoroughly clean the OR after an infected patient, further described in decontamination. If a separate COVID-19 OR is used, one should also have a separate COVID-19 hallway for infected patients. Infected patients should only undergo surgery if it is very urgent; if not, one should wait for the patient to recover before performing surgery.

**Treatment** can be used as a performance measure, which is described above. Nevertheless, it is also essential to keep an exact minimum of medicine and ventilation devices. This can then be used for the absolute necessary surgeries and patients in the ICU.

**Decontamination** is essential when infected patients have to undergo surgery. Before a non-infected patient goes into the OR, everything has to be thoroughly cleaned. Apart from the regular cleaning activities, the OR has to be cleaned with alcohol as well and after that, the room has to be aired for a set period. Those cleaning activities take approximately 1 hour extra. COVID-19 surgeries are treated with the MRSA+ protocol; therefore, all non-necessary appliances from the OR have to be removed to prevent possible spread. Both those things cost extra time, which has to be included in the planning.

**Scheduling** focuses on multiple things. Keeping the outflow towards the ICU and the ward low is already in the performance measures. However, there is also a clear boundary for a maximum number of patients who can go to those departments; this should be set as a model rule. If surgery is performed on an infected patient, both the induction and the recovery have to be done in the operating room. Those actions cost extra time, approximately 15 minutes for the induction and 1 hour for recovery, which should be included in the planning. Due to limited visits to the clinic and because patients are hesitant to visit a hospital during COVID-19, fewer patients are available for surgery. This gives possible reduced input for the model.

**Staff protection** makes it essential to keep a strict minimum of PPE available. Just like with treatment, this is for acute surgeries and the ICU.

## 1.8. The goal of this research

The goal of this research is to advise the RdGG on what planning model can be used to assist the OR planning process during COVID-19. This leads us to the following research question:
**What planning model should the Reinier de Graaf hospital use to assist the OR planning process during COVID-19?**

To answer this question, multiple things should be investigated, split into three different phases. In the first phase, the planning during the last COVID-19 wave is checked to see if it complies with OR planning demands according to the RdGG and the literature. In the second phase, potential OR planning models are checked for applicability and missing parts. The feasibility of those OR planning models for the hospital is checked together with the hospital. The third phase is the modeling phase; in this phase, components of the model are checked by a proof of principle. This leads us to the following sub-questions:

- **How was the OR planning in the Reinier de Graaf hospital during the COVID-19 crisis of the first half of 2020?**
- **How do potential OR planning models comply with the OR planning demands during COVID-19?**
- **Which planning models are the most feasible for the Reinier de Graaf hospital?**
- **How does a proof of concept of the OR planning model perform?**

All different phases are described in this report. Every phase has its introduction, method, results, and discussion. In the final discussion, all different aspects will be combined to answer the full research question.

# 2

# Part 1: Introduction - Operating room planning in the Reinier de Graaf

Before a recommendation can be made on what OR planning model should be used in the RdGG during a COVID-19 crisis, it will be checked what happened during the first COVID-19 wave in that same hospital. Therefore, this chapter focuses on the subquestion: "How was the OR planning in the Reinier de Graaf hospital during the COVID-19 crisis of the first half of 2020?". An analysis of the previous OR planning during the first COVID-19 wave will be performed. Interviews with experts in the field are held; after that, the OR's planning data is checked.

## 2.1. The experience of experts in the field

To see how the OR planning performed during the fist COVID-19 wave in the RdGG, interviews are held with experts. The focus is on what went well and what things could have gone better during the last COVID-19 wave regarding the OR planning. The details on how these interviews are performed can be found in Appendix A.2. During the interviews, the good points and points of improvement of the OR planning during the last COVID-19 wave were discussed. A summary of all those points is mentioned here.

Isolation of infected patients was done very well, as there was a separate OR for infected patients. Decontamination was correctly done as after surgery of infected patients, the OR was cleaned thoroughly, which takes approximately 1 hour extra. Also, all non-necessary appliances were removed from the OR during COVID-19 surgery to prevent infection via surfaces. In scheduling, multiple things went well. There was a maximum of one OR patient going to the ICU, as the ICU had less available capacity. There was a strict quota for the number of patients going to the ward. The number of patients going to the ward had to be lower as there was less available capacity and also because most of the surgeries were for oncological patients, which usually stay longer in the ward. With the new schedule, there were no surgeries canceled. Lastly, patient priority was kept into account. All surgeries that needed to happen immediately or quickly were done within time. To make sure this could happen, the surgeons made a list together in order of which patients should undergo surgery first, partly based on the NZA priority list [16].

The interviewees also mentioned some points that can use improvement. The main thing that nearly every interviewee mentioned was that the OR was scaled down too quickly. During the first wave, without knowing what was going to happen, this was an understandable choice. However, in the next COVID-19 wave, this is not necessary. Less downscaling results in more time to help patients. Also, during the first COVID-19 wave, the OR's respiratory devices had to go to the ICU for COVID-19 patients. As only anesthetic personnel knew how to operate those devices, they had to go there as well. The leave of anesthetic personnel is not beneficial to the OR. Luckily, there are more respiratory devices, so it is unnecessary to transfer anesthetic personnel during a new COVID-19 wave. Lastly, OR personnel was rescheduled to the emergency department among other departments; this is not beneficial for the OR and should therefore be prevented during a next COVID-19 wave.

## 2.2. Data analysis

To see how the OR planning during COVID-19 performed in the RdGG, a data-analysis is done. This data analysis should give insights into the planning during COVID-19 compared to regular times.

### 2.2.1. Goal of analysis

The Reinier de Graaf hospital's planning data is unavailable for the researcher; therefore, the performed surgeries will be analyzed. Those performed surgeries are based on the planning schedule and will therefore give a realistic representation of the planning. The comparison of before and during COVID-19 will focus on what is thought to be relevant in literature and by experts, as can be found in Sections A.1 and 2.1. This leads us to the following questions to be answered with data analysis:

Patient priority:

- Are acute and semi-acute surgeries still performed when the capacity is lower?

Leveling:

- Is the outflow towards the ICU and the ward lower during COVID-19?
- Is the outflow towards the ICU and the ward kept constant?
- Is the number of occupied beds for patients coming from surgery in the ICU and the ward lower during COVID-19?
- Is the number of occupied beds for patients coming from surgery in the ICU and the ward kept constant?

Utilization:

- How is the utilization of the ORs?

The above questions are based on the available data (a detailed overview of the available data is given in the results, Section 4.1). Due to missing data, it is not possible to check: If infected patients were isolated. How and if the spread was prevented. If extra time was planned for cleaning, removing appliances, and the surgery itself. If there were separate COVID-19 ORs. If anesthetic and OR personnel was rescheduled and if there were no surgeries canceled after the downscaling. If surgeries were performed within the stated time of the NZA [16]. If there was an influence of the amount of propofol, respiratory devices, and PPE. Lastly, there was no difference made between the ICU and ward in the outflow.

## 2.3. Approach

The data analysis will focus on what happened during the first COVID-19 wave of 2020. To see the effect of COVID-19, 2020 will be compared to 2019. First, a broad overview will be given; after that, a more detailed view of two weeks before, during, and after the COVID-19 wave are shown and compared. The selected weeks will not contain holidays to make a fair comparison. Two weeks that took place before the wave are compared to check if there was already a difference between 2019 and 2020; if so, the differences during and after the wave might not be caused by COVID-19. For all the overviews, only surgeries of weekdays are analyzed, as, during the weekend, only acute care is performed, which has to be done immediately and has nothing to do with the planning. For the number of days on the ICU and ward, only full days are considered with a maximum of 14 days. This maximum is chosen since most elective patients do not stay in the hospital for more than two weeks after surgery [22].

# 3

# Part 1: Methods - Operating room planning in the Reinier de Graaf

This chapter covers the methods used for the data analysis of the performed surgeries in the RdGG.

## 3.1. The data

All surgeries by the RdGG from January 1, 2019, up to September 30, 2020, are selected. Of those surgeries, multiple parameters are selected, also based on availability. The selected parameters can be found in Section 4.1.

## 3.2. Data preparation

To prepare the data for analysis, several adjustments are made. Only weekdays are selected. Only surgeries within the timeframe are taken; surgeries without a registered date are excluded. Only OR 1 to 8 are selected as those are the main ORs of the RdGG. Within specific visualizations, extra adjustments are made by removing unknowns. For example, in overviews of surgical time split per urgency, the unidentified urgencies are excluded.

## 3.3. Data transformation

To visualize the results, additional data transformations were done to create insights. A patient is said to go to the ICU or ward if the departure date of other departments is at least one day later than the surgical date. The number of surgical hours is calculated as the sum of surgical hours. The number of operational ORs is defined by counting the number of unique ORs with at least one surgery planned on that day. To check if the outflow is kept constant, the deviation to the average outflow is calculated by subtracting the two-week average from the outflow. To check if the number of patients on the ward and ICU is kept constant, a similar calculation is done. The occupied number of beds is calculated by taking the date of surgery as the date of entry to the ICU or ward, and the date of departure is taken as the last date. The occupied number of beds is the sum of patients that are in the ICU or ward based on these criteria.

## 3.4. Data visualization

The data is visualized for the questions asked in the introduction. The general overview focuses on the surgical time, overall and split between urgency, on the outflow, and on the number of open ORs. The detailed overview focuses on surgical time split between urgency, outflow, constant outflow, occupied beds, constant occupied beds, and utilization. A more detailed overview of what data exactly is visualized is given in Appendix A.3.

## 3.5. Statistical tests

To analyze the influence of COVID-19 on the previously mentioned factors, statistical tests are performed on the detailed overview. The sums per day are compared for the weeks between the two years. The predictor, COVID-19 or not, is categorical; the outcomes, for example, the number of patients and number of surgical hours, are continuous quantitative variables. The predictor's effect is tested on a different population; it covers the same ORs; however, the surgeries are different every day. Therefore an independent t-test (normally distributed data) or a Mann-Whitney U test (not normally distributed data) should be used [10].

# 4

# Part 1: Results - Operating room planning in the Reinier de Graaf

In this chapter, the results of both the data analysis and the interviews regarding the OR planning in the RdGG during COVID-19 are discussed.

## 4.1. The data

The data acquired from the hospital contains the surgeries performed between January 1, 2019, up until September 30, 2020. A total of 22814 surgeries are included. Of those surgeries, the parameters found in table 4.1 are included. Not all parameters are entered for all surgeries, sometimes this is because it was non-applicable (for example, with the date of death), but sometimes it was not appropriately registered (for example, with the surgical date or priority).

Table 4.1: Available parameters per performed surgery

| | |
|---|---|
| Encrypted patient number | Actual admission date |
| Diagnose code (national) | Actual admission time |
| Surgical code (hospital-based) | Actual leave date |
| Surgical explanation | Actual leave time |
| Indication | Age of patient |
| Priority: urgent, semi-urgent, and elective | Date of death |
| Specialist code | Patient district code |
| Specialty | Patient district name |
| Date of surgery | OR room |
| Planned admission date | Starting-time surgery (when the patient enters OR) |
| Planned admission time | End-time surgery (when the patient leaves OR) |
| Planned leave date | Surgery duration |
| Planned leave time | |

## 4.2. Data preparation

The adjustments made to the data, as described in Section 3.2, are applied. If the end-time is 0:00, this is most likely specified; therefore, those surgeries are excluded in visualizations and calculations of the surgical time. If urgency is not defined, the surgeries are excluded for visualizations and calculations of the urgency.

## 4.3. Data transformation

To visualize the results, additional data transformations were done to create insights. The surgical duration is calculated by extracting the starting time of surgery from the end time; this is then translated into hours. A 1 is added if the patients went to the ICU or ward, or a 0 if not. The number of occupied beds is calculated.

## 4.4. Data visualization and results

Below, the data is visualized for all questions that need to be answered, and the results are described.

### 4.4.1. General overview

The following three figures consider the general overview of the data. Those show what happens in the OR on a weekly basis. First, the sum of surgical hours is shown; next, the sum of surgical hours is split into acute, semi-acute, and elective care, then the outflow towards the ICU and ward is visualized, and lastly, the number of opened ORs is shown.

In Figure 4.1, the sum of surgical time per week is shown. This figure shows that the number of surgical hours is similar for 2019 and 2020 at the beginning of the year. There is a dip in the surgical hours, starting in week 12 of 2020 (halfway March); before that, it is roughly 250 hours per week and it goes to around 100 hours per week. Up to week 24 (early June), the hours increase gradually to around 250 hours per week. In week 30 (halfway July), the number of surgical hours is dropping again; the same can be seen in 2019.

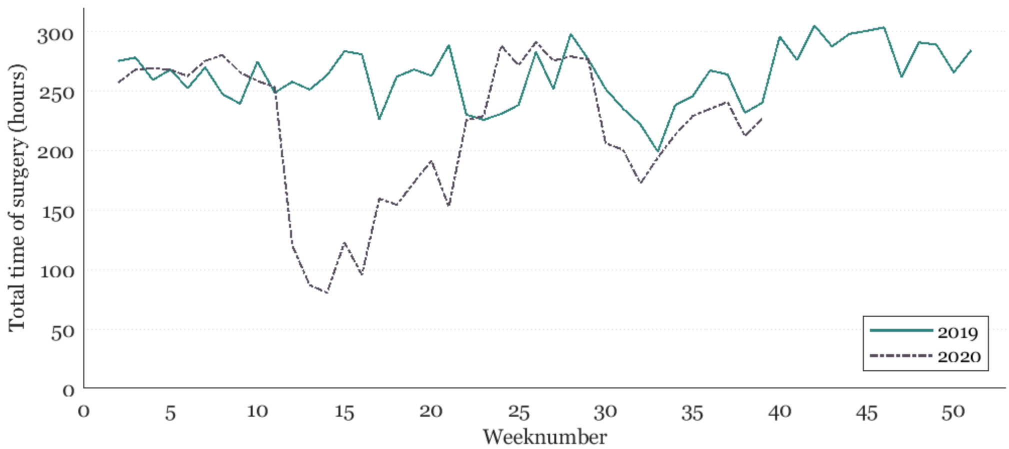


Figure 4.1: The total surgical time per week for weekdays in 2019 and 2020.

In Figure 4.2, the sum of surgical time per week is shown, split into acute, semi-acute, and elective care. Some surgeries are not assigned to one of the three; those are excluded from this figure. The figure shows that acute and semi-acute care stay roughly the same, even during week 12 of 2020. Elective care is downscaled during that period.

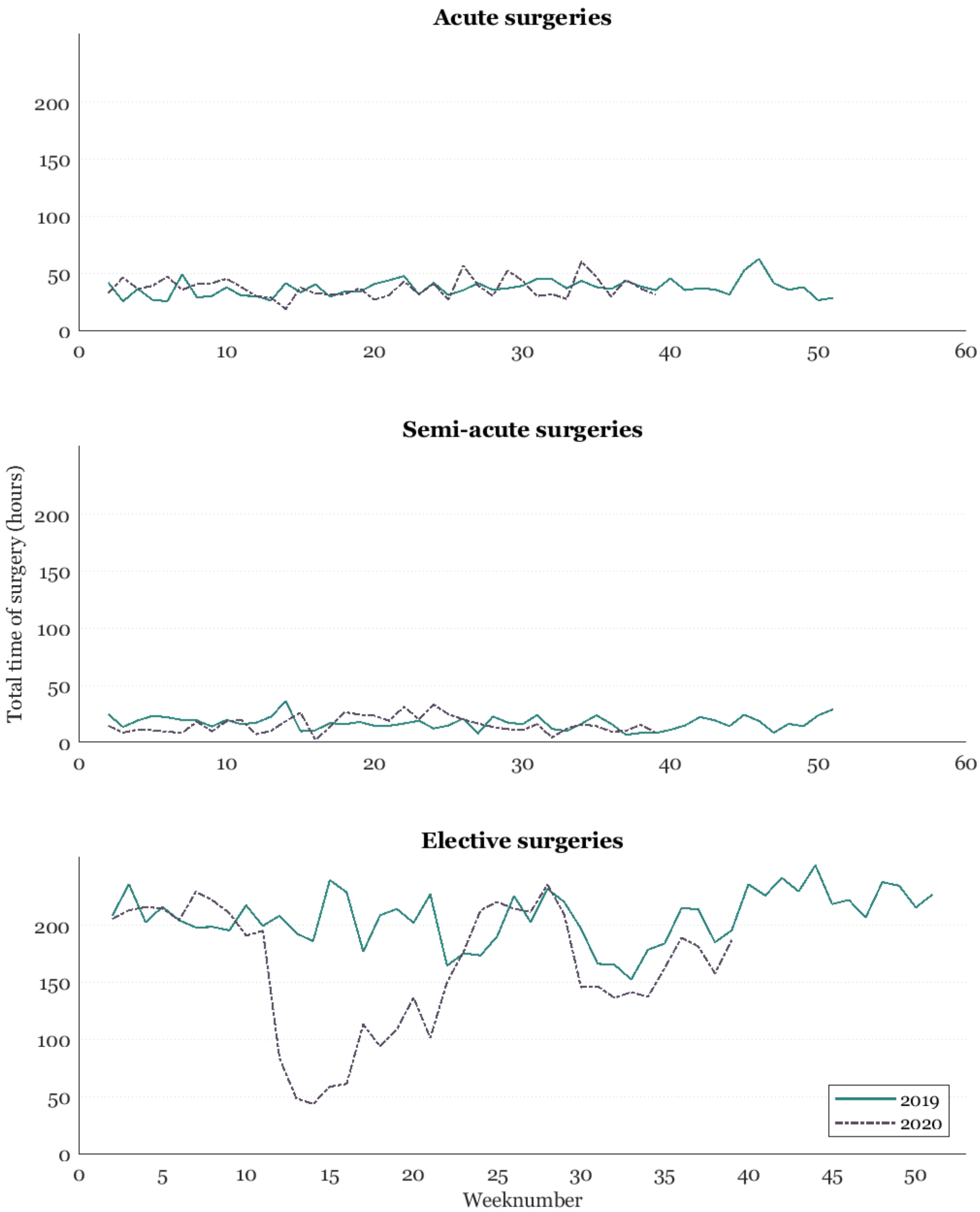


Figure 4.2: The total surgical time per week for weekdays in 2019 and 2020, including the urgency levels.

In Figure 4.3, the outflow of elective patients to the ICU or ward can be seen. It shows that the number of elective patients going to the ICU or ward is lower around the COVID-19 wave of 2020. The average number of patients going to the ICU or ward in 2019 is calculated and is 17.

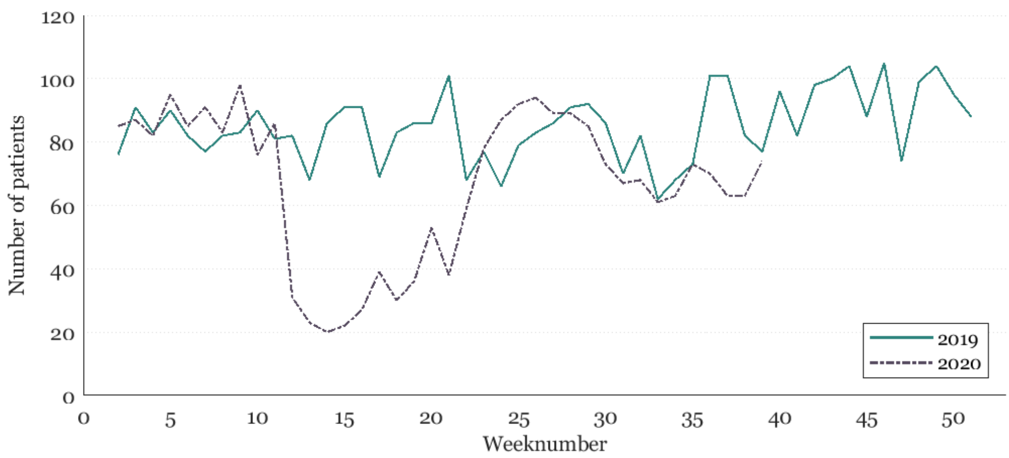


Figure 4.3: The number of elective patients going to the ICU or ward per week for weekdays in 2019 and 2020.

In Figure 4.4, the average number of open ORs per day can be seen. This figure shows that in 2019 there are, on average, around 7 to 8 ORs open; sometimes, this is lowered to 6 ORs. In weeks 12, 13, 14, 15, and 16, this number is around 4 open ORs. From week 14, the number is slowly rising.

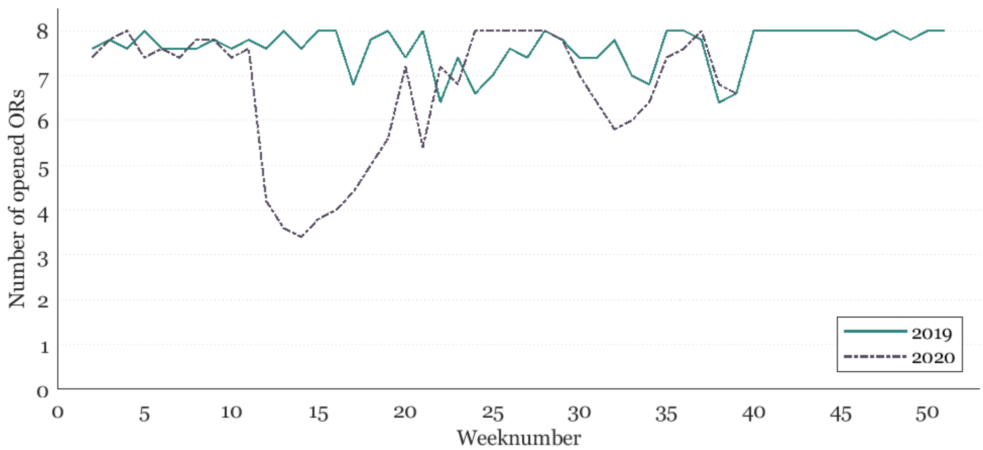


Figure 4.4: The weekly average number of open ORs per weekday in 2019 and 2020.

### 4.4.2. Detailed overview

The upcoming figures show a more detailed view of the data; they compare two weeks during COVID-19 with comparable two weeks a year before that. Week 4 and 5, 12 and 13, and 26 and 27 are compared between 2019 and 2020. Next, the normality is checked for all figures; the results can be found in Appendix A.4. If the data is normally distributed, an independent t-test is done; if the data is not normally distributed, a Mann-Whitney U test is done. Those tests will be used to see if the difference between 2019 and 2020 is statistically significant for the selected weeks.

### 4.4.3. Surgical hours

Figure 4.5 shows the sum of surgical hours per two weeks at three different moments in 2019 and 2020. The sum of surgical hours is split into acute, semi-acute, and elective care; unassigned surgeries are excluded. The data is not normally distributed (A.4), and therefore a Mann-Whitney U test is used to compare the weeks. In tables 4.2, 4.3, and 4.4, the results of the Mann-Whitney U tests and averages of 2019 and 2020 are displayed. There are no significant differences in surgical hours for acute care ($p=0.427$, $p=0.850$, and $p=0.186$). There are significantly fewer surgical hours for semi-acute surgery time before COVID-19 ($p=0.0376$) and during the COVID-19 wave ($p=0.0211$), and for elective surgeries during the COVID-19 wave ($p<0.001$). In acute care, the average daily surgical hours were between 5.61 and 9.60. In semi-acute care, the average daily number of surgical hours was 4.24 and 2.19 before COVID-19 in 2019 and 2020 respectively, and 3.98 and 1.72 during the COVID-19 wave. In elective care before COVID-19, the averages are 41.9 and 43.1 surgical hours for 2019 and 2020 respectively. During the COVID-19 wave, this is 40.1 and 13.2 hours, respectively. In the stable COVID-19 situation, the averages are 42.8 and 42.6, respectively.

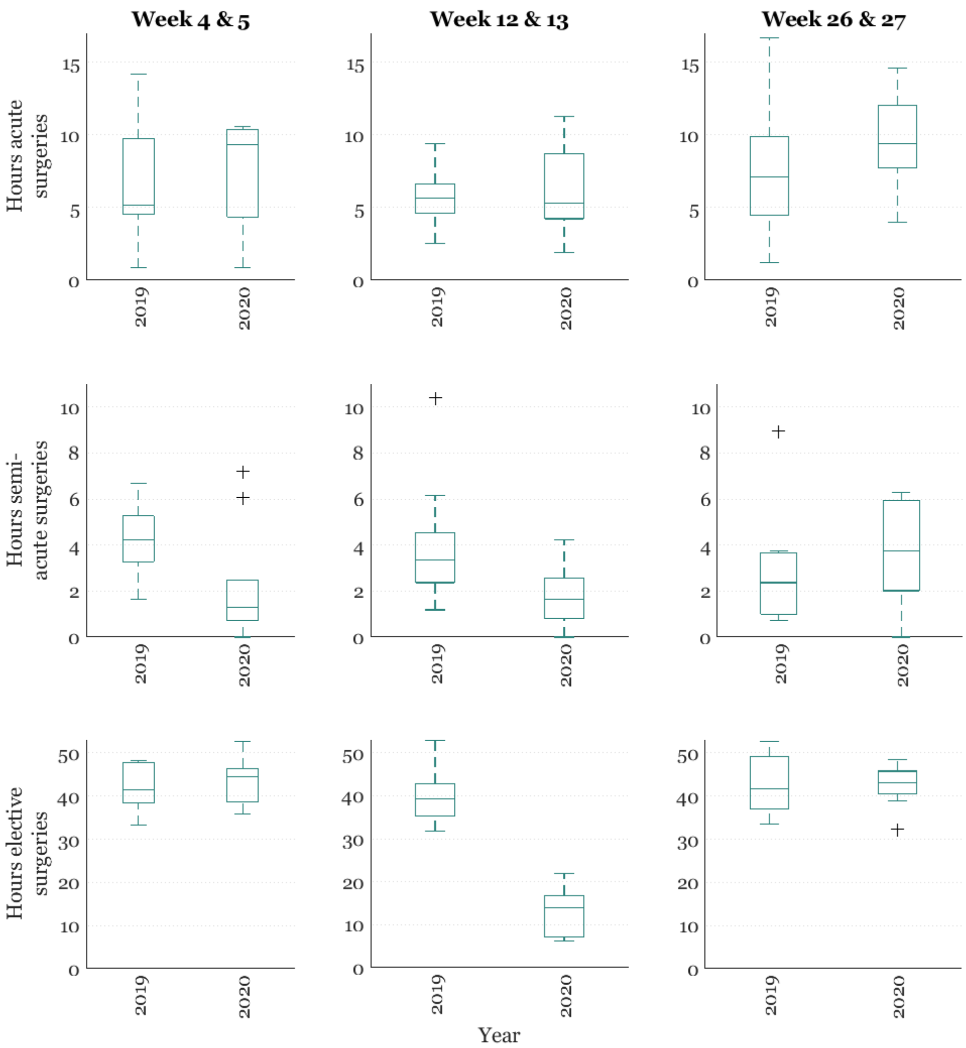


Figure 4.5: The total surgical time per week for weekdays in 2019 and 2020, before, during, and after the COVID-19 wave, including the urgency levels.

Table 4.2: The difference between the total surgical time per week for weekdays in 2019 and 2020, before, during, and after the COVID-19 wave, for acute care.

| | p-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.427 | 6.28 | 7.52 |
| COVID-19 wave | 0.850 | 5.61 | 5.86 |
| Stable COVID-19 | 0.186 | 7.64 | 9.60 |

Table 4.3: The difference between the total surgical time per week for weekdays in 2019 and 2020, before, during, and after the COVID-19 wave, for semi-acute care.

| | p-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.0376 | 4.24 | 2.19 |
| COVID-19 wave | 0.0211 | 3.98 | 1.72 |
| Stable COVID-19 | 0.273 | 2.87 | 3.66 |

Table 4.4: The difference between the total surgical time per week for weekdays in 2019 and 2020, before, during, and after the COVID-19 wave, for elective care.

| | p-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.791 | 41.9 | 43.1 |
| COVID-19 wave | <0.001 | 40.1 | 13.2 |
| Stable COVID-19 | 0.910 | 42.8 | 42.6 |

### 4.4.4. Outflow

In Figure 4.6, the number of patients going to the ICU or ward after surgery is visualized. The data is not normally distributed (A.4), and therefore a Mann-Whitney U test is done, as can be seen in Table 4.5. This table shows that the number of patients was statistically lower in 2020 compared to 2019 in weeks 12 and 13 ($p<0.001$). The average number of patients going to the ICU or ward per day were 24.0 and 25.6 in weeks 4, 21.8 and 10.7 in weeks 12 and 13, and 24.5 and 20.3 in weeks 26 and 27 for 2019 and 2020, respectively.

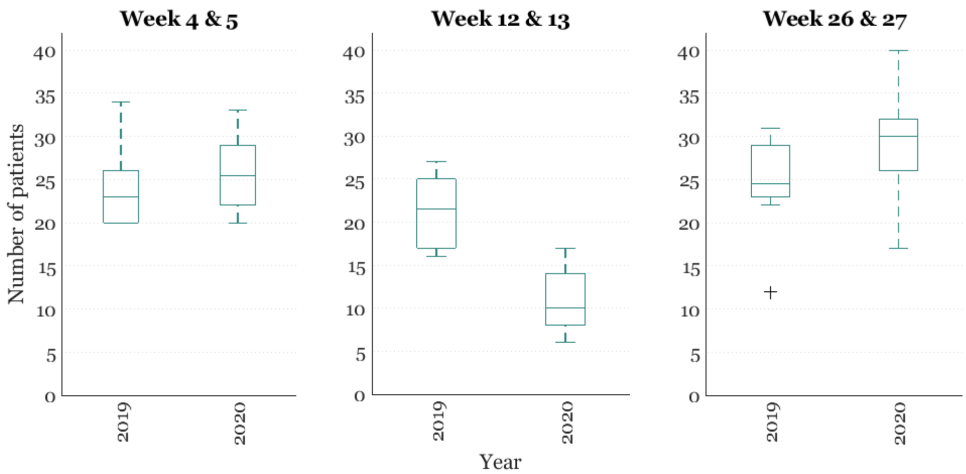


Figure 4.6: The number of patients going to the ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

Table 4.5: The difference between the number of patients going to ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

| | P-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.304 | 24.0 | 25.6 |
| COVID-19 wave | <0.001 | 21.8 | 10.7 |
| Stable COVID-19 | 0.0535 | 24.5 | 29.3 |

### 4.4.5. Constant outflow

Figure 4.7 shows the deviation to the average number of people that go to the ICU or ward per day. The data is not normally distributed (A.4), and therefore, a Mann-Whitney U test is used to see if 2019 and 2020 are significantly different. In Table 4.6, the outcomes of the Mann-Whitney U test can be seen. All p-values are larger than 0.05, and therefore none of the differences are significant.

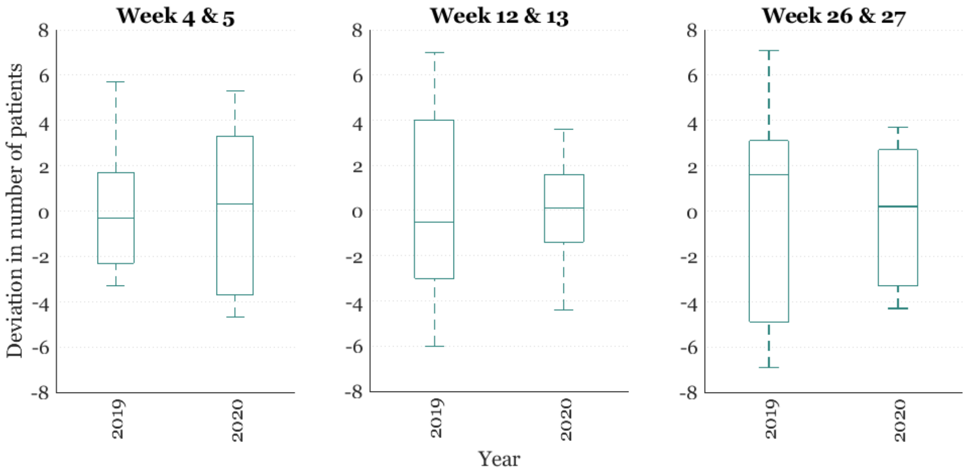


Figure 4.7: The deviation to the two week average of patients going to ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

Table 4.6: The difference between the absolute deviation to the two week average of patients going to ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

| | P-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.733 | 3.40 | 3.60 |
| COVID-19 wave | 0.520 | 3.40 | 2.84 |
| Stable COVID-19 | 0.677 | 3.70 | 4.44 |

### 4.4.6. Occupied beds

In Figure 4.8, the number of beds occupied in the ICU and ward by patients coming from the OR is shown per day. The data is not normally distributed (A.4), and therefore, a Mann-Whitney U test is used to check the differences between 2019 and 2020. In table 4.7 can be seen that during weeks 4 and 5, and weeks 26 and 27, the occupied beds are significantly higher in 2020 compared to 2019 ($p=0.0492$ and $p=0.0492$), and in weeks 12 and 13, the number is significantly lower in 2020 ($p<0.001$). The average number of occupied beds per day was 73.5 and 85.7 in weeks 4 and 5, 73.4 and 44.2 in weeks 12 and 13, and 73,9 and 89.5 in weeks 26 and 27 for 2019 and 2020, respectively.

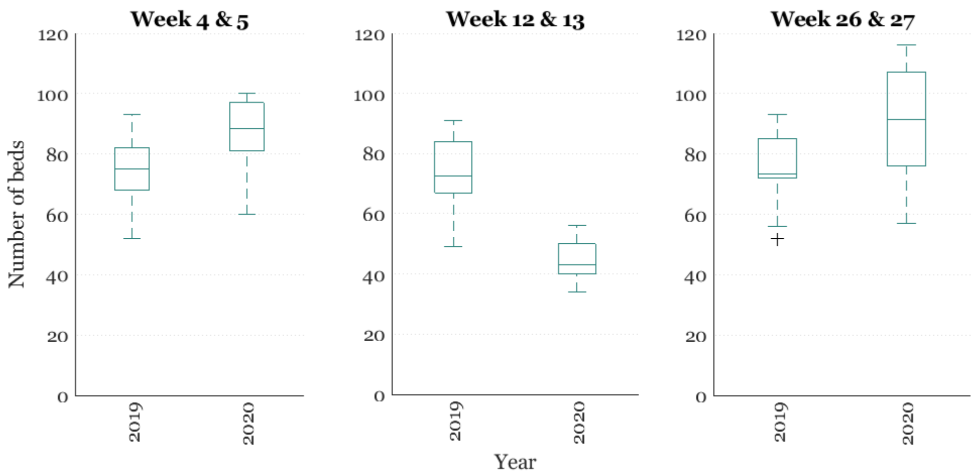


Figure 4.8: The number of occupied beds per weekday in 2019 and 2020, before, during, and after the COVID-19 wave.

Table 4.7: The difference between the number of occupied beds per weekday in 2019 and 2020, before, during, and after the COVID-19 wave.

| | P-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.0492 | 73.5 | 85.7 |
| COVID-19 wave | <0.001 | 73.4 | 44.2 |
| Stable COVID-19 | 0.0492 | 73.9 | 89.5 |

### 4.4.7. Occupied beds kept constant

Figure 4.9 shows the deviation per day to the two week average of the number of occupied beds in the ICU and ward. This data is not normally distributed; therefore, the Mann-Whitney U test is used to see if 2019 and 2020 are significantly different. In Table 4.8 can be seen that the differences between 2019 and 2020 are not significant. The average deviations range from 5.64 to 16.7.

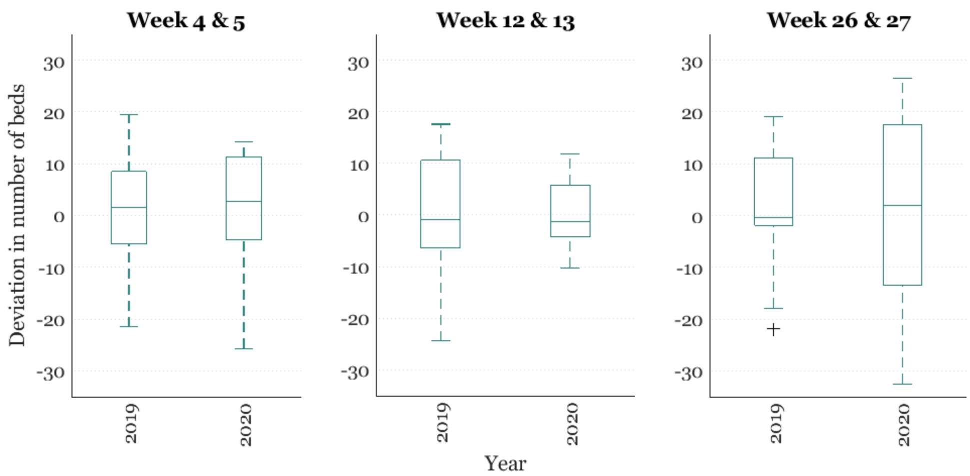


Figure 4.9: The deviation to the two week average of the number of occupied beds in the ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

Table 4.8: The difference between the deviation of the two week average of occupied beds in the ICU or ward during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

| | P-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.850 | 9.90 | 11.0 |
| COVID-19 wave | 0.212 | 9.60 | 5.64 |
| Stable COVID-19 | 0.0752 | 8.70 | 16.7 |

### 4.4.8. Utilization

Figure 4.10 shows the ORs' daily utilization in percentages. The data is not normally distributed; therefore, a Mann-Whitney U test is used to check if the differences between 2019 and 2020 are statistically significant. Table 4.9 shows that the utilization is significantly lower in 2020 for weeks 12 and 13 (p=0.0257). The average utilization per day was 84.5% and 87.4% in weeks 4 and 5, 81.9% and 66.3% in weeks 12 and 13, and 89.0% and 88.5% in weeks 26 and 27 for 2019 and 2020, respectively. An optimal OR utilization is between 85% and 90% [23].

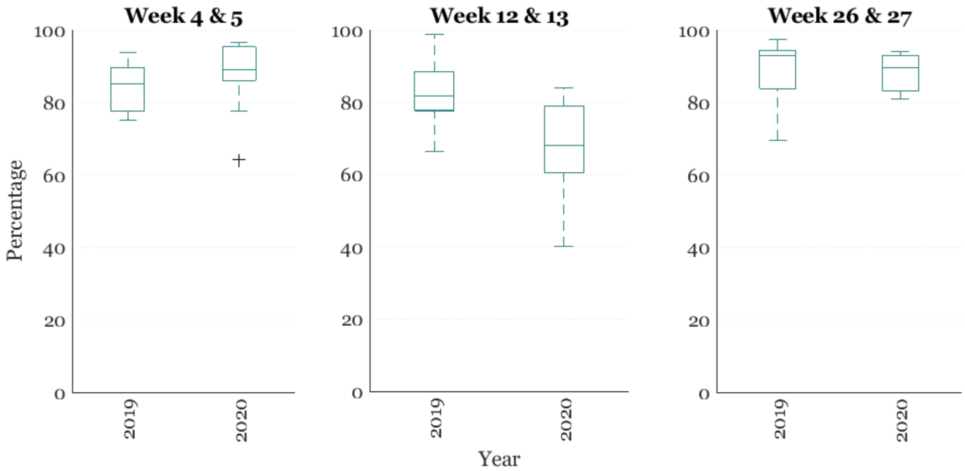


Figure 4.10: The utilization in percentages during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

Table 4.9: The difference between the utilization in percentages during weekdays in 2019 and 2020, before, during, and after the COVID-19 wave.

| | P-value | Average 2019 | Average 2020 |
|---|---|---|---|
| Before COVID-19 | 0.212 | 84.5 | 87.4 |
| COVID-19 wave | 0.0257 | 81.9 | 66.3 |
| Stable COVID-19 | 0.427 | 89.0 | 88.5 |

# 5

# Part 1: Discussion - Operating room planning in the Reinier de Graaf

In this chapter, the first research question, "How was the OR planning in the Reinier de Graaf hospital during the COVID-19 crisis of the first half of 2020?" will be answered. To answer this question, first, a summary on what is essential for an OR planning during COVID-19 is given, and next will be checked if the RdGG complied with that.

## 5.1. The operating room planning

It is vital during COVID-19 that acute and semi-acute surgeries are still performed, even when the capacity is lower. Also, the outflow towards the ICU and ward has to be lower and kept constant. The number of occupied beds in the ICU and ward also have to be lower and constant. Lastly, the utilization has to stay high during COVID-19.

### 5.1.1. Performing acute and semi-acute care

The interviews stated that only elective care scaled-down but that acute and semi-acute surgeries were still performed during the first COVID-19 wave. In the data can be seen that acute surgeries were still performed. The number of hours spent on semi-acute surgeries was lower before and during the COVID-19 wave. Therefore the difference during COVID-19 does not have to be because of COVID-19. Expected is that those differences are there because there are only a few semi-acute surgeries performed. If more weeks were taken, the differences both before and during COVID-19 might not be significant. The elective care is significantly downscaled during COVID-19, as is expected. It is good that acute care was still performed during the COVID-19 wave. More data points should be checked to see if semi-acute care was indeed continued during COVID-19, but as the interviewees stated that it was, it probably was.

### 5.1.2. Outflow

In the interviews is stated that the outflow towards the ICU was a maximum of one person per day from the OR and that the outflow to the ward was lower as well. This can also be seen in the data; the outflow towards the ICU and ward during COVID-19 was significantly lower, which is desired. The outflow towards the ICU and ward separately was unavailable to the researcher and should still be checked.

The outflow to the ICU and ward should be kept constant as taking in new patients from the OR costs much time in the ICU and ward. If all patients come in simultaneously, there are not enough nurses to care for all patients. Trying to keep a constant outflow was not done differently during COVID-19 as opposed to regular times. By having meetings to discuss the upcoming surgeries, this is somewhat covered. The data confirms that the outflow was indeed not more or less constant during COVID-19. However, the outflow also does not seem to be constant during regular times. The difference between the outflow was up to 14 patients between two days in two weeks. Future research should focus on what fluctuations in outflow are acceptable to the RdGG.

### 5.1.3. Occupied beds

During the COVID-19 wave, fewer beds were available, so there should be fewer patients from the OR going to the ICU and ward. The data shows that there were indeed significantly fewer patients going to the ICU or ward during the COVID-19 wave. However, there were also significantly more patients in the ICU or ward before and after the COVID-19 wave. Therefore, it cannot be stated that the difference in occupied beds by surgical patients during COVID-19 is due to COVID-19. However, as the number of occupied beds was higher around the COVID-19 wave and the outflow was lower, this is highly expected.

Keeping the number of beds occupied by surgical patients constant is essential as there are only a certain amount of beds available for patients. If the number of beds is not entirely used, this cannot be compensated for on the other days. Also, keeping the number of occupied beds constant can result in better efficiency in the different departments as the number of necessary staff can be more easily planned upfront. The number of occupied beds closely relates to the outflow of the OR. There were lots of fluctuations in the outflow that can also be seen in the number of beds. Sometimes the difference is up to 59 occupied beds in one week. As for the fluctuations in outflow, future research should be done to determine what fluctuations in occupied OR beds are acceptable for the RdGG.

### 5.1.4. Utilization

Utilization is one of the most vital aspects of an OR planning, especially during COVID-19, when the resources are lower than usual. During the COVID-19 wave, the utilization of the OR was significantly lower. This outcome is expected as all elective care was downscaled. However, it was most likely possible to plan the OR more efficiently without opposing extra pressure on the OR and ward and with the available staff by performing elective surgeries that had a low chance of going to the ICU or ward.

## 5.2. Future operating room planning

In an OR planning for another COVID-19 wave when the OR has to downscale again, it might not be necessary to scale down as much as was done during the first wave. An eye should be kept on lowering the outflow and the occupied beds by surgical patients as was done correctly during the first wave. This was also the case for downscaling the OR as much as necessary given the available staff. In a future wave, however, the utilization of the OR should be taken into account. Lastly, the outflow and number of occupied beds are not leveled, not during COVID-19 and not in regular times. Extra research should be done to see if doing this can improve the processes at the RdGG.

# 6

# Part 2: Introduction - Possible operating room planning models

This chapter focuses on the research subquestions "How do potential OR planning models comply with the OR planning demands during COVID-19?" and "Which planning models are the most feasible for the Reinier de Graaf hospital?".

## 6.1. Aspects to consider in a model

Before making a model, choices are made on how the model should function. In Section 1.7, the different aspects that have to be taken into account are mentioned. Those are patient features (elective or non-elective), performance measures, constraints, solution techniques, uncertainty (deterministic or stochastic), and planning level. As stated in Section 1.7.1, the performance measures that should be used in an OR planning model during COVID-19 are [26]:

- Humanitarian goals
- Leveling
- Patient deferral
- Utilization
- Waiting time
- Other
  - Medicinal stock
  - PPE stock

To advise on what type of OR planning model should be used during COVID-19 in the RdGG, choices have to be made about the different aspects described above. This is done in two different ways; first, several planning models from the literature are selected based on different criteria; this selection process is described in Appendix A.5. From those five planning models, the implementation of the aspects described above is described. Next, an interview is held to confirm or reject the literature's conclusions and add additional information.

# 7

# Part 2: Methods - Possible operating room planning models

In this chapter, the methods are explained on how to find what different aspects should be used in an OR planning model during COVID-19 in the RdGG.

## 7.1. Existing operating room planning tools and their use during COVID-19

Five different planning models are selected from the literature, as described in Section A.5. The selected articles are Van Houdenhoven et al. [27], Tan et al. [22], Van Essen et al. [25], Gerami and Saidi-Mehrabad [11], and Ozkarahan [18]. First, a summary of those models is given. From those models, different aspects are extracted and described. The aspects looked at are patient features (elective or non-elective), performance measures, constraints, solution techniques, uncertainty (deterministic or stochastic), and planning level. The performance measures are humanitarian goals, leveling, patient deferral, utilization, waiting time, and medicinal and PPE stock.

## 7.2. Feasibility for the hospital

To make recommendations on what type of planning models should be used in the RdGG during COVID-19, one needs to know what the RdGG finds feasible and with what they are able to work. To explore this, an interview is done with a staff member of the planning department. This interview will explore what the most important aspects of a planning model during COVID-19 are: what extra things need to be taken into account, what planning level is most useful, what type of patients should be included, if stochastic or deterministic values should be included, how patient priority and leveling should be applied, how to plan efficiently, and if the model should include recommendations on whether or not ORs should be closed. The questions are based on the existing OR planning tools explained in Section 7.1. Therefore the interview questions will be made after the results of the existing OR planning models are known and are thus explained in Section 8.2.

# 8

# Part 2: Results - Possible operating room planning models

In this chapter, the results of possible OR planning models are displayed. First, the explored existing OR planning models are displayed, and next, the interview results focussing on feasibility for the hospital are displayed.

## 8.1. Existing operating room planning tools and their use during COVID-19

To check if the OR planning models of Van Houdenhoven et al. [27], Tan et al. [22], Van Essen et al. [25], Gerami and Saidi-Mehrabad [11], and Ozkarahan [18] might be applicable for OR planning during COVID-19 in the RdGG, those articles are read, summarized and the most important aspects extracted and displayed in Table 8.1. First, all articles are described separately to give an overview of what they focus on; next, all performance measures are checked to see if the articles incorporate them, and if so, how. Lastly, the solution techniques, uncertainty, and planning levels are checked and documented.

### 8.1.1. Included articles

Van Houdenhoven et al. [27] focus on making a cyclic case schedule, an MSS, to improve utilization of scarce resources and coordination in the supply chain. They do this by maximizing the OR utilization by reducing the unused OR capacity and subsequently leveling the ICU bed requirements. First optimal operating room day schedules are made with a column-generation approach, which are then organized throughout the week to level the ICU beds. The use of this MSS could improve the OR utilization by 6.3%. The model of Van Houdenhoven et al. [27] is explained in the article of Van Oostrum et al. [29]; this is used to get the aspects stated below; however, it is still referred to as Van Houdenhoven et al. [27] because this is the way Van Houdenhoven et al. [27] did their research.

Tan et al. [22] present a method for generating weekly elective operating room schedules in two stages. First, it considers all cases that need to be scheduled and assigns them to different days. Next, each case is assigned to an operating room and operating time. Only the first stage is described in his research. During this process, they take pre and post-operative bed capacity into account and constraints such as operating theater, surgeon, and patient availability. They use lexicographic goal planning because the objectives have very opposite and different priority levels. The model will achieve less artificial variability and likely attain a smoother surgical patient flow than the current hospital's planning.

Van Essen et al. [25] focus on a decision support system to assist the OR manager in adjusting the OR schedule when necessary. First, all preferences of patients, surgeons, and even up to the logistics department are rated. The goal of the model is to minimize the deviation from the preferences of those stakeholders. All stakeholders' preferences are weighted equally. Deviation from the preferences imposes a penalty in the system. Canceling a surgery imposes a bigger penalty than the sum of the preferences. When a change in the schedule needs to be made, the model is run,and the penalty will be minimized. Therefore canceling a surgery is unlikely, however possible. The problem is modeled as an integer linear program.

Gerami and Saidi-Mehrabad [11] established a reactive rescheduling algorithm to help reactive scheduling for the OR under the uncertain arrival of non-elective patients. Several models were made with this algorithm. They included human objectives as well as financial goals. Restrictions on the waiting room and post-anesthetic care unit (PACU) capacity are also included in the mathematical model. When an emergency enters, the possible ORs are determined, and the entrances for surgeries are calculated. The OR with maximum total free time is selected. The remaining patients in that OR are rescheduled. If necessary, the remaining patients in the other ORs are also rescheduled.

Ozkarahan [18] presents a goal programming model that can produce schedules to suit a hospital's needs. It minimizes idle time and overtime and increases the satisfaction of surgeons, patients, and staff. First, patients are scheduled for surgery on some future date. Next, the sequence of surgical cases on a given day is determined. The model loads operations to the ORs while keeping block restrictions, surgeon preferences, ICU capabilities, and OR utilization into account.

The patient features, performance measures, constraints, solution techniques, uncertainty, and planning level are extracted from the articles and can be found in Table 8.1. Based on this table, the different approaches are explained below.

### 8.1.2. Patient features

The OR planning models focus on elective patients or a combination of elective and non-elective patients. Van Essen et al. [25] and Gerami and Saidi-Mehrabad [11] integrate both elective and non-elective patients in their schedule; this is because they adjust the existing OR schedule based on non-elective patients entering. Van Houdenhoven et al. [27], Tan et al. [22], and Ozkarahan [18] only focus on elective patients as they create a planning longer than one day.

### 8.1.3. Performance measures: Humanitarian goals

Gerami and Saidi-Mehrabad [11] and Ozkarahan [18] both include humanitarian goals. Gerami and Saidi-Mehrabad [11] include three levels of patient priority by minimizing patients' exit time with a higher priority, which results in earlier surgery for those patients. The decision-maker prioritizes patients. Ozkarahan [18] incorporates humanitarian goals by asking specialties to prepare their lists of patients in increasing order of importance or urgency (from now on called urgency). Each specialty has its block of OR time. Patients are weighted with an increasing level of urgency, and postponed patients impose a penalty, which is minimized. This results in urgent surgeries being performed first and less urgent surgeries being postponed.

### 8.1.4. Performance measures: Leveling

All articles except Gerami and Saidi-Mehrabad [11] focus on leveling. Van Houdenhoven et al. [27] level the ICU beds by making daily OR schedules, which are subsequently shifted around the week and different ORs, to fit the expected ICU stay so that the number of ICU patients from the OR stays leveled. Tan et al. [22] levels bed occupancy volumes throughout the post-operative units with three goals. The first goal is reducing the bed occupancy exceeded by each service. The second goal is to balance the number of beds occupied by each service on each day. Lastly, the third goal is to minimize the bed occupancy on the days following the schedule week, to reduce the impact on future schedules. Those three goals are weighted, where the first is the most important and the last the least, and minimized. The leveling of the holding and recovery in the article of Van Essen et al. [25] is done by giving penalty costs when the number of patients exceeds a certain threshold. Ozkarahan [18] levels the number of ward beds by asking specialisms to only present lists with patients that fit in their ward. The number of beds in the ICU cannot exceed a certain threshold.

### 8.1.5. Performance measures: Patient deferral

Only Van Essen et al. [25] consider patient deferral by minimizing the number of canceled patients.

Table 8.1: The aspects from the different operating room planning models selected from literature.

| **Model** | **Patient features** | **Performance measures** | | | | | | **Included constraints** | **Solution technique** | **Uncertainty** | **Planning level** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Humanitarian goals* | *Leveling* | *Patient deferral* | *Utilization* | *Waiting time* | *Medicinal / PPE stock* | | | | |
| Van Houden-hoven et al. [27] | Elective | | ICU beds | | Maximize OR utilization | | | Available ORs, available operating time and capacity succeeding departments | Combination of integer linear programming with column generation | Stochastic | Creating a MSS |
| Tan et al. [22] | Elective | | Post operative beds | | Minimize OR under-utilization | | | Operating theatre, surgeon and patient availability | Lexicographic goal programming | Deterministic | Planning surgical procedures without a MSS |
| Van Essen et al. [25] | Elective and non-elective | | Considers capacity of holding and recovery | Prevent cancelling patients | | | | Availability of patient, availability of OR with OR assistants, surgeon and anesthestist, capacity of holding and recovery | Integer linear program | Deterministic | Adjusting OR schedule |
| Gerami and Saidi-Mehrabad [11] | Elective and non-elective | Patient satisfaction, justice, individual freedom, patient rights, medical ethics | | | Minimize OR overtime | | | Waiting room capacity and PACU capacity | Mixed integer programming | Stochastic | Adjusting OR schedule |
| Ozkarahan [18] | Elective | Patient urgency | Ward and ICU beds | | Minimize idle time and overtime | | | Block restrictions and surgeons preferences | Goal programming | Deterministic | Allocating surgical procedures |

### 8.1.6. Performance measures: Utilization

Utilization is described by all articles except Van Essen et al. [25]. Van Houdenhoven et al. [27] maximizes OR utilization by reducing the unused OR capacity. This is done by calculating operating room day schedules, calculating the unused time, and, using linear programming, making new operating room day schedules that contain less unused time. Tan et al. [22] split utilization into two goals. The first goal reduces underutilized OR time and overtime. The second goal minimizes the maximum number of days that any surgeon is scheduled to perform surgery to prevent them from operating on an unnecessarily large number of days to satisfy the surgeons. Gerami and Saidi-Mehrabad [11] tries to reduce overtime and idle time. Ozkarahan [18] minimizes underutilization and overtime by minimizing the deviation between available time and scheduled operation time.

### 8.1.7. Performance measures: Waiting time

Waiting time is not addressed by the articles.

### 8.1.8. Performance measures: Medicinal/PPE stock

The medicinal or PPE stock is not included in the articles.

### 8.1.9. Included constraints

All articles include constraints in their models. Van Houdenhoven et al. [27] include the available ORs, available operating time, and succeeding departments' capacity. Tan et al. [22] take constraints such as operating theater, surgeon, and patient availability into account. Van Essen et al. [25] include all relevant constraints imposed on the OR schedule, including the availability of the patient, an OR including assistants, a surgeon, and an anesthetist, and the capacity of the holding and recovery. Gerami and Saidi-Mehrabad [11] add constraints to the waiting room and PACU to prevent two patients being assigned to the same bed. Ozkarahan [18] gives priority to plan surgery for the owner of the block. Surgeons' preferences are included by keeping the number of preferred rooms equal to the total number of preferences.

### 8.1.10. Solution technique

Different solution techniques are used in the models. Van Houdenhoven et al. [27] use a combination of integer linear programming to create operating room day schedules, and column generation to place the day schedules within the week while leveling the outflow to the ICU. Tan et al. [22] use lexicographic goal programming to generate the OR planning. Lexicographic goal programming is used when there is no trade-off between criteria allowed. The approach begins by addressing priority level one with a linear programming model. After solving, the approach moves on to the next priority level to solve a new linear programming model. This is repeated until the linear programming models for all priority levels are included or when the value of structural values becomes fixed and will not change regardless of any remaining priority levels. Van Essen et al. [25] use integer linear programming to minimize the penalties applied by deviating from the preferences of different included stakeholders and canceling a surgery. Mixed-integer linear programming is used by Gerami and Saidi-Mehrabad [11] to minimize unwanted and maximize wanted outcomes. Ozkarahan [18] uses goal programming to make the OR planning. Each important measure is given a goal to achieve; deviations from these goals are minimized.

### 8.1.11. Uncertainty

Tan et al. [22], Van Essen et al. [25], and Ozkarahan [18] only use deterministic values and do, therefore, not include uncertainty. Van Houdenhoven et al. [27] use stochastic values; in this way, they include the uncertainty of the duration of surgical procedures. Gerami and Saidi-Mehrabad [11] also use stochastic values.

### 8.1.12. Planning level

Van Houdenhoven et al. [27] create an MSS for elective procedures that occur quite frequently. The duration of the MSS is tested for cycle periods of one week to one year. Tan et al. [22] plan patients into the schedule that replaces the need for using an MSS; however, the amount of allocated OR time for each surgeon still needs to be determined. The model of Van Essen et al. [25] is used to assist the OR manager in adjusting the OR schedule by providing the three best options. Gerami and Saidi-Mehrabad [11] use their model to reschedule elective patients and schedule non-elective patients when they arrive. The model of Ozkarahan [18] allocates patients based on an existing MSS; it is possible to deviate from this MSS, however not preferable.

As stated in Section 1.7.1, the performance measures that should be used in an OR planning model during COVID-19 are:

- Humanitarian goals
- Leveling
- Patient deferral
- Utilization
- Waiting time
- Other
  - Medicinal stock
  - PPE stock

Looking at the five OR planning models found in the articles, none of the articles include all performance measures that ought to be important during COVID-19. As shown in Table 8.1, Van Houdenhoven et al. [27] and Tan et al. [22] include leveling and utilization, however humanitarian goals, patient deferral, waiting time, and medicinal and PPE stock are not included. Van Essen et al. [25] include leveling and patient deferral; however, humanitarian goals, utilization, waiting time, and medicinal and PPE stock are not included. Gerami and Saidi-Mehrabad [11] include humanitarian goals and utilization, but not leveling, patient deferral, waiting time, and medicinal and PPE stock. Lastly, Ozkarahan [18] includes humanitarian goals, leveling, and utilization; but patient deferral, waiting time, and medicinal and PPE stock are not included.

This means that not one of the models includes all necessary performance measures.

## 8.2. Feasibility for the hospital

To see what OR planning models would be feasible for the hospital, an interview is held. The interview questions focused on the most critical aspects of an OR planning during COVID-19, how these are incorporated in the planning models found in literature, and how they should be implemented in a planning model for the RdGG. The interview also focused on what other aspects are essential to include in an OR planning model and what choices to make on patient features, constraints, solution techniques, uncertainty, and the planning level. The questions asked can be found in Appendix A.6. One interview was held with an OR planner in the RdGG to check what OR model would be feasible for the hospital. The interview of 1 hour, has been conducted in Dutch via Zoom and was recorded. The interviewee gave permission to record the interview. The results of the interview are stated below.

According to the literature, an OR planning model can be made in multiple levels: an MSS, planning patients, or adjusting an existing planning. A model planning patients will be most helpful for the RdGG. This can be done while keeping the MSS into account or by eliminating the need for an MSS. Ideally, a planning is made eight weeks in advance; however, during COVID-19, the planning can change day by day as the ward's and ICU's capacity is very uncertain. What would be possible is a model that plans a couple of weeks but can be run daily. As the RdGG would prefer a planning model that plans upcoming patients a couple of weeks ahead, only elective and semi-acute patients are planned. In the OR, the planning is changed such that acute patients for that day can be planned. Semi-acute patients have to be planned within a week. It is not always best to plan them as soon as possible; for example, with an ankle fracture, one ideally waits for the swelling to disappear before performing surgery. Therefore five to seven days would be best. This timeframe is different per semi-acute surgery. The planning is done in a deterministic manner, and this works well for the hospital. The median of the last 19 similar surgeries of the same surgeon is used to estimate surgery duration. Including patient priority and flow towards the ICU and wards are the most vital aspects of an OR planning during COVID-19. While making this planning, it is also essential to keep utilization into account. Patient priority can be included by making a waiting list sorted by the urgency with the most urgent patients on top. Patients can become more urgent by being on the waiting list for a more extended period. For example, if surgery has to be performed within two weeks, but the patient is already on the waiting list for a week, it should be placed at the bottom of the one-week priorities. It should also be possible for specialists and planning personnel to change and overrule the order in patients' urgency list. The flow towards the ICU and the wards should stay under a certain threshold, which can be different for every ward. Right now, the planning department has a quota for the number of patients that are allowed to the ward or ICU daily. The number of days that the patient will probably spend there is not included. This would, however, be a useful addition. The flow towards the ward and ICU should be kept under a certain threshold in an OR planning model. However, sometimes it is possible to clear up an extra bed, so the threshold does not have to be strict. As the number of available beds fluctuates throughout time, the number of available beds should be adaptable. To optimize utilization, it is necessary to minimize downtime while also minimizing overtime. It is also helpful to plan similar surgeries one after another to perform those surgeries optimally.

Other aspects that are important to keep into account are the following:

- OR time schedule
- Grouping surgeries per specialist
- Necessary equipment including X-ray
- Cleaning protocol for an infected patient
- Available personnel
- Available PPE
- Available medication
- Previously planned patients.

The regular time schedule of the OR is essential to include in a planning model. In the RdGG, the first surgery starts at 8:00 (patient enters OR), and the last surgery should end at 16:30. If the day is split into multiple specialisms, the morning shift ends at 12:00, and the afternoon shift starts at 12:30; this results in a total of 8 to 8.5 hours of surgical time. Normally the OR planning starts with an MSS in which each specialism plans one specialist per shift. During the last COVID-19 wave, surgeries were planned without a master surgical schedule, and multiple specialists could be planned in one shift. This was possible because the specialists were very flexible and happy to be able to perform surgery. Also, because lots of their polyclinical care was canceled. If the OR has to downscale a lot during the next COVID-19 wave, this might be possible another time. It is, however, preferable to group the surgeries of one surgeon. With an OR planning model, it is essential to keep the needed appliances and x-ray into account because not everything is available in every room, and there is only a certain amount of appliances. When it is vital to perform surgery on an infected patient, one should plan extra time for cleaning. It is also possible to open a separate COVID-19 OR; however, this is not deemed necessary as only a handful of infected patients undergo surgery. The number of available OR staff is always crucial to take into account. Even without sending OR staff to other departments, there is a staff shortage. It is unlikely that it is necessary to send staff to other departments; however, if it is needed, the amount of staff should be closely monitored, and the OR planning should be downscaled accordingly. If there will be another PPE shortage, even worse than during the last COVID-19 wave, it might be necessary to downscale the OR, as PPE is necessary to perform surgery. This might be similar for propofol, but this is unknown to the interviewee. When the planning should be downscaled, it is preferable to prioritize patients that were already planned over patients that have not yet been planned while keeping the patient priority into account. One last thing that might be helpful to include in the model is advice on closing one or more ORs. This will make the planners aware of this possibility so that ORs can be closed in time if they have no or little additional benefits. Closing one of the ORs should be a suggestion that is easily overruled.

# 9

# Part 2: Discussion - Possible operating room planning models

In this discussion, the answers to the subquestions "How do potential OR planning models comply with the OR planning demands during COVID-19?" and "Which planning models are the most feasible for the Reinier de Graaf hospital?" will be given.

## 9.1. Aspects for an operating room planning model

Below the aspects for a COVID-19 OR planning model in the RdGG are defined. The aspects from the five articles are checked to see if they apply to the RdGG. The articles' information is combined with the interview to give a good overview of what would be applicable for the RdGG.

### 9.1.1. Patient features

According to the interview, it is most feasible for the RdGG to make a planning of elective and semi-acute patients. Acute patients are planned in the OR and, therefore, not included in the planning department. Elective patients will be planned further ahead, and semi-acute patients will be added to the planning afterward.

### 9.1.2. Performance measures: Humanitarian goals

Including patient priority is one of the most vital aspects of an OR planning during COVID-19. Priority should be defined by combining both the patient's urgency and the time they are on the waiting list. Gerami and Saidi-Mehrabad [11] includes patient priority, in which the decision-maker gives the patients a priority level. While rescheduling the OR this results in less urgent surgeries that are canceled if anything has to be canceled. Gerami and Saidi-Mehrabad [11] incorporate patient priority in a way that applies to rescheduling the OR. As this is not the focus for the RdGG, their method is not used. Ozkarahan [18] asks specialties to sort the patients based on urgency, in which patients are weighted with an increasing level of urgency. Postponed patients impose a penalty. In this way, the difference between two following patients is always similar; however, in a real situation, it is possible that, for example, patients 1 and 2 are equally important, and patient 3 is way less important. Another problem with this planning is that patients have to be ordered manually. This has happened during the first COVID-19 wave but might cost a lot of time and bring up much discussion, so it should be prevented. An automatically generated priority score based on, for example, the NZA priority list [16] and time on the waiting list might bring a solution. This should and will be further explored in part III, starting in Section 10.

### 9.1.3. Performance measures: Leveling

Leveling is another of the most vital aspects of an OR planning during COVID-19. Shifting around daily OR schedules throughout the week, as done by Van Houdenhoven et al. [27], will result in shifting around prioritized patients, which is unfavorable. Ozkarahan [18] asks specialisms to only present patients that fit their ward; this is unfeasible for the RdGG. Van Essen et al. [25] uses a penalty when the number of patients exceeds a certain threshold; this is a basic way to prevent too many patients going to the ICU or ward; however, it does not level the number of patients and is therefore not fit for the RdGG. Tan et al. [22] reduce exceeding the thresholds and balances the occupied beds by each service each day. This seems like a right combination for the RdGG as there will not be too many beds planned, and the outflow is also balanced. One thing that has to be added is that there should not be too many patients going to the ward simultaneously, as this puts a lot of pressure on the ward.

### 9.1.4. Performance measures: Patient deferral

Patient deferral is mainly of focus when rescheduling patients, to try and minimize the number of cancellations. When the OR is downscaled during COVID-19, patients have to be canceled. The focus is on which patients should be planned. However, when planning patients again, it is possible to give previously planned patients a higher priority. This should only be done if there is enough time to plan all patients within their stated NZA timeframe. Including this is a possibility for the RdGG. How this can be done should be further investigated

### 9.1.5. Performance measures: Utilization

Utilization of the OR is always essential, also during COVID-19. However, it has to be considered how this relates to patient priority and leveling. At one point in time, patient priority might be way more important than utilization, whereas they might be equally important at another point in time. All articles but Van Essen et al. [25] focus on utilization by minimizing overtime and undertime. Extra research has to be done to see which of their methods is most successful for the RdGG.

### 9.1.6. Performance measures: Waiting time

Patients' waiting time should be minimized; however, this is more important for urgent patients than for less urgent patients. Therefore waiting time can be included in the priority of patients.

### 9.1.7. Performance measures: Medicinal/PPE stock

The medicinal or PPE stock is not included in the articles. This is not surprising as during the time writing the articles, there was no need to minimize the use of medicine or PPE stock because of (global) shortages. This performance measure should only be used if there are massive shortages of medicine or PPE. As this is not expected, it might not be necessary to include this in the planning model. However, it should be actively monitored.

### 9.1.8. Constraints

Lots of constraints should be added to the model to make it feasible. For example, the available ORs and time [22, 27], surgeon and patient availability [22], no duplicate assignments [11, 18], prioritizing the owner of the block [18], but also the availability of necessary equipment like X-ray, certain surgeries that can only be performed in particular ORs, and many more. More extensive research has to be done at the planning department of the RdGG to extract all the necessary constraints.

### 9.1.9. Solution techniques

All articles use some form of linear programming to find an optimal solution to the planning problem. Some articles use lexicographical goal programming [18, 22]. This optimizes one goal first and then optimizes the second goal. It is also possible to add a weighting to the goals to prevent prioritizing one goal over the other goal. In future research should be checked what solution technique should work best in the RdGG. A weighted goal optimization is probably suited better than lexicographical goal programming, as patient priority, leveling, and utilization are all very important.

### 9.1.10. Uncertainty

Including uncertainty is not necessary for the planning for the RdGG. The duration of surgery is now taken by the median of the last 19 similar surgeries. This seems to work well for the hospital, though it can be investigated if other ways would work even better.

### 9.1.11. Planning level

The COVID-19 OR planning of the RdGG should focus on making a new OR planning. During a COVID-19 wave, when elective care is downscaled, the MSS can be overruled. Therefore it might be best to plan patients without a surgical schedule while still trying to combine surgeries of one surgeon, comparable to the model of Tan et al. [22].

## 9.2. Feasibility for the hospital

None of the selected OR planning models comply with all OR planning demands during COVID-19. Therefore a new OR planning model should be made. To make a feasible model, all the aspects described above should be included. Also, additional research should be done to find additional aspects to include.

# 10

# Part 3: Introduction - Proof of concept

In this chapter, the approach of both the proof of concept and the testing of the proof of concept are explained. This chapter focuses on the research subquestion "How does a proof of concept of the OR planning model perform?".

## 10.1. Focus of proof of concept

To answer the research question, "What planning models should the Reinier de Graaf hospital use to assist the OR planning process during COVID-19", we need to define how to incorporate the most critical performance measures. In previous sections is found that patient priority and patient leveling are the most critical performance measures for an OR planning model during COVID-19. In literature, many different models look at the leveling of the outflow towards the ICU and the ward and have success in achieving those goals [5, 7, 21, 22]. However, there are only a few models that focus on patient priority [13]. Planning patients based on priority ensures that patients who need surgery within a specific period should indeed have surgery within that period. Of the selected models that plan further than one day ahead, only Ozkarahan [18] includes patient priority. He states that other ranking techniques than his should be investigated. To give a good recommendation to the RdGG, it has to be investigated how patient priority can be used in a planning model. Therefore the focus will be on making a proof of concept to check if it is possible to schedule patients based on their priority differently than Ozkarahan [18] did and compare this way with his.

## 10.2. Planning patient priority in the Reinier de Graaf

In the RdGG, the goal is to plan patients on the waiting list within five weeks; however, this is usually impossible. Patient priority values are not used to differentiate between those patients, except for more urgent patients communicated to the planning department by the doctors. Acute care (<24h) is not planned by the planning department but is planned directly at the OR department. Acute care is mostly planned in the timeslots reserved for acute care. For example, on Monday, this is one afternoon (4 hours) for general acute surgeries. Semi-acute care (<1 week) does not enter the waiting list and is directly planned into the existing surgical schedule. The surgeries already planned for that day can be moved around or rescheduled if necessary. Because both acute and semi-acute patients do not enter the waiting list, those are excluded from the planning model.

## 10.3. Approach

Based on the articles of Tan et al. [22] and Ozkarahan [18], an optimization algorithm is used to plan prioritized patients. Below this approach is stated. More details can be found in Appendix A.7. A schematic overview of the model can be found in Figure 10.1.

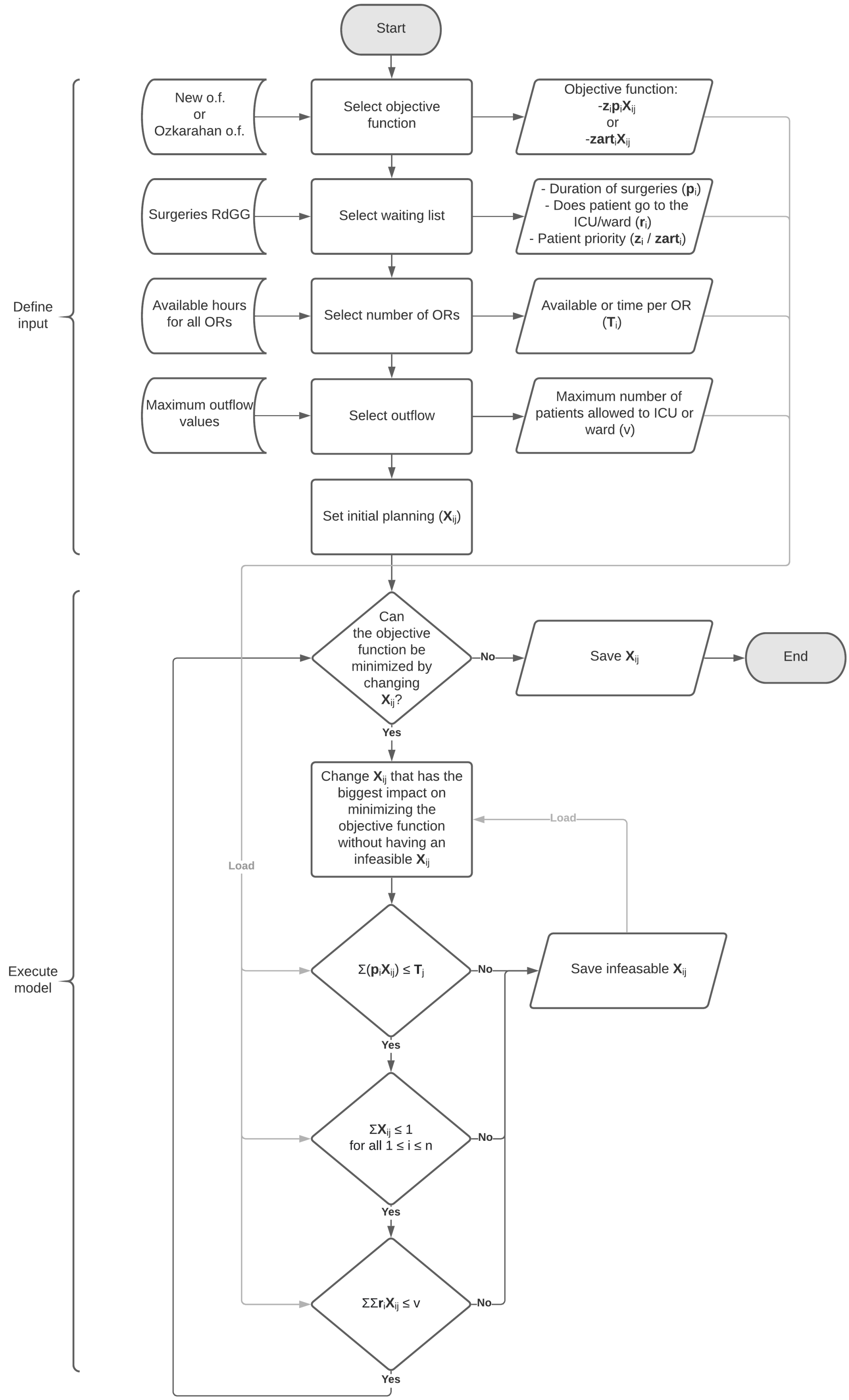


Figure 10.1: Flowchart of the model used to test the difference between the objective functions. It describes defining the input and model execution. $i$ refers to the n surgeries on the waiting list. $j$ refers to the m ORs. $\mathbf{X}_{ij}$ defines if a patient is planned (1) or not (0) in an OR. $\mathbf{p}_i$ is the duration of surgery. $\mathbf{T}_i$ is the available OR time per OR. $\mathbf{r}_i$ defines if a patient goes to the ICU or ward after surgery. $v$ is the maximum number of patients allowed to go to the ICU or ward. $\mathbf{z}_i$ is the priority value. $\mathbf{zart}_i$ is the article's priority value.

### 10.3.1. Objective functions

Two objective functions will be compared, a new one and one from the article of Ozkarahan [18]. The new objective function tries to maximize the planned priority values of patients per time. It is expected that in this way, the patients with the highest priority will be planned first until there is not enough surgical time available. Then the next patient with the highest priority value that fits will be planned. This will be called the article's objective function. As it is unknown what patients were more urgent according to doctors, the patient priority of the NZA[16] will be taken to prioritize the patients to be planned, as described in Appendix A.7. The priority value is the sum of the NZA level's value and the number of days on the waiting list, as shown in Table 10.1.

The second objective function is the one by Ozkarahan [18]. He sorts the patients based on who should be treated first, gives the least urgent patient priority value 1, gives the next least urgent patient value 2, and so on. The most urgent patient, therefore, receives the highest priority value. In the article of Ozkarahan [18], the priority is based on what the surgeons say is the most urgent patient; this information is unavailable in this research. Therefore, the most urgent patient is the patient who gets the highest score in the article's objective function, and so on, as shown in Table 10.1. With those priority values, a good comparison can be made between the two objective functions. The formulations for the objective functions can be found in Section 11.2.3.

Table 10.1: Different examples of priority values based on NZA level and the number of days on the waiting list.

| Patient | NZA level | Time on waiting list | **Priority article's** | **Piority Ozkarahan** |
|---|---|---|---|---|
| I | C | 0 | **164** | **7** |
| II | D | 0 | **147** | **6** |
| III | E | 0 | **117** | **4** |
| IV | F | 0 | **86** | **3** |
| V | G | 0 | **0** | **1** |
| VI | E | 30 | **147** | **5** |
| VII | G | 10 | **10** | **2** |

### 10.3.2. Model testing

To test the effect of the two different patient priority objective functions, different situations will be evaluated for both objective functions. The outflow towards the ICU and ward is set to a maximum of either 17 or 5 to represent a normal situation and a severe COVID-19 situation. Also, two different situations of OR availability are evaluated. The number of ORs tested is set to 8 ORs to represent the normal situation and 4 ORs to represent the COVID-19 wave, as shown in Section 4.4.1. Lastly, three different waiting lists are examined. The model selects patients to plan from those waiting lists. As the real waiting lists from the RdGG are not available, waiting lists will be generated from the performed surgeries. If during COVID-19 the elective care is downscaled, the waiting list can get longer as new patients get on the waiting list, but fewer surgeries are performed. According to the interviews, as shown in Section A.2, it might also be possible that fewer patients will be on the waiting list, as there can be fewer screenings during COVID-19 times. For those two reasons, there will be three different waiting lists made, a regular one, a long one, and a short one. The different maximum outflow, number of open ORs, and waiting lists result in 12 different situations to test for two objective functions, so 24 situations in total.

# 11

# Part 3: Methods model phase

This chapter describes the methods of the comparison of the two objective functions that prioritize patients. First, the model is explained, in which the assumptions, constraints, and objective functions are addressed. Next, it is explained how the model tests are performed.

## 11.1. Description of the model

The built model will plan elective surgeries for one day to save time running the model. Assumed is that this will give similar results as a planning for one week or even longer. Matlab R2020b is used to program everything. The minimization is done using the simplex method, as described in Appendix A.7.

### 11.1.1. Assumptions

In order to make a model, assumptions are made. The first three assumptions are based on interviews with the RdGG. It is assumed that:

- A surgery starts when the patients enter the room and ends when the patient exits.
- Fifteen minutes of clean up and set up time have to be planned between every patient.
- In 7 of the ORs, there are 8 hours of surgical time available, and in 1 OR, there are 4 hours of surgical time available.
- The surgeries planned by the planning department are elective surgeries.
- NZA priority codes are known for every surgery to be planned.
- The estimated surgical duration is the real surgical duration.
- The estimate if a patient goes to the ICU or ward is set to yes if the date of departure is at least one day after the date of surgery.
- The waiting lists created from surgeries in 2019, week 13, and the weeks before, are realistic.

## 11.2. The model in formulas

### 11.2.1. Notations

The notation used in the formulation is given below:
$i$ refers to the n surgeries on the waiting list.
$j$ refers to the m ORs.
$\mathbf{X}_{ij}$ is a decision variable: $\mathbf{X}_{ij}$= 1 if surgery $i$ is assigned to OR $j$; and 0 otherwise, where $i = 1,...,n$ and $j = 1,...,m$.
$\mathbf{p}_i$ is the duration of surgery $i$ including 15 minutes clean up and set up time; where $i = 1,...,n$.
$\mathbf{T}_i$ is the available OR time per OR, including an extra 15 minutes; where $j = 1,...,m$.
$\mathbf{r}_i$ is a decision variable, $\mathbf{r}_i$=1 if the patient will go to the ICU or ward, and 0 otherwise; where $i = 1,...,n$.

$v$ is the maximum number of patients allowed to go to the ICU or ward.
$\mathbf{z}_i$ is the priority value assigned to operation $i$; where $i = 1,...,n$. This priority value is based on the NZA priority level of the surgery, and on the duration the patient has been on the waiting list. The full explanation of how $Z$ is calculated can be found in Section 10.3.1
$\mathbf{zart}_i$ is the article's priority value assigned to operation $i$; where $i = 1,...,n$. This priority value is $n$ for the highest value in $\mathbf{z}_i$ and 1 for the lowest.

### 11.2.2. Constraint formulations

**Constraint 1: OR utilization restriction**

Every OR can only be used for a maximum amount of time per day.

$$\sum_{i=1}^{n} \mathbf{p}_i \mathbf{X}_{ij} \leq \mathbf{T}_j \tag{11.1}$$

**Constraint 2: Unique assignment restriction**

Every patient can only be assigned to 1 OR.

$$\sum_{j=1}^{m} \mathbf{X}_{ij} \leq 1 \forall 1 \leq i \leq n \tag{11.2}$$

**Constraint 3: Outflow restriction**

The daily outflow of patients cannot exceed a certain amount.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \mathbf{r}_i \mathbf{X}_{ij} \leq v \tag{11.3}$$

### 11.2.3. Objective functions

**Objective function 1: Patient priority**

The importance of the surgeries is defined by a priority value. The objective of this goal is to plan as much time as possible with the most urgent patients. The negative of the planned surgeries' priority times the surgeries duration should be minimized.

$$Minimize: -\mathbf{z}_i \mathbf{p}_i \mathbf{X}_{ij} \tag{11.4}$$

**Objective function 2: Patient priority by Ozkarahan [18]**

A priority value defines the importance of the surgeries. The objective of this goal is to ensure that the most important surgeries are scheduled. The negative of the planned surgeries' articles priority should be minimized.

$$Minimize: -\mathbf{zart}_i \mathbf{X}_{ij} \tag{11.5}$$

## 11.3. Model testing

To test if the model does what it should, tests with simplified models are performed; those are explained in Appendix A.8. To test how the two objective functions perform in comparison with each other, different situations are simulated. The model is run for the availability of 8 and 4 ORs, for an available outflow towards the ICU and ward of a maximum of 17 or 5 patients, and for three different waiting lists, a short one, a regular one, and a long one. The effect of the different situations on the output is also checked. The following performance measures are compared:

- Number of planned patients
- Utilization of the OR
- Assigned priority value of planned patients
- Assigned priority of planned patients per hour
- Amount of planned patients per position on the waiting list
- Number of patients per NZA priority

- Time on the waiting list of planned patients

The results are visualized and compared with statistical tests to see if the outcomes of the objective functions are statistically different. First, the data's normality is checked; if the data is normally distributed, a t-test is performed; if not, a Whitney U test is performed. To compare the number of planned patients between the different situations, a paired t-test or a Wilcoxon signed-rank test is performed. A p-value lower than or equal to 0.05 is significant. [10] The models will be run on surgeries performed in the RdGG. The waiting lists will be made as follows:

Shorter waiting list:
Surgeries priority C are selected from weeks 12 and 13 in 2019.
Surgeries priority D are selected from weeks 11 to 13 in 2019.
Surgeries priority E are selected from weeks 10 to 13 in 2019.
Surgeries priority F and G are selected from weeks 9 to 13 in 2019.

Regular waiting list:
Surgeries priority C are selected from weeks 12 and 13 in 2019.
Surgeries priority D are selected from weeks 10 to 13 in 2019.
Surgeries priority E are selected from weeks 8 to 13 in 2019.
Surgeries priority F and G are selected from weeks 6 to 13 in 2019.

Longer waiting list:
Surgeries priority C are selected from weeks 12 and 13 in 2019.
Surgeries priority D are selected from weeks 10 to 13 in 2019.
Surgeries priority E are selected from weeks 6 to 13 in 2019.
Surgeries priority F and G are selected from weeks 2 to 13 in 2019.

# 12

# Part 3: Results - Proof of concept

The results of the model's testing, as described in Chapter 11, are displayed in this chapter. The article's objective function is compared to the objective function of Ozkarahan [18]. First, the waiting lists are visualized and then the two objective functions are compared.

## 12.1. Data

The model is tested on the performed surgeries done in the RdGG. The short waiting list consists of 655 patients adding up to 780 surgical hours, the regular waiting list consists of 1000 patients, covering 1149 surgical hours, and the long waiting list consists of 1381 patients, with 1589 surgical hours. In Figure 12.1, the number of patients per priority level is shown for the three waiting lists. The short waiting list has the most patients around priority values 100 and 160. The regular and long waiting lists have more patients with a high priority value.


Figure 12.1: The number of patients per priority value of the patients on the short, regular, and long waiting lists.

In Figure 12.2, the number of surgical hours per priority value is shown. The distribution of the surgical hours looks roughly similar to the distribution of the number of patients.

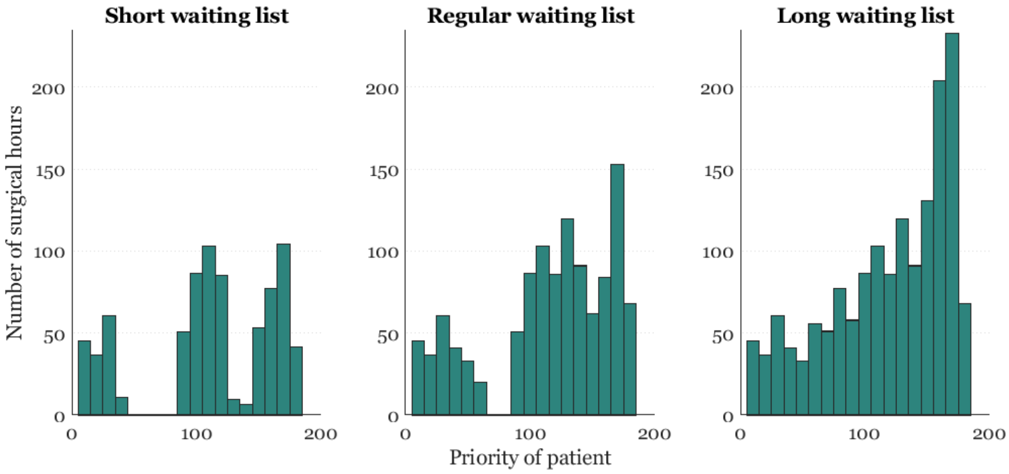


Figure 12.2: The number of surgical hours per priority value of the patients on the short, regular, and long waiting lists.

In Figure 12.3, the probability distribution of the NZA priority levels can be seen per waiting list. This shows that in all waiting lists, most patients have priority level F, which means surgery should be performed within 3 months. Priority levels C (<2 weeks) and E (<2 months) have the smallest amounts. Levels E and G (>3 months) have a relatively lower probability than the levels before them as there were fewer surgeries with those levels in the previous planning.

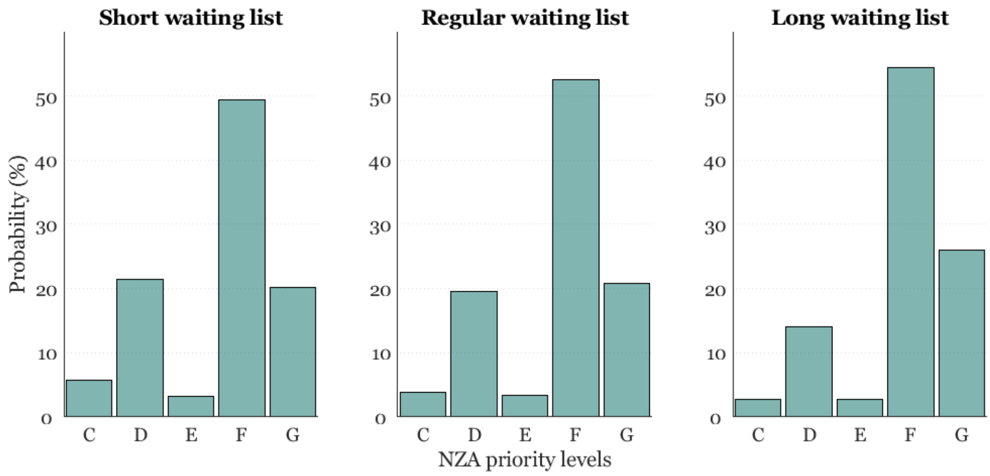


Figure 12.3: The NZA priority levels of the patients on the short, regular, and long waiting lists.

## 12.2. Comparison of objective functions

The objective functions are compared by looking at different performance measures. The performance measures are:

- Number of planned patients
- Utilization of ORs
- Assigned priority value of planned patients
- Assigned priority value of planned patients per hour
- Position on the waiting list of planned patients
- Number of patients per NZA priority
- Time on the waiting list of planned patients

The two models are run for the 12 different situations, as described in Section 11.3, which gives 24 different outputs. All the above objective functions' figures are visualized for the 24 different outputs in Appendix A.10. In this section, a more summarized overview is given, with box plots of all the data points of the different runs per objective function and the comparison between the objective functions with statistical tests. In the box plots, the results of all the runs are displayed as dots, scattered only in the x-direction. The average of the medians of all 12 runs per objective value is given with the p-value of the statistical test. The average of medians of the values is notated as $\bar{x}$. As all distributions are not normally distributed, which can be seen in Appendix A.9, Whitney U-tests are used for the statistical comparison. Only to compare the number of planned patients between the different situations, a Wilcoxon signed-rank test is performed.

### 12.2.1. Number of planned patients

In Figure 12.4, the distribution of the planned number of patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow. Table 12.1 shows that the article's objective function plans significantly less patients than the objective function of Ozkarahan [18] (p<0.001, $\bar{x}_{art} = 26.7$, $\bar{x}_{Ozk} = 102.6$).

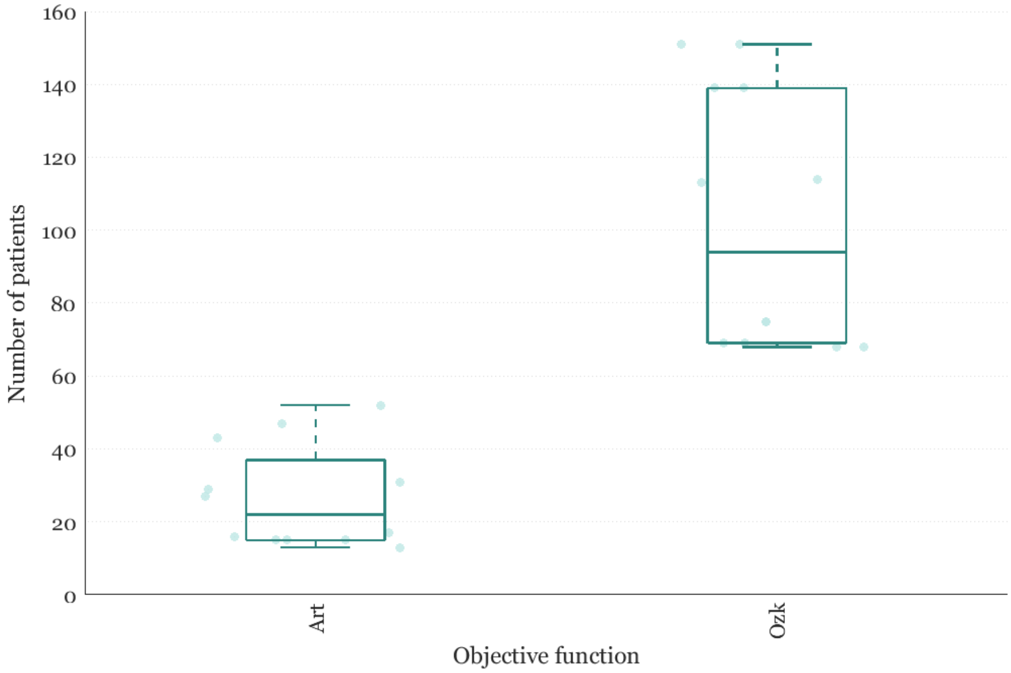


Figure 12.4: The number of planned patients per run for the article's objective function and the objective function of Ozkarahan [18].

Table 12.1: P-value of the Wilcoxon signed rank-test to compare the article's objective function with the objective function by Ozkarahan [18] for the number of planned patients and its averages.

| P-value | Average article's objective function | Average objective function Ozkarahan [18] |
|---|---|---|
| <0.001 | 26.7 | 102.6 |

### 12.2.2. Assigned priority value of planned patients

In Figure 12.5 the distribution of utilization of the ORs per situation is shown. Table 12.2 shows that the utilization is significantly higher with the article's objective function compared to the objective function of Ozkarahan [18] (p<0.001, $\bar{x}_{art} = 88.7\%$, $\bar{x}_{Ozk} = 43.8\%$).

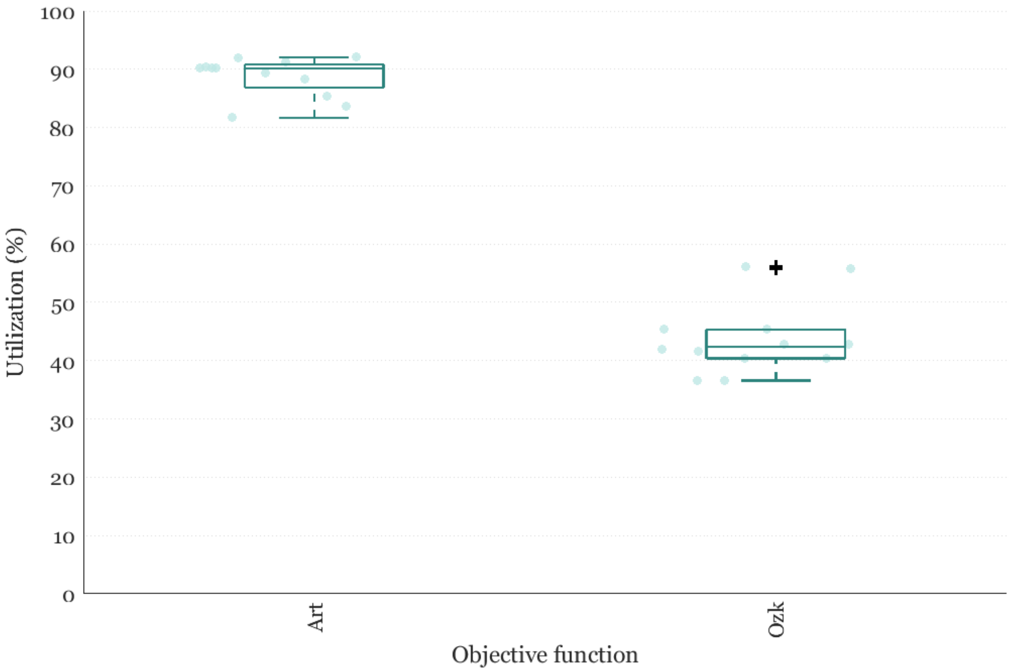


Figure 12.5: The utilization of the ORs of all 12 runs for the article's objective function and the objective function of Ozkarahan [18].

Table 12.2: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the utilization of the ORs and its averages.

| Difference between | P-value | Average article's objective function | Average objective function by Ozkarahan [18] |
|---|---|---|---|
| Objective functions | <0.001 | 88.7% | 43.8% |

### 12.2.3. Assigned priority value of planned patients

In Figure 12.6, the distribution of assigned priority value of all planned patients per situation is shown. Table 12.3 shows that the assigned priority value is significantly higher with the article's objective function compared to the objective function of Ozkarahan [18] ($p<0.001$, $\bar{x}_{art} = 171$, $\bar{x}_{Ozk} = 137$).

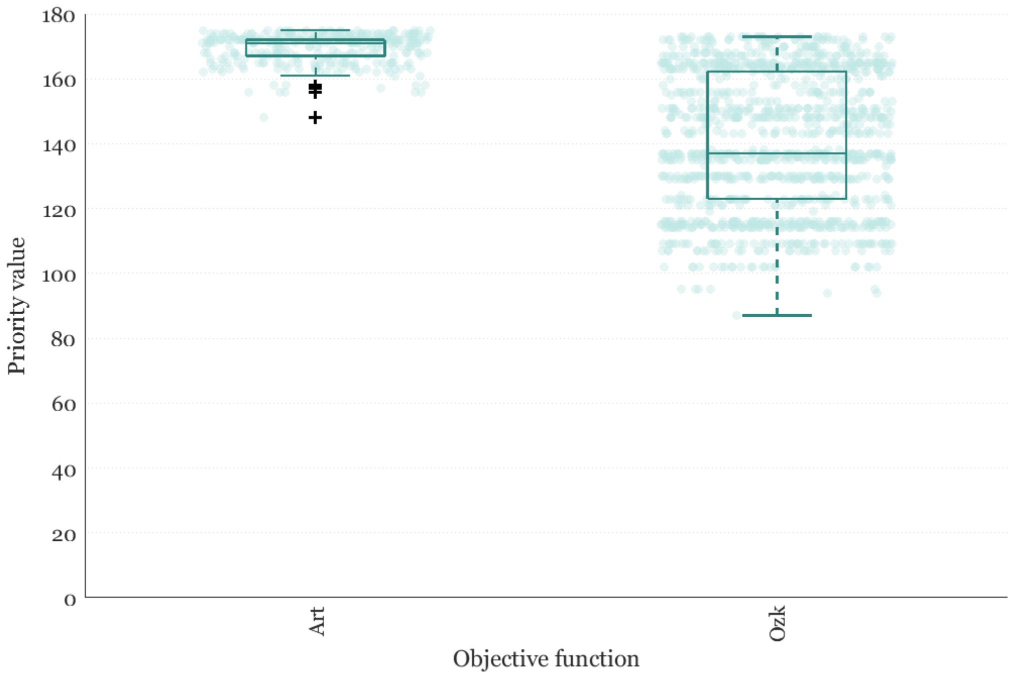


Figure 12.6: The assigned priority value of all planned patients of all 12 runs for the article's objective function and the objective function of Ozkarahan [18].

Table 12.3: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the assigned priority value of planned patients and its averages.

| P-value | Average median article's objective function | Average median objective function by Ozkarahan [18] |
|---|---|---|
| <0.001 | 171.0 | 137.0 |

### 12.2.4. Assigned priority of planned patients per hour

In Figure 12.7, the distribution of the assigned priority of planned patients per hour per situation is shown. Table 12.4 shows that the assigned priority of planned patients per hour is significantly higher for the article's objective function as opposed to that of Ozkarahan [18] (p<0.001, $\bar{x}_{art} = 173.5$, $\bar{x}_{Ozk} = 142.7$).

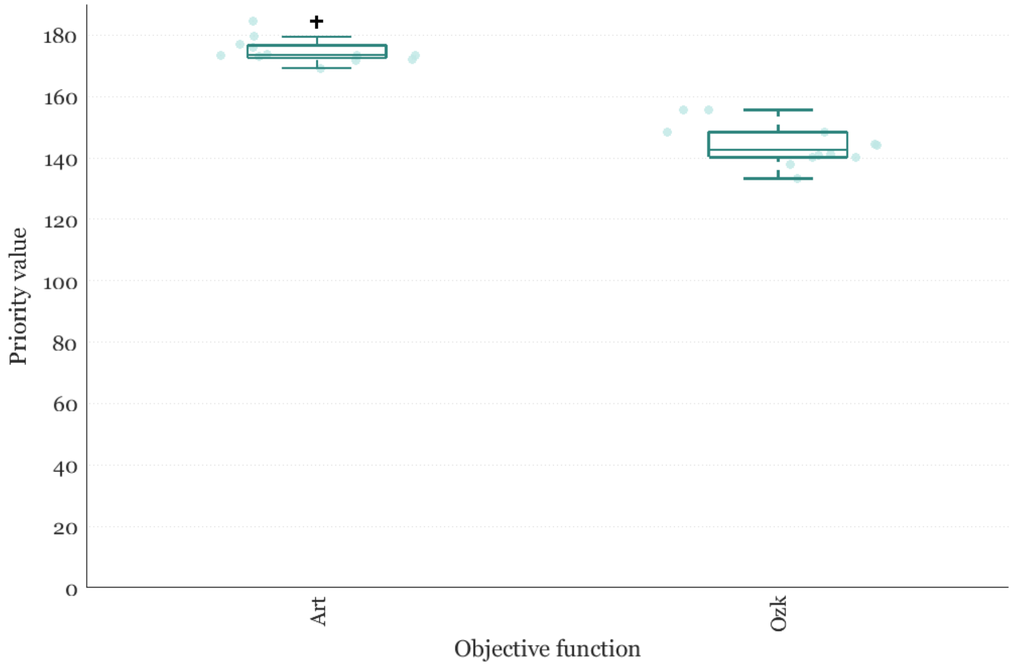


Figure 12.7: The assigned priority value per hour of all planned patients of all 12 runs for the article's objective function and the objective function of [18]

Table 12.4: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the assigned priority of planned patients per hour and its averages.

| P-value | Average median article's objective function | Average median objective function by Ozkarahan [18] |
|---|---|---|
| <0.001 | 173.5 | 142.7 |

### 12.2.5. Position on the waiting list of planned patients

In Figure 12.8, the distribution of the position on the waiting list of all planned patients per situation is shown. The most urgent patient gets position number 1, the second number 2, this continues down the waiting list. Table 12.5 shows that the position on the waiting list of planned patients is significantly higher for the objective function of Ozkarahan [18] as opposed to the article's objective function (p<0.001, $\bar{x}_{art} = 22$, $\bar{x}_{Ozk} = 293$).

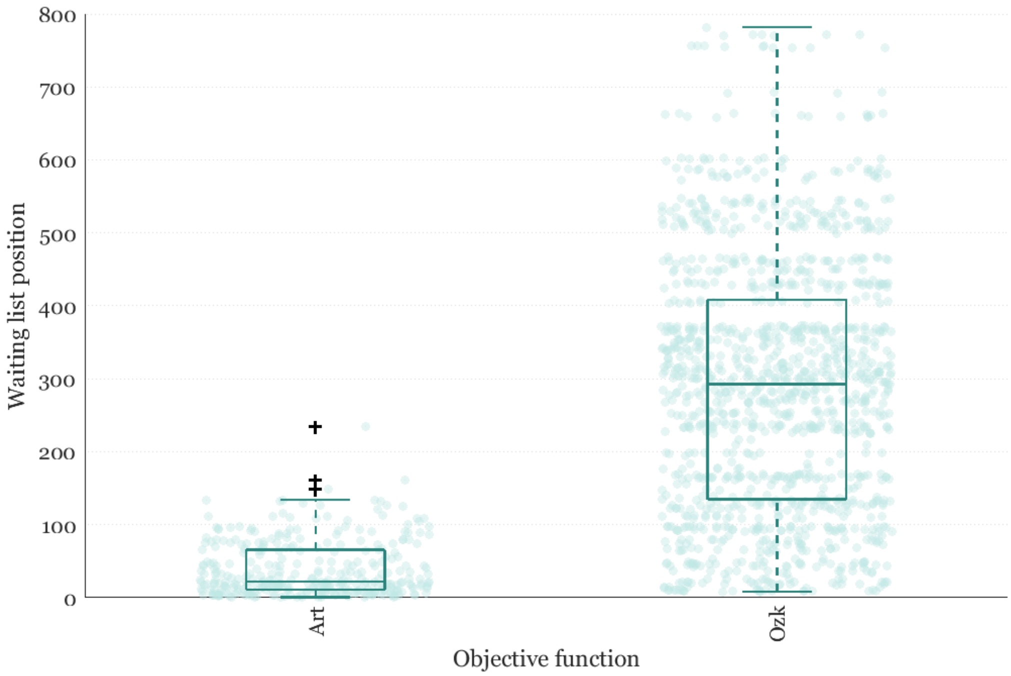


Figure 12.8: The position on the waiting list, sorted on priority value, of all planned patients of all 12 runs for the article's objective function and the objective function of [18]

Table 12.5: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the position on the waiting list of planned patients and its averages.

| P-value | Average median article's objective function | Average median objective function by Ozkarahan [18] |
|---|---|---|
| <0.001 | 22.0 | 293.0 |

### 12.2.6. NZA priority

In Figure 12.9, the distribution of the NZA priority of all planned patients per situation is shown. The NZA priorities are approximated by the numbers 1 to 5, referring to categories C to G, respectively. Table 12.6 shows that the NZA priority of the planned patients is significantly lower (which means more urgent NZA priority) for the article's objective function compared to the objective function of Ozkarahan [18] ($p<0.001$, $\bar{x}_{art} = 1.6$, $\bar{x}_{Ozk} = 3.3$).

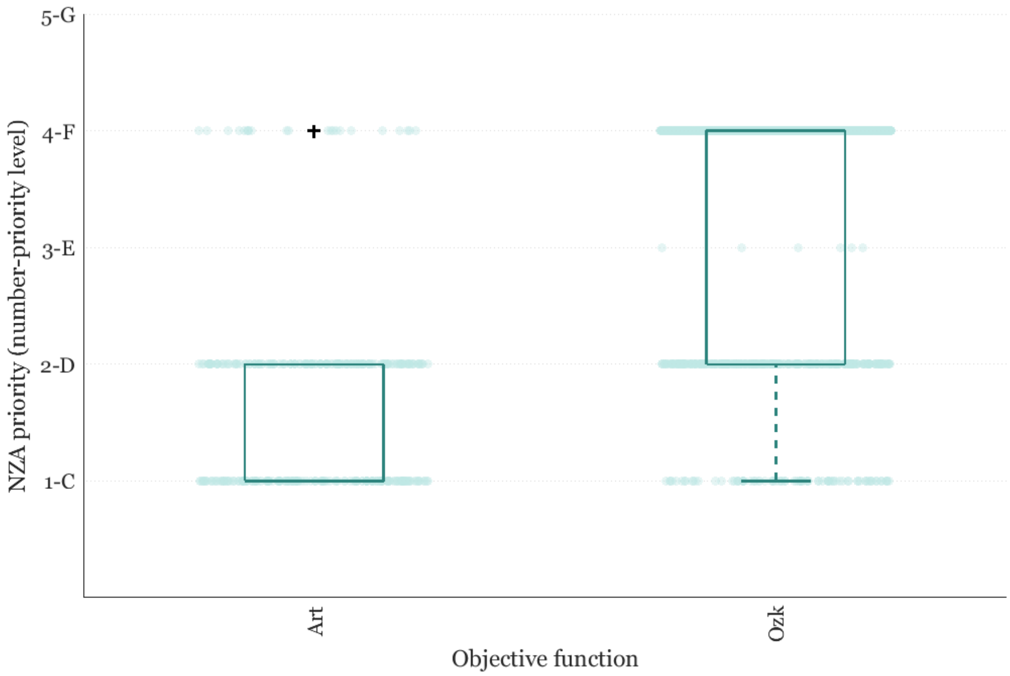


Figure 12.9: The NZA priority scaled to numbers where C is 1 and G is 5 of all planned patients of all 12 runs for the article's objective function and the objective function of [18]

Table 12.6: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the NZA priority of the planned patients and its averages.

| P-value | Average mean article's objective function | Average mean objective function by Ozkarahan [18] |
|---|---|---|
| <0.001 | 1.6 | 3.3 |

### 12.2.7. Time on the waiting list of planned patients

In Figure 12.10, the distribution of the time on the waiting list of all planned patients per situation is shown. Table 12.7 shows that patients that are selected to be planned had a significantly shorter waiting time for the article's objective function than for Ozkarahan [18] (p<0.001, $\bar{x}_{art} = 11.0$, $\bar{x}_{Ozk} = 30.0$).

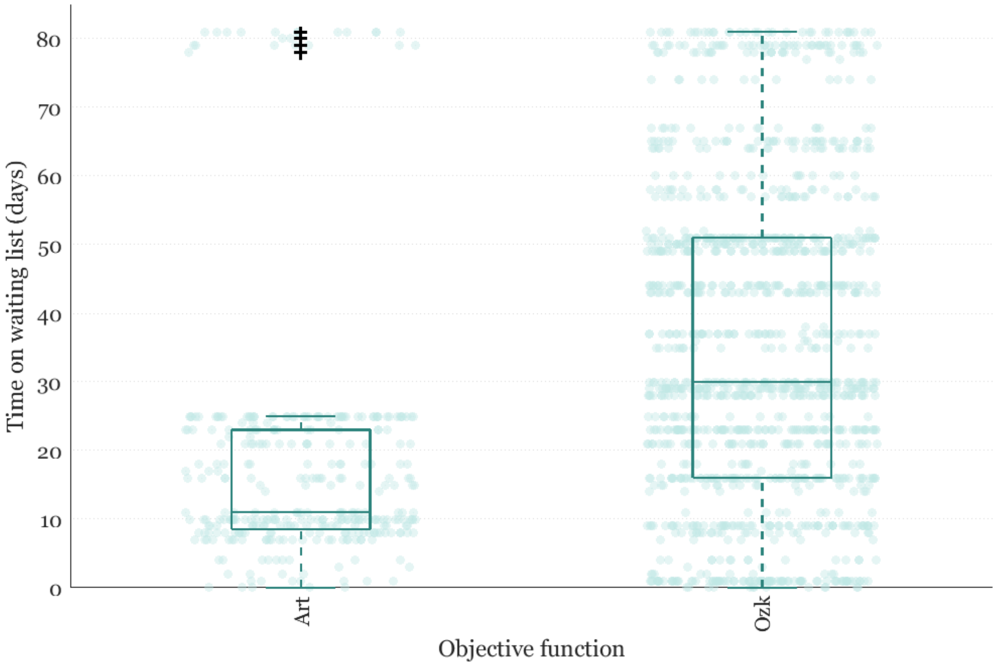


Figure 12.10: The time patients are on the waiting list of all planned patients of all 12 runs for the article's objective function and the objective function of [18]

Table 12.7: P-value of the Whitney U-test to compare the article's objective function with the objective function by Ozkarahan [18] for the time on the waiting list of planned patients and its averages.

| P-value | Average median article's objective function | Average median objective function by Ozkarahan [18] |
|---|---|---|
| <0.001 | 11.0 | 30.0 |

# 13

# Part 3: Discussion - Proof of concept

Part 3 focuses on planning patients based on their priority. This can be a part of an OR planning model and should be part of an OR planning model for the RdGG. In Section 9.1.2, the method of Ozkarahan [18] is described. There are, however, a few flaws that can be immediately seen in his model. Ozkarahan [18] ranks patients and gives all a priority value that increases by urgency. With his way of ranking, the difference between two consecutive patients is always the same, which does not have to be the case in real life. Ozkarahan [18] also asks the specialist to rank all their patients on the waiting list based on their urgency. This is unfeasible for the hospital. To plan patients based on their priority without these stated flaws, a new method has been created, called the article's method. This article's method aims to plan patients based on their urgency. This urgency is a combination of the NZA priority [16] and the time a patient has been on the waiting list. Two patients can have the same priority value if they have the same NZA priority and admission date to the waiting list. Patients can also have the same priority value if the patient with a lower NZA priority is on the waiting list for a more extended period. The article's method's goal is to plan patients with the highest priority values first and then fill the spare time with surgeries that have a priority value as high as possible.

## 13.1. The model

### 13.1.1. Minimization algorithm

The model was made in Matlab; Matlab was chosen because it works well with optimization, and as the researcher had experience with the program. In Matlab, multiple functions can be used for minimization. Planning patients gives a discrete (even binary) input to the optimization formulas. Many of Matlab's functions focus on continuous input variables. A continuous optimization method can be used with constraints to get binary inputs; however, this will make the model less efficient as it will still search for continuous input variables. Therefore a function that uses discrete input variables will be used. Matlab has two of those: mixed-integer linear programming, "intlinprog", which finds the minimum of a linear problem, and the genetic algorithm, "ga", which finds the minimum of both linear and non-linear functions using the genetic algorithm. [1]. Intlinprog is chosen as all five articles of part 2 use linear programming, including Tan et al. [22]. Intlinprog makes use of the Simplex Method. The Simplex Method always finds the global solution, so one can be sure of getting the right output. Primal Simplex is selected to speed up the process. Primal Simplex will find the optimal solution; dual Simplex will find what other solutions are optimal as well [14]. As only one optimal solution is needed in this case, the primal Simplex Method suffices. The optimization is cut off after two hours of optimizing if it has not finished. This means that it might be possible that the optimal solution is not found yet. However, as the Simplex Method optimization starts by making changes that have the most significant impact on the output, the solution found after two hours is most likely very close to the optimal solution. If the solution is close to optimal, this will probably be good enough for the OR, as this suboptimal solution most likely leaves a few minutes of available OR time unplanned, or planned a patient with a slightly lower priority value than should have been planned.

### 13.1.2. Assumptions

To create the model, different assumptions were made. Those assumptions can influence the outcome. The assumptions are described below, including why they were chosen and what the influence of the assumptions might be. Fifteen minutes of cleaning and preparation time are taken; this is a rough estimate based on what the planners in the RdGG use. When similar surgeries are planned after each other, the preparation time might be lower. Therefore when a full planning model is created for the RdGG, more research should be done on the cleaning and preparation time. Right now, only elective care is planned. In a full RdGG model, the option of adding semi-acute care should be available. It should be investigated how this will be done: by canceling already planned patients or by keeping some time on the schedule empty. If some time in the schedule is kept empty, this can be filled with elective care a couple of days in advance if there are no semi-acute surgeries to be planned. Assumed is that NZA priority codes are known for all surgeries to be planned. In the RdGG, this is not the case. Therefore if this is used, specialists should add the NZA priority before the surgery gets planned. Based on the NZA list, this can be partly automized by giving the specialist pre-defined options based on diagnosis codes. Because performed surgeries were created, it was known beforehand if a patient would go to the ICU or ward afterward. In a real situation, this is not known for all surgeries, for example, surgeries with unexpected complications. More research can be done on how to incorporate this. An option could be to multiply the chance a patient goes there by one and add up all these values; this estimates the number of people who will go to the ICU or ward. It is assumed that in 7 ORs, there are 8 hours of surgical time available. This can be 8.5 hours if one specialism performs surgery during the morning and afternoon. The real available time should be taken into account when planning the OR; this is easily changeable. The waiting lists are based on performed surgeries; therefore, they can differ from what they would be. Week 13 in 2019 and before are chosen to make waiting lists because week 13 is a week where there was no holiday and because it seems no different from the weeks around it in the general overview. Taking a different week as a basis will generate a different waiting list. However, a different waiting list will most likely not change anything in the results of the comparison of the two objective functions.

### 13.1.3. Validation

In Appendix A.8, the model is tested with a simplified output. This shows that the model plans the patient with the highest priority first until the next patient with the highest priority does not fit in the OR schedule. Then the next patient with the highest priority that fits in the left time is chosen. If the next patient leaves a time gap that other patients cannot fill, the model might choose two patients with a lower priority value that fits the schedule better. This results in higher utilization of the OR but can result in high priority patients not being planned. To make it more important to plan patients with a high priority, the priority value can be squared, which results in the priority value weighing more than previously compared to utilization. What choice should be made here depends on the hospital's situation and what ought to be necessary by the hospital.

## 13.2. Comparison of the objective functions

During COVID-19, it is vital to plan patients based on their priority. This priority depends on within what time a patient should undergo surgery (NZA priority [16]) and for how long the patient has been on the waiting list. A priority value has been made to combine the two. To see how the two objective functions perform, the number of patients planned, OR utilization, priority values, priority value per hour, position on the waiting list, NZA categories, and time waiting have been compared. It can be seen that the article's objective function plans fewer patients and has a better utilization than the objective function of Ozkarahan [18]. This is because Ozkarahan [18] plans many patients of short duration. As every surgery is followed by 15 minutes of cleaning and preparing the OR, the utilization of Ozkarahan [18] is very low. The article's objective function plans only patients with a high priority value. Ozkarahan [18] plans both patients with high priority values as patients with medium priority values. To see the effect of this, the planned priority per hour is also shown, in which the article's objective function also shows higher planned priority, as is to be expected. The patients are sorted on the waiting list based on their priority value. This gives the patient to be treated first, the first position on the waiting list, which is number 1. The article's objective function plans patients with lower values. Ozkarahan [18] plans patients from the top of the waiting list to about halfway. The priority value is based on the NZA priority and since when the patients are on the waiting list. Therefore those two are shown separately as well. The article's objective function plans mostly patients from category C and D, Ozkarahan [18] plans mostly patients from category D and F. This means that the article's objective function plans more patients that need to undergo surgery within a shorter amount of time. The article's objective function plans mostly patients that are on the waiting list for not that long, compared to Ozkarahan [18]. This is probably because of the way the waiting lists are made. Patients with a higher NZA priority were taken from shorter periods in the past, and therefore do have not been on the waiting list for long. Ozkarahan [18] plans many patients, both on the waiting list for a short and longer period of time.

When comparing the article's objective function with the objective function of Ozkarahan [18], the first thing that can be seen is that Ozkarahan [18] plans many patients compared to the article's objective function. This is because Ozkarahan [18] tries to maximize the sum of the planned priorities. This means that the more priorities are planned, the higher the sum. So when shorter surgeries are planned, more surgeries can be planned. For Ozkarahan [18], it would be better to plan three 20 minute surgeries with a priority value of 50 than one with a priority value of 100. This also explains the spread in priority values, positions on the waiting list, and time on the waiting list.

# 14 Discussion

To make room for COVID-19 patients, hospitals had to scale down their elective care all over the hospital, including in the OR. The same happened in the RdGG during the first COVID-19 wave. During this first wave, they scaled their surgeries down to only acute and semi-acute. In future downscaling, it might not be necessary to scale down as much. However, it is hard to define how much the OR should downscale. Also, there are no national plans on how hospitals should downscale and prioritize their waiting lists. When the COVID-19 situation suddenly changes, there is only a little time to change the OR schedule. Making a new OR schedule with only a little time and lots of extra COVID-19 related variables can be challenging. Plannings are made for only one day ahead because making the new schedule is so time-consuming, making it hard for certain specialisms to find patients willing to undergo surgery. A planning model can help the planning department in making an OR planning while keeping the COVID-19 related variables into account and while planning further than one day ahead.

## 14.1. The operating room planning of the Reinier de Graaf

To check if a planning model can help in the RdGG and see what improvements can be made, the OR planning in the RdGG is analyzed. In a COVID-19 OR planning, it is vital to take the priority of patients, leveling of the outflow, and utilization of the OR time into account. Prioritizing patients during the first COVID-19 wave went very well. All acute and semi-acute care was still performed, and only elective care was downscaled. The OR's outflow was downscaled as well; there were a maximum number of patients going towards the ICU and the ward. There was no specific focus on leveling the patients, but it is also unknown if they should be leveled more. The utilization of the OR was a lot lower during the COVID-19 wave, 66.3%, compared to 81.9% the year before. This means that there could have been more patients planned in the OR, as the open ORs were staffed, surgeons had enough available time, and not all patients have to go to the ward or ICU after surgery.

## 14.2. Existing planning models

To see what OR planning models are already available, multiple articles were analyzed. There are already many models in the literature focusing on leveling and utilization that can be used as inspiration for the RdGG. However, there are only a few that focus on patient priority. Of the selected articles, the way Ozkarahan [18] incorporates patient priority is the only feasible one for the RdGG. However, this way of prioritizing patients still seems to have its flaws. His prioritizing method makes the priority difference between all successive patients on the waiting list the same, which is never the case in real life. He also wants specialists to order patients manually. Therefore another prioritizing method should be made.

In the planning during regular times, the RdGG does not prioritize all patients. They only prioritize acute and semi-acute patients. Occasionally if a patient needs surgery quickly, the specialist calls the planning department. All the remaining patients are planned from the top of the waiting list; new patients are added to the bottom. All surgeries should be planned within five weeks; however, in reality, this is rarely feasible. This method works well for the hospital during regular times. When the OR's capacity is lower, for example, during COVID-19, this method will result in all surgeries to be delayed. For some surgeries, this might not be a problem; however, it will be for others. Therefore a different way of prioritizing patients should be used.

After the downscaling of the first COVID-19 wave, the RdGG could slowly start the elective surgeries again. Patients were planned based on their urgency. All specialists joined to make a priority list of the patients that had to be planned; their priority was based on their judgment and the NZA list [16]. This worked very well during the upscaling of the OR. The making of this priority list worked this well because all specialists worked together and were willing to give up their own surgical time for patients that needed it most. Now that specialists are more used to the COVID-19 situation, they are less willing to give up their surgical time. This can lead to discussions in prioritizing patients. Even if there will be no discussions, prioritizing patients in such a way is very time-consuming. Therefore, a different way of prioritizing patients should be used to automatically plan patients based on their priority.

## 14.3. Prioritizing patients

A new prioritizing method has been made that aims to plan the most urgent patients based on their NZA priority[16] and time on the waiting list while keeping a high utilization of the OR. This prioritizing method is compared to that of Ozkarahan [18] and outperforms that of Ozkarahan [18] based on utilization and planning more urgent patients. The two objective functions are compared in a simplified model containing only constraints to prevent exceeding the available OR time, exceeding the maximum outflow, and assigning patients more than once. Therefore, it is not tested how the objective functions would perform in a full model. When utilization and leveling are added as additional objective functions, the model of Ozkarahan [18] will most likely start to plan longer surgeries as well. However, when weighted goal optimization is used, the article's objective function will most likely still outperform that of Ozkarahan [18].

### 14.3.1. Applicaiblity for the Reinier de Graaf hospital

The article's objective function sorts patients based on their NZA priority value and how long they have been on the waiting list. During the first COVID-19 wave, specialists sorted patients awaiting surgery based on their urgency, in which they used the NZA priority list [16] as a guideline. Therefore sorting patients based on their NZA priority and time on waiting lists will most likely result in a similarly sorted waiting list. It should be researched if the change in priority value based on duration on the waiting list is realistic. These values might need to be changed, based on experience.

With a rough literature scan, the researcher checked other OR planning models that included patient priority. From this scan, it seemed that other patient priority methods were not necessarily better than the one designed in this article. However, additional research can be done on this matter.

## 14.4. Operating room planning model in the Reinier de Graaf hospital

### 14.4.1. During COVID-19

A planning model might improve the planning and planning process of the RdGG during COVID-19. As stated earlier, a model can incorporate patient priority without bringing all the specialists together every time. Also, an OR planning model can help justify why certain specialists get more OR time, as they have more urgent patients. An OR planning model can use available staff as an input to see how many ORs can stay or be opened. With an OR planning model, the outflow of the OR can be predicted and acted upon. If deemed necessary, the outflow can also be leveled. The model can also be used to take a look at what patients will be planned if the outflow has to be lower, to decide if ORs should be closed or not. More research should focus on how the downscaling of ORs should be incorporated into the model. Lastly, an OR planning model can make it less time consuming to plan, making it easier for planners to plan for more than one day when rescheduling all surgeries.

### 14.4.2. During regular times

An OR planning model is not only helpful during COVID-19 but can also be useful during regular times. Even though outflow might not be as crucial as during COVID-19, keeping the outflow into account while planning can prevent possible cancellations for surgeries. Also, monitoring appliances like x-ray while planning is currently a hard thing to do. When this is incorporated in a planning model, it can help the planning staff. Planning based on priority is currently done only slightly in the RdGG. Even though the current method seems to work, additional research can be done to see if this can be improved. Lastly, using a planning model can give more insight into the necessary surgical hours per specialism and specialist. At the moment, the MSS is based on previous years, but some say that the partition of hours is not up to date anymore. Taking away surgical hours can be a sensitive task; insight into the necessary number of hours can help.

### 14.4.3. Aspects of the operating room planning model

The aspects that should be included in an OR planning model during COVID-19 for the RdGG can be found in Table 14.1. As the COVID-19 OR planning model will assist the planning department during COVID-19, it is most useful to plan patients without using an MSS. It is, however, preferable to cluster surgeries by the same specialties and specialists. Weighted goal optimization is probably most suitable for the RdGG as patient priority, leveling, and utilization importance can change per situation, and its model focus can be easily adapted when using weighted goal optimization. However, other solution techniques should be considered and tested to see if some work better than others. The duration of running a model should also be considered as the Simplex Algorithm sometimes did not find the optimal solution after 2 hours of running a one-day planning. Future research should check what time the model should run to have a solution, optimal enough for planning the OR even though it might not be the most optimal solution. The patients planned by the model should be elective and semi-acute, as those are currently planned by the planning department. Patient priority includes both the NZA priority and the time on the waiting list, as is done by the newly made objective function of this article. Therefore, this refers to the performance measures of humanitarian goals and waiting time. It is also possible to include patient deferral by giving canceled patients a higher priority. This should only be done if there is enough time to plan patients within their priority timeframe. One point of attention for the patient priority is that the NZA priority should be added to the patients on the waiting list manually. Leveling the patients should be done by limiting exceeding the set thresholds and leveling the outflow towards the ICU and ward. Future research should focus on how important this leveling is and how it can best be done. Utilization should be optimized by minimizing overtime and undertime of the OR. More research should be done on how this can be best included in the planning model. Multiple constraints should be added, of which some are described in Table 14.1. More research should be done to see what extra ones should be included as well.

Table 14.1: Aspects to include in an OR planning model during COVID-19 for the Reinier de Graaf.

| | |
|---|---|
| **Planning level** | Plan patients without the use of an MSS. |
| **Solution techniques** | Use weighted goal optimization. |
| **Patient features** | Plan elective and semi-acute patients |
| **Goals:** | |
| - Patient priority | Include priority based on the NZA priority and the time on the waiting list; this is the new objective function stated in this article. It is also possible to give previously canceled patients a higher priority. |
| - Leveling | Limit exceeding the threshold and level the outflow of patients going towards the ICU and ward. |
| - Utilization | Minimize under- and overtime. |
| **Constraints** | Add multiple constraints, including the available ORs and OR time, surgeon and patient availability, equipment availability, and preferred ORs. |

## 14.5. Operating room planning model in other hospitals

This research focuses on what type of OR planning model would work best for the RdGG during COVID-19. There is even explained that using an OR planning model might be relevant outside of COVID-19. Expected is that such a model is not only applicable to the RdGG but might also be of use in different hospitals. All the research done has focused on the RdGG, the surgical data used was of the RdGG, and the interviewees were all from that hospital. However, the surgical data used does not significantly impact the outcome of this research, and it is expected that surgical data from another hospital will give similar results. Also, nearly all Dutch hospitals operate similarly, expected is therefore that a similar model would work in other Dutch hospitals as well. However, other countries might have different hospital systems and therefore need a different hospital. For example, some American private hospitals might find that underutilization is less important if that means canceling fewer surgeries. Therefore, before applying an OR planning model to a hospital, research has to be done to see what factors are essential to that hospital and how the model should be tweaked and implemented.

# 15 Conclusion

The OR planning during the COVID-19 crisis of the first half of 2020 performed well, but there were also some points of improvement. Acute and semi-acute surgeries were still performed, the outflow towards the ICU and ward was lower than normal, and the number of occupied beds in the ICU and wards by surgical patients was lower. However, the outflow towards the ICU and ward and the number of occupied beds by surgical patients in the two was not kept constant. Also the utilization was lower during the COVID-19 wave compared to the year before.

Different models have different aspects that comply with the OR planning demands during COVID-19. The models incorporated different patient levels, humanitarian goals, leveling, patient deferral, utilization, waiting time, constraints, solution techniques, and uncertainty. None of the models included medicinal or PPE stock.

There were no existing OR planning models found that are feasible for the RdGG during COVID-19. Therefore a combination of different models can be made. There was no feasible method found to plan patients based on their priority, so a new one had to be found here.

A comparison between one of the existing patient priority methods and a newly designed patient priority method was made. The newly designed method focused on planning patients based on within what period they needed to undergo surgery, based on the NZA priority list [16], and on their waiting time. The new method of prioritizing patients outperformed the existing method in terms of planning patients that are more urgent and in utilization.

This combined gives that the RdGG should make a planning model in which they plan patients without using of an MSS. The optimization should be done with weighted goal optimization to plan elective and semi-acute patients. Patient priority should be included based on the NZA priority and the waiting time. The outflow towards the ICU and the ward should not exceed a certain threshold and might have to be leveled more. Over- and undertime should be minimized. Lastly, multiple constraints should be added, including the availability of ORs, OR time, surgeons, patients, and equipment.

To conclude, using an OR planning model can help the RdGG assist their planning process. The model can help plan patients based on their priority while keeping the outflow below the threshold and leveled, and while keeping a high utilization of the OR. This will give the planning staff more time to plan patients further ahead and give them a better overview of how many ORs to open if the maximum outflow is reached, and on the usage of appliances.

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# A

# Appendix

## A.1. Performance measures for operating room planning models during COVID-19

To find performance measures that should be used to evaluate an OR planning model during COVID-19 a literature research is done (citetVanHartingsveldt2020). A quick summary of this research will be given here.

Scopus, PubMed and Web of Science are systematically searched for regular performance measures of OR planning models and for actions described by contingency plans for hospitals during pandemics. Studies are included based on predetermined inclusion criteria. Relevant characteristics are extracted from the included studies. Additional interviews are held with experts in the field to extract even more relevant characteristics and to confirm the previously found ones. Those results are then combined to find the performance measures that should be used for OR planning models during COVID-19.

### A.1.1. Performance measures

To get the performance measures that are important for an OR planning during COVID-19, OR models' performance measures are combined with actions described by contingency plans, both from literature and with the experience from experts in the field. This results in the following performance measures:

- Humanitarian goals
- Leveling
- Patient deferral
- Utilization
- Waiting time
- Other
  - Medicinal stock
  - PPE stock

**Humanitarian goals** is about saving as many lives as possible. When planning, starting with the most urgent surgery and postponing less urgent ones can save lives. This choice in who should undergo treatment first is called triage. If the OR has to be downscaled, there is less capacity for surgeries. Therefore it might be necessary to use triage. Prioritizing patients can be done based on the priority list by the NZA [16] in cooperation with specialists. Acute care should still be performed, even if the OR is downscaled. The RdGG chose to make oncological surgeries a high priority as well. If a patient belongs to the risk group and has to undergo elective surgery, the doctor can decide to postpone it.

**Leveling** is about keeping the outflow of the OR constant. During COVID-19, more capacity is needed in the ICU and new COVID-19 departments are created. Therefore there is less capacity for regular ICU patients.

There is also less capacity in the wards as both beds and nurses might be redistributed to the COVID-19 departments and the ICU. Therefore the number of patients going from the OR to both the ICU and ward should be lower than usual.

**Patient deferral** usually happens when an urgent patient arrives and an elective patient has to make room for this patient. If the OR is downscaled, there is less flexibility to do emergency surgeries in between as there are fewer rooms available. Therefore an emergency OR can be necessary when the OR is downscaled.

**Utilization** refers to the utilization of the OR, so how efficiently the OR is being used. In this way, as many patients as possible can undergo surgery. For example, this can be done by including streets of surgeries like groin ruptures in the planning.

**Waiting time** also refers to which patient should undergo surgery first; the so called triage. Because certain patients should undergo surgery within a certain time frame. Optimizing the waiting time, based on priority, is one way to add triage to the model.

**Other** performance measures are also essential to keep in mind, focusing on the stock of both medicine and PPE. In the ICU, propofol is used to keep infected patients that are on mechanical ventilation asleep. Propofol is also used in the OR to keep patients asleep. Therefore, the amount of propofol should be monitored to see if there might arise problems in the stock amount.

During the last COVID-19 wave, there was a shortage of respiratory devices in the ICU, so they had to be taken from the OR. To prevent this during a new COVID-19 wave, additional ICU respiratory devices have been added to the hospital. Because of this, it is not expected that there will be another shortage of respiratory devices. However, as during a pandemic the number of patients is insecure; the number of available devices should be actively monitored.

One can also extract model inputs and rules that should apply to an OR planning during COVID-19:

- Isolation
  - Isolate infected patients
  - Prevent possible spread
- Treatment
  - Keep a minimum level of ventilation devices
  - Keep a minimum level of medicinal stock
- Decontamination
  - Plan extra time for cleaning and removing appliances
- Scheduling
  - Keep a maximum outflow
  - Plan extra time for surgery of infected patients
  - Realize fewer patients available for surgery
- Staff protection
  - Keep a minimum level of PPE stock

**Isolation** of infected patients is essential. Suspected patients are treated as isolated patients and therefore need to be isolated as well. Preventing the possible spread of the virus is also very important. To do this, one can use a separate COVID-19 OR, which is only used for (suspected) cases. This separate OR also needs its own surgical team. Instead of using a separate OR, one can also decide to thoroughly clean the OR after an infected patient, further described in decontamination.

If a separate COVID-19 OR is used, one should also have a separate COVID-19 hallway for infected patients. Infected patients should only undergo surgery if it is absolutely necessary; if not, one should wait for the patient to recover before performing surgery.

**Treatment** can be used as a performance measure, which is described above. Nevertheless, it is also essential to keep an exact minimum of medicine and ventilation devices. This can then be used for the absolute necessary surgeries and patients in the ICU.

**Decontamination** is essential when infected patients have to undergo surgery. Before a non-infected patient goes into the OR, everything has to be thoroughly cleaned. Apart from the regular cleaning activities, the OR has to be cleaned with alcohol as well and after that, the room has to be aired for a set period. Those cleaning activities take approximately 1 hour extra. COVID-19 surgeries are treated with the MRSA+ protocol; therefore, all non-necessary appliances from the OR have to be removed to prevent possible spread. Both those things cost extra time, which has to be included in the planning.

**Scheduling** focuses on multiple things. Keeping the outflow towards the ICU and the ward low is already in the performance measures. However, there is also a clear boundary for a maximum number of patients who can go to those departments; this should be set as a model rule.

If surgery is performed on an infected patient, both the induction and the recovery have to be done in the operating room. Those actions cost extra time, approximately 15 minutes for the induction and 1 hour for recovery, which should be included in the planning.

Due to limited visits to the clinic and because patients are hesitant to visit a hospital during COVID-19, fewer patients are available for surgery. This gives possible reduced input for the model.

**Staff protection** makes it essential to keep a strict minimum of PPE available. Just like with treatment, this is for acute surgeries and the ICU.

## A.2. The experience of experts in the field regarding the OR planning during the first COVID-19 wave

To see how the OR planning performed during the fist COVID-19 wave in the RdGG, interviews are held with experts. In those interviews, the focus is on what went well and what things could have gone better during the last COVID-19 wave regarding the OR planning.

### A.2.1. Method

The interviews are performed in the Reinier de Graaf hospital in Delft, the Netherlands. The hospital is situated in the province of South Holland; therefore, it was not in the Dutch hotspot of the COVID-19 wave of spring 2020. The hospital has around 500 beds and is a top clinical hospital, focusing on the elderly, oncology, and mother and child care. Seven interviews are held with people that had to do with either the OR (planning), the ICU or ward, or with COVID-19 related decision making during the COVID-19 wave in spring. The interviews are semi-structured, which has the advantages of enabling follow-up questions based on participants' responses, which leads to more depth if necessary [20]. The questions asked can be found in Section A.2.3. To give an overview of all things that went well and what things could have been better in the OR planning during COVID-19 according to experts in the field, all mentioned aspects are derived from the interviews. Those aspects are then compared and combined.

### A.2.2. Results

Seven people were interviewed to determine what things went well in the OR planning during the COVID-19 wave and what things could have gone better. The people interviewed were: the head of the OR, anesthetics, and recovery, the head of the ICU, the head of one of the nursing departments, two planners of the OR department, the project leader of capacity management, and the manager of acute care, all of the Reinier de Graaf hospital (RdGG) in Delft. All of those people had to do with either the OR (planning), the ICU or ward, or COVID-19 related decision making. All interviews have been conducted in Dutch and were voice recorded. The interviewees gave permission to record the interview. The interviews took place in the RdGG in personal offices or meeting rooms. They took between 30 and 45 minutes.

During the interviews, the good points and points of improvement of the OR planning during the last COVID-19 wave were discussed. The points that were mentioned by the interviewees are categorized into categories similar to those found in literature as described in Section 1.7.1. The positive points are the following:

- Isolation
- Decontamination
- Scheduling
- Other

Isolation of infected patients was done very well, as there was a separate OR for infected patients. There are two possibilities in preventing the spread of the virus; one can either use a separate OR or the cleaning protocol should be more extensive.

Decontamination was correctly done as after surgery of infected patients, the OR was cleaned thoroughly, which takes approximately 1 hour extra. Also, all non-necessary appliances were removed from the OR during COVID-19 surgery to prevent infection via surfaces.

In scheduling, multiple things went well. There was a maximum of one OR patient going to the ICU, as the ICU had less available capacity. There was a strict quota for the number of patients going to the ward. The number of patients going to the ward had to be lower as there was less available capacity and also because most of the surgeries were for oncological patients, which usually stay longer in the ward. Lastly, with the new schedule, there were no surgeries canceled.

In the category other, triage was kept into account. All surgeries that needed to happen immediately or quickly were done within time. To make sure this could happen, the surgeons made a list together in order of which patients should undergo surgery first, partly based on the NZA priority list [16].

Furthermore, the points that can use improvement according to the interviewees are the following:

- Scheduling
- Staff protection

Multiple things went well with the planning, but also some that can use some improvement. The main thing that nearly every interviewee mentioned was that the OR was scaled down too quickly. During the first wave, without knowing what was going to happen, this was an understandable choice. However, in the next COVID-19 wave, this is not necessary. Less downscaling results in more time to hep patients. During the first COVID-19 wave, the OR's respiratory devices had to go to the ICU for COVID-19 patients. As only anesthetic personnel knew how to operate those devices, they had to go there as well. The leave of anesthetic personnel is not beneficial to the OR. Luckily, there are more respiratory devices, so it is unnecessary to transfer anesthetic personnel during a new COVID-19 wave. Lastly, OR personnel was rescheduled to the emergency department among other departments; this is not beneficial for the OR and should therefore be prevented during a next COVID-19 wave.

### A.2.3. Interview questions

The interviews start with asking if it is okay to record the interview. Then a brief background of the author and an small explanation of the research are given. The interviews are held in Dutch, therefore the following questions are in Dutch as well. During the interview extra questions are added which are relevant for a different research, therefore not all of the answers to the following questions can be found in this research.

Zou je wat willen vertellen over jezelf en je rol?

Ik begin met vragen over de corona situatie in het algemeen en daarna stel ik ziekenhuis specifieke vragen over het Reinier de Graaf Gasthuis. Als laatste zou ik graag dingen toetsen waarvan ik zelf denk dat ze relevant kunnen zijn en die uit mijn literatuuronderzoek naar voren zijn gekomen. Laat het vooral weten als dingen niet duidelijk zijn of als je opmerkingen hebt!

Dus als eerste algemeen:
Wat is er belangrijk bij een OK-planning tijdens corona wat normaal minder of niet van belang is? In algemene zin, maar ook vanuit vakgebied.
*Als deze vraag niet begrepen wordt worden deze twee voorbeelden genoemd: Je kan bijvoorbeeld denken aan dat er minder ruimte kan zijn op de IC waardoor je minder patiënten wil opereren met een hoge IC kans, of aan meer tijd tussen operaties om de OK extra goed te reinigen.*

En specifiek voor jullie ziekenhuis:
Hoe was de OK-planning tijdens de eerste coronagolf?
Welke dingen gingen er goed bij de OK tijdens de eerste coronagolf?
Welke dingen hadden er beter gekund bij de OK tijdens de eerste coronagolf?
Welke dingen bleken uiteindelijk onnodig bij de OK tijdens de eerste coronagolf?

Kort samenvatten wat er gezegd is.

De laatste vragen gaan over wat ik uit literatuur en eerdere gesprekken heb gehaald, een deel zullen inkoppers zijn maar het is voor mijn onderzoek belangrijk om deze informatie uit formele interviews te halen.

Is het belangrijk om flow vanuit de OK naar de IC lager dan normaal te hebben?
Is het belangrijk om flow vanuit de OK naar de verpleegafdeling lager dan normaal te hebben?

Is het belangrijk om rekening te houden met een beperkt aantal anesthesiemedewerkers?
Is het belangrijk om rekening houden met ander personeel dat weg gaat?
Is het belangrijk om extra naar personeelstekorten te kijken?
Is het weer nodig om rekening te houden met het aantal beademingsapparatuur?

Kan het belangrijk zijn om operaties uit te stellen als een patiënt een te hoog covid risico heeft?

Kan het nodig zijn om rekening te houden met een tekort aan medicatie voor operaties?
Kan het belangrijk zijn om rekening te houden met het aantal persoonlijke beschermingsmiddelen zoals mondkapjes?

Kan het belangrijk zijn om urgentie van patiënten mee te nemen in de planning?

Kan het handig zijn om logistiek makkelijke operaties snel tussendoor te doen?

Is het belangrijk om (mogelijke) covid patienten te isoleren?
Is het belangrijk om bezig te zijn met het voorkomen van mogelijke verspreiding
Is het belangrijk om je personeel goed te beschermen tegen covid
Is het belangrijk om extra goed te ontsmetten (of is de huidige manier op de OK goed genoeg)?
Duurt het langer om alles schoon te maken?

Draagt men andere beschermende kleding op de OK bij een mogelijke covid patient? *Zo ja:*
*Is het nodig om kortere shifts of meer pauzes te hebben vanwege beschermende kleding?*
*Is het handig om routine taken te doen als men beschermende kleding draagt?*

Kan het handig zijn om je stafgroep te splitsen

Is het handig te beginnen opereren patiënt minste covid kans eindigen met bevestigde?

Wat voor inzichten zijn er fijn bij een planningsmodel?

Heb je duidelijke grafieken nodig om specialisten uit te overtuigen waarom ze minder snijtijd krijgen?

## A.3. How the detailed overviews of part 1 are made

**Are acute and semi-acute surgeries still performed when the capacity is lower?**
The number of hours of acute and semi-acute surgeries will be compared between the different weeks. Both acute and semi-acute hours are taken as those two types of surgeries should always continue, as those patients have no or limited time to wait for surgery. The surgical hours are calculated by summing all the hours spend on acute and semi-acute surgeries per day.

**Is the outflow towards the ICU and the ward lower during COVID-19?**
The outflows towards the ICU and ward are compared between the different weeks. For outflow, the sum of patients going to the ICU and ward per day are compared between the different weeks.

**Is the outflow towards the ICU and the ward kept constant?**
In the available data is registered if a patient will stay in the hospital after surgery. The data showing to which department the patient goes is unavailable, so it is unknown if a patient goes to the ward or the ICU; there-

fore, those two are combined. To calculate if the outflow remains constant, the deviation to the selected two weeks' average will be calculated per day and compared. To illustrate this, for example, if the average outflow of the two weeks in January 2019 is ten patients per day and on the first day, the outflow is nine, this day will get a value of -1 and so forth. Assumed is that a patient goes to the ward or ICU when the date leaving the ward or ICU is later than the day of surgery.

**Is the number of occupied beds for patients coming from surgery in the ICU and the ward lower during COVID-19?**
The capacity of ICU and ward is lower, so expected is to see a lower amount of patients on these departments during COVID-19. The number of patients at the OR and ward are compared between the different weeks.

**Is the number of occupied beds for patients coming from surgery in the ICU and the ward kept constant?**
The literature states that the number of patients going towards the ICU and ward should be kept constant [26]. However, the number of patients on the ward is also significant. For example, if one sends in five patients on Monday that stay for one day, and then again 5 patients on Tuesday that stay for a day, there are 5 patients at the ward in total. However, if one sends in five patients on Monday that stay for a week, and then again 5 patients on Tuesday, there are 10 patients at the ward in total. Therefore the total number of occupied beds for patients coming from surgery is also compared. One thing to note here is that there are only a few surgeries performed on weekends, if any; therefore, there could be slight deviations in the number of patients due to the day of the week. To check if the number of patients in the ward and ICU stays constant, the number of patients on the ward and ICU will be calculated by taking the day of surgery as the starting date and the day of leave as the end date. Only full days are considered with a maximum of 14 days.

**How is the utilization of the ORs?**
The utilization is the amount of uptime of the OR. This will be calculated by taking the sum of surgical duration, defined as the time spent at the OR by the patient, divided by the time the OR can be scheduled. Sometimes the OR is scheduled with a lunch break and sometimes without, however, this data is unavailable. Therefore the possible time to schedule the OR is taken without the lunch time and is therefore 8 hours.

## A.4. Checking normality for the results of part 1

In Figure A.1 the distribution of the daily surgical hours can be seen per urgency level and per week. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.1. All of them are significant, which means that the data is not normally distributed.

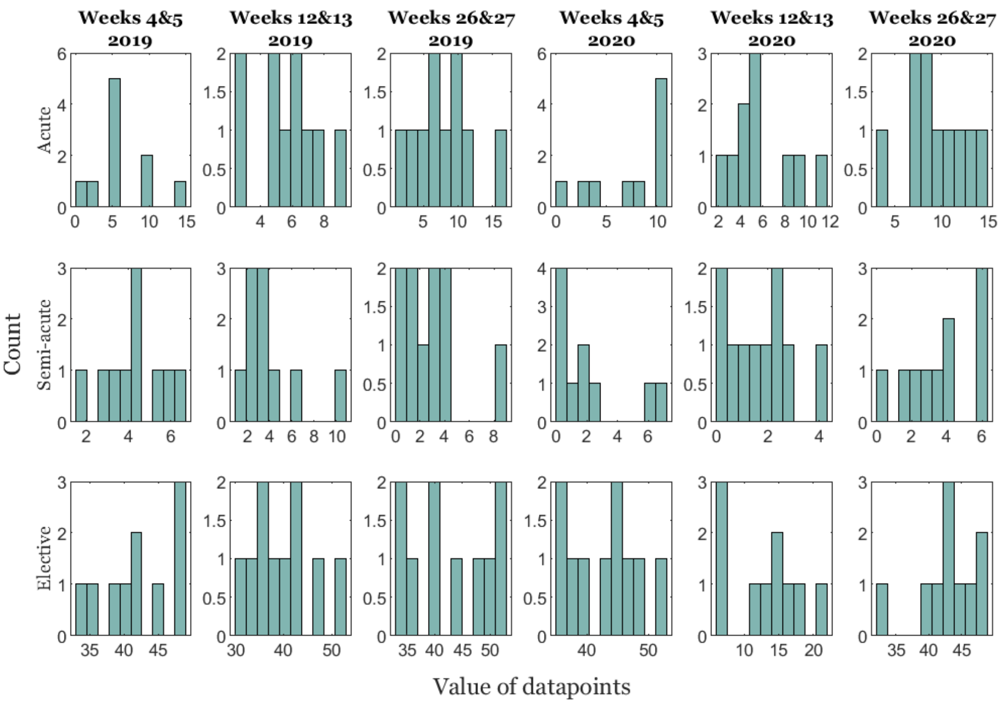


Figure A.1: Distribution of daily surgical hours per urgency level per week

Table A.1: The p-values of the Kolmogorov-Smirnov tests of the distribution of daily surgical hours per urgency level per week

| | Weeks 4&5 | Weeks 12&13 | Weeks 26&27 | Weeks 4&5 | Weeks 12&13 | Weeks 26&27 |
|---|---|---|---|---|---|---|
| Acute | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Semi-acute | <0.001 | <0.001 | <0.001 | 0.002 | <0.001 | <0.001 |
| Elective | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

The distribution of this data can be seen in Figure A.2. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.2. All of them are significant, which means that the data is not normally distributed.

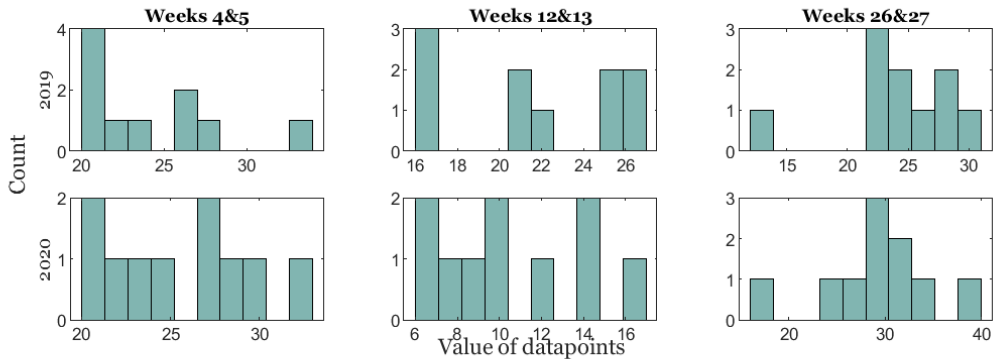


Figure A.2: Distribution of number of patients going to the ICU or ward

Table A.2: The p-values of the Kolmogorov-Smirnov tests of the number of patients going to the ICU or ward

| | Weeks 4&5 | Weeks 12&13 | Weeks 26&27 |
|---|---|---|---|
| 2019 | <0.001 | <0.001 | <0.001 |
| 2020 | <0.001 | <0.001 | <0.001 |

In Figure A.3 the distribution of the deviation to the average number of people that go to the ICU or ward per day can be seen. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.3. Some of them are significant, which means that the data of those is not normally distributed. Therefore statistical tests have to be selected for non-uniform data, so assumed is that all data is non-uniform.

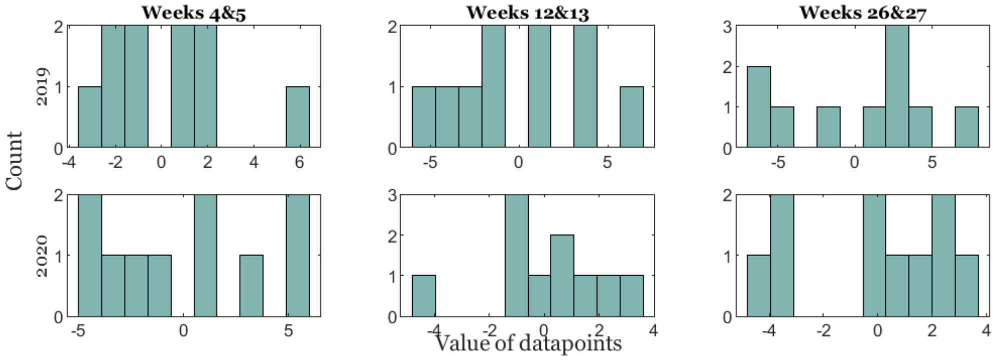


Figure A.3: Distribution of deviation to two week average of patients going to ICU or ward

Table A.3: The p-values of the Kolmogorov-Smirnov tests of the deviation to two week average of patients going to ICU or ward

| | Weeks 4&6 | Weeks 12&14 | Weeks 26&28 |
|---|---|---|---|
| 2019 | 0.056 | 0.013 | 0.012 |
| 2020 | 0.056 | 0.209 | 0.123 |

Figure A.4 shows the distribution of the number of beds that are occupied in the ICU and ward. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.4. All of them are significant, which means that the data is not normally distributed.

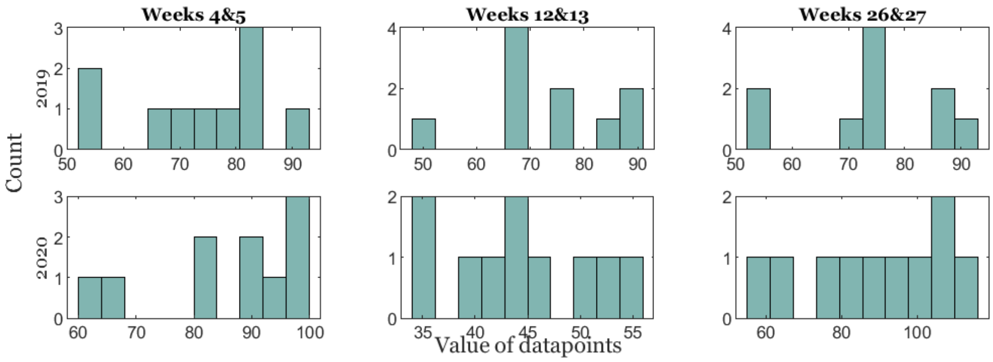


Figure A.4: Distribution of number of occupied beds per day

Table A.4: The p-values of the Kolmogorov-Smirnov tests of the number of occupied beds per day

| | Weeks 4&7 | Weeks 12&15 | Weeks 26&29 |
|---|---|---|---|
| 2019 | <0.001 | <0.001 | <0.001 |
| 2020 | <0.001 | <0.001 | <0.001 |

In Figure A.5 the deviation per day to the two week average of the number of occupied beds in the ICU or ward can be seen. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.5. Some of them are significant, which means that the data of those is not normally distributed. Therefore statistical tests have to be selected for non-uniform data, so assumed is that all data is non-uniform.

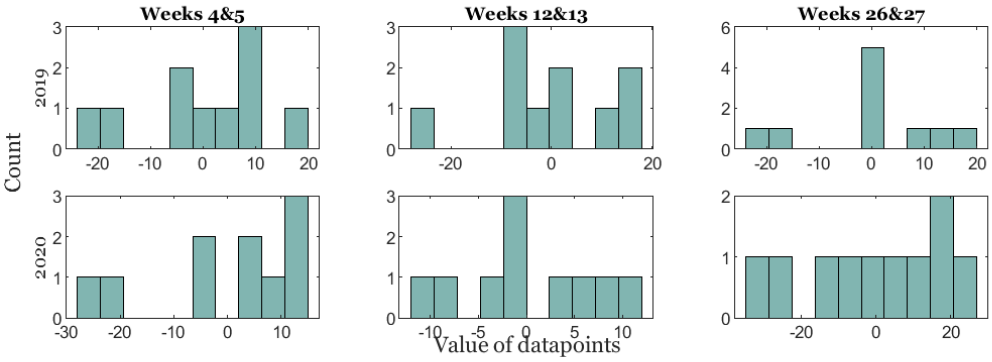


Figure A.5: Distribution of deviation to two week average of occupied beds in the ICU or ward

Table A.5: The p-values of the Kolmogorov-Smirnov tests of the deviation to two week average of occupied beds in the ICU or ward

| | Weeks 4&8 | Weeks 12&16 | Weeks 26&30 |
|---|---|---|---|
| 2019 | 0.008 | 0.008 | 0.219 |
| 2020 | <0.001 | 0.011 | 0.008 |

In Figure A.6, the distribution of the daily utilization of the ORs in percentages is visualized. The p-values of the Kolmogorov-Smirnov tests can be found in Table A.6. All of them are significant, which means that the data is not normally distributed.

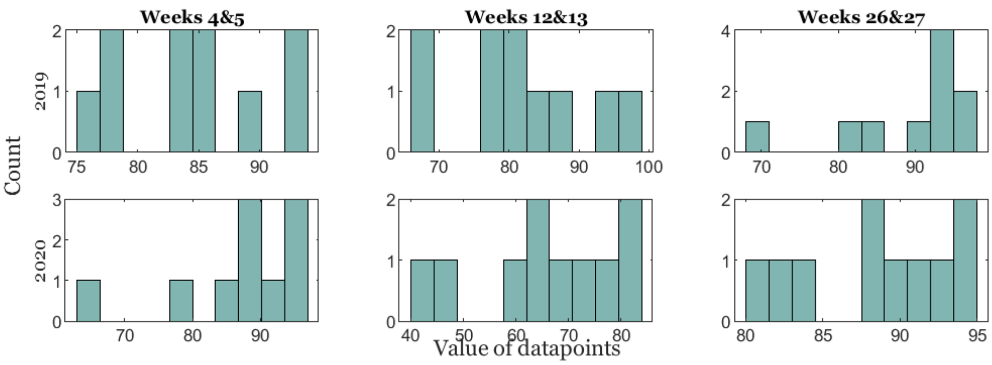


Figure A.6: Distribution of utilization in percentages

Table A.6: The p-values of the Kolmogorov-Smirnov tests of the utilization in percentages

| | Weeks 4&9 | Weeks 12&17 | Weeks 26&31 |
|---|---|---|---|
| 2019 | <0.001 | <0.001 | <0.001 |
| 2020 | <0.001 | <0.001 | <0.001 |

# A.5. Selecting operating room planning tools from literature

To see what OR planning models already exist, a literature search has been done.

## A.5.1. Method

In the literature research preliminary to this research, a systematic search was done to find all reviews focusing on OR planning models that include performance measures[26]. Those reviews, Cardoen et al. [7], Samudra et al. [21] and Gur and Eren [13], were used to select OR planning models.

The OR planning models were selected based on pre-defined performance measures. Those performance measures were based on the literature research and are the following:

- Humanitarian goals
- Leveling
- Patient deferral
- Utilization
- Waiting time

Humanitarian goals is thought to be the most crucial performance measure by the author because saving lives is one of the goals of medicine [6]. Leveling is the second most crucial, as, during COVID-19, this is one of the biggest bottlenecks Van Hartingsveldt [26].

To find different OR planning tools, articles are selected from the reviews. The applicable performance measures are combined, and articles that are in humanitarian goals or leveling, combined with at least one other performance measure are included. The combination of humanitarian goals and waiting time is not considered, as those two represent the same category of staying within the maximum waiting time for surgery, as described by Van Hartingsveldt [26].

The selected articles were read, and if they applied to the inclusion criteria, they were included. The inclusion criteria are:

- Written in English or Dutch
- Full article is available
- Explanation of the solution technique is present

### A.5.2. Results

The reviews contained different performance measures. Both Cardoen et al. [7] end Samudra et al. [21] did not include the category of humanitarian goals. Therefore they were both checked on leveling in combination with patient deferral, utilization, and waiting time. Cardoen et al. [7] only had leveling articles that had utilization as well. Gur and Eren [13] did not include the performance measure leveling, so only combinations of humanitarian goals with patient deferral, utilization, and waiting time were included. In total Cardoen et al. [7] yielded two articles, Samudra et al. [21] five, and Gur and Eren [13] three. Of those ten articles, two duplicates were removed. Those eight articles were checked by inclusion criteria, and another three articles were removed; one because the full article was unavailable and two because the solution technique was not explained. This lead to five selected articles, as can be seen in Figure A.7 on page 77.

The selected articles are Van Houdenhoven et al. [27], Tan et al. [22], Van Essen et al. [25], Gerami and Saidi-Mehrabad [11], and Ozkarahan [18].

## A.6. Interview questions about the feasibility for the hospital

Goedenmiddag, We zijn nu virtueel bij elkaar zodat ik kan laten zien wat voor soort modellen er zijn beschreven in de literatuur en om vervolgens te kijken wat voor modellen jullie zou kunnen helpen in het ziekenhuis.

Is het voor jullie goed als ik dit gesprek opneem? Dan kan ik het straks rustig verwerken.

Voor we echt beginnen, hoe gaat het nu bij jullie? Hoe is de situatie?

Eerst nog even heel snel een korte samenvatting van mijn onderzoek, om helder te hebben waar dit interview voor is.

Ik ben aan het kijken naar de operatiekamerplanning in coronatijd. Met als doel een aanbeveling doen voor wat voor planningsmodel jullie goed zou kunnen helpen bij het plannen. Het doel van dit model is om te helpen en als leidraad of voorbeeld te zijn, het echte plannen wordt nog steeds door jullie gedaan omdat een model niet op weegt tegen de kennis en ervaring van de planners.

Voordat ik bij deze aanbeveling kom heb ik veel literatuuronderzoek gedaan naar wat belangrijk is bij een planning tijdens corona en naar wat voor OK planningsmodellen er al zijn. Vervolgens ga komende week bezig met een opzet maken voor een planningsmodel. Dit gaat een sterk versimpelde versie zijn en helaas dus ook nog niet bruikbaar om mee te plannen.

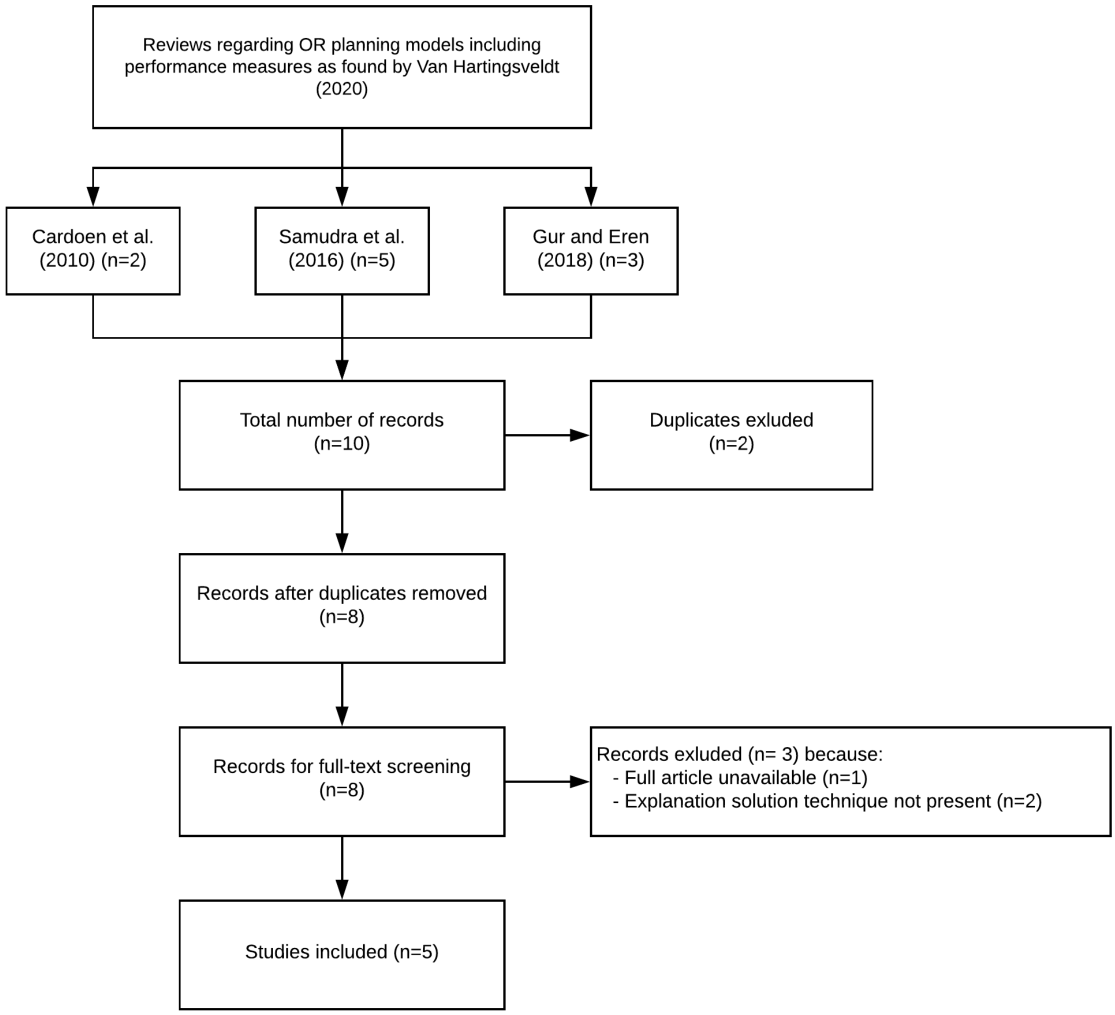


Figure A.7: Flow chart of the selection of OR planning model articles

Het doel van dit gesprek is informatie verzamelen voor het doen van een aanbeveling voor een planningsmodel. Daarom wil ik nog extra ingaan op wat belangrijk is in de planning en wat er echt aanwezig moet zijn in het model. En op welk niveau dit planningsmodel moet gaan werken.

Uit mijn voorgaande onderzoek is naar voren gekomen dat:

- De urgentie van patiënten meenemen
- Doorstroom naar de IC en verpleging constant en onder vaste waarden houden

het belangrijkste is tijdens COVID-19. Daarbij blijft het belangrijk om wel efficiënt te plannen
Zijn jullie het eens met dat dit de belangrijkste dingen zijn voor een planning tijdens COVID-19, of hebben jullie nog dingen die jullie toe willen voegen of aanpassen?

Verder zijn de volgende zaken ook belangrijk om mee te nemen:

- De standaardtijden OK, start van de dag + einde, eventuele pauzes
  - Hoe laat start en eindigt de OK?
  - Is er een lunchpauze?
- Zo veel mogelijk rekening houden met per dagdeel 1 specialisme (en operateur)
  - Tijdens COVID-19was dat minder belangrijk, hoe is dit nu en hoe verwachten jullie dat dit is als deze golf heftiger wordt?
- Benodigde apparatuur + röntgen
  - Wat valt er verder onder benodigde apparatuur?
- Rondom geïnfecteerde patiënt extra tijd voor de schoonmaak of een aparte COVID-19 OK.
  - Nog steeds alleen operaties aan geïnfecteerde patiënten als het acuut is?
- Hoeveelheid beschikbaar personeel
  - Hoewel we verwachten dat er waarschijnlijk geen OK personeel weg hoeft.

Verder:

- Verbruik persoonlijke beschermingsmiddelen OK monitoren en eventueel op plannen?
  - Zou bij een heel erg tekort aan persoonlijke beschermingsmiddelen, dus nog minder dan bij de vorige golf, dat een indicatie zijn om de OK af te schalen?
- Verbruik medicatie (propofol) op de OK monitoren en eventueel op plannen?
  - Zou bij een heel erg tekort aan medicatie, dus nog minder dan bij de vorige golf, dat een indicatie zijn om de OK af te schalen?
- Bij het wijzigen van de planning voorrang meenemen van patiënten die al gepland stonden.

In de literatuur zijn er veel verschillende modellen te vinden die gebruikt kunnen worden om de operatiekamer planning te maken. Daarvan heb ik vijf modellen geselecteerd die rekening houden met prioriteit van patiënten of met het gelijk houden van de uitstroom. In een model worden er verschillende keuzes gemaakt, daarvan neem ik er graag een aantal met jullie door.

Op welk niveau maak je een planning?
Kies je voor een planningsmodel dat een grondrooster maakt op basis van de wachtrij, een model dat patiënten indeelt, al dan niet op basis van een grondrooster, of kies je voor een planningsmodel dat bij acute patiënten helpt met de wijziging van het bestaande OK rooster?
Waar zouden jullie het meeste behoefte aan hebben?
Hoeveel weken zouden jullie vooruit willen plannen zoals corona nu is? Of een paar weken terug?

Hoeveel weken zouden jullie vooruit willen plannen tijdens een golf?

Wat voor patiënten neem je mee in je planning? Acuut of electief?

*Dit is ook afhankelijk van de keuze bij de vorige vraag. Stel er wordt gezegd grondrooster of patiëntenrooster. Hoe wordt dan het aantal urgent bepaald? Op basis van afgelopen weken? Of wordt de standaard aangehouden die nu gebruikt wordt. Is het aantal blokken dat nu voor acuut gebruikt wordt voldoende?*

Verder, als je een semi-spoed patiënt hebt die binnen een week geopereerd moet worden. Maakt het dan nog uit of je die zo snel mogelijk doet, of is over 5 dagen ook goed?

Bij het plannen wordt de OK duur toch bepaald door de gemiddelde duur van de afgelopen 10? operaties?

Plannen jullie alleen vaste tijden in voor operaties of houden jullie alvast rekening met eventuele uitloop?

De vijf modellen uit literatuur die ik uitgebreid heb bekeken hebben verschillende dingen gedaan. Voor de prioritering van patiënten zijn er twee mogelijkheden gebruikt:

1. Patiënten worden gesorteerd op urgentie, waarbij de meest urgente patiënt als eerste geopereerd wordt, en de minst urgente als laatste
2. Patiënten worden in urgentiegroepen opgedeeld, en de starttijd van hoge urgentie wordt geminimaliseerd

Wat vinden jullie hiervan?

Wat ik had bedacht voor het RdGG is om met een urgentielijst te werken: Urgentiegroep A en B zijn acuut en worden buiten beschouwing gelaten Urgentiegroep C komt bovenaan, daarna komt D, E enzovoorts Binnen de urgentiegroepen worden patiënten gesorteerd op wanneer ze binnen zijn gekomen op de wachtlijst.

Als een patiënt bijvoorbeeld binnen 4 weken geopereerd moet worden, maar al 2 weken niet gepland is, dan komt hij onderaan op de binnen 2 weken wachtlijst en klimt vanaf daar omhoog Etc. Zijn jullie het daar mee eens?

Voor het gelijk houden van de doorstroom naar de IC en de bedden zijn in de literatuur de volgende dingen gedaan:

1. Aantal bedden onder bepaalde waarde houden
   (a) Mogen er echt niet meer zijn dan bepaalde waarde
   (b) Proberen onder bepaalde waarde te houden
2. Specialisten leveren niet meer patiënten aan om te plannen dan ze kwijt kunnen op de afdeling
3. Dagroosters maken, dagroosters door de week heen schuiven zodat de uitstroom constant blijft.

Wat vinden jullie hiervan?

Wat mij handig lijkt voor het RdGG, is om de uitstroom constant te houden. Hierbij bij voorkeur onder een bepaalde waarde, waarbij er soms een overheen mag. En om een strakke afkapping te maken, er mogen er nooit meer dan zoveel door. Zijn jullie het daar mee eens?

Voor het efficiënt plannen wordt in de literatuur vooral gekeken naar:

1. Het minimaliseren van de tijd dat een OK leeg staat In de praktijk is het denk ik goed om daaraan toe te voegen dat straatjes van dezelfde ingreep ook voordelig zijn omdat hiermee tijdswinst behaald kan worden.

Hoe denken jullie hier over?

Overig: Zou het goed zijn om in een model een advies toe te voegen wanneer een OK gesloten zou kunnen worden? Bijvoorbeeld doordat er onvoldoende bedden beschikbaar zijn en te weinig dagbehandeling operaties, of door een tekort aan personeel, propofol of persoonlijke beschermingsmiddelen.

## A.7. Background information on the model

### A.7.1. Intlinprog in Matlab

The minimization of the model is done in Matlab, with mixed integer linear programming, "intlinprog", because it can handle discrete input values. In this case the input values are if a patient is planned (1) or not (0). Intlinprog makes use of the simplex method[2]. In the simplex method the optimization problem is defined by an objective function and various constraint formulas. To find an optimal solution, the simplex algorithm starts with an initial basic solution. To optimize this basic solution, it optimizes the variable with the highest improvement rate as much as possible, while still regarding the constraints. After the first iteration, the next variable with the highest improvement rate is optimized. This happens for all variables, until no further changes can be made that will optimize the objective function.[14]

Several options can be selected with intlinprog. In this model the selected algorithm is primal simplex instead of the default dual simplex, to speed up the calculation. The maximum time running an optimization is 2 hours, this is the default of intlinprog and is used for this model as well.

### A.7.2. NZA values

The NZA priority code is not assigned to the performed surgeries, therefore those are added based on the priority status of the hospital, acute, semi-acute, and elective, and on the diagnose code. The NZA uses code A for surgeries that have to be performed within 24 hours, B for within 1 week, C for within 2 weeks, D for within 1 month, E for within 2 months, F for within 3 months and G for over 3 months. Therefore acute and semi-acute care of the RdGG are assigned to code A and B respectively. For all elective and unassigned surgeries, the diagnose code of the surgery is compared to the NZA priority list's diagnose-codes and matched to priority levels C to G. Only levels C through G are considered as acute and semi-acute care are already assigned. If a diagnose code referred to multiple priority levels the highest priority level is chosen. For example if a diagnose code has both priority C or E, priority C is chosen. When there is no match between the surgeries' diagnose code and those of the NZA, this surgery will randomly get one of the priority levels, while keeping the proportion of previously assigned priorities the same.

### A.7.3. Priority value

The priority value is based on the NZA urgency combined with the time that patient has been on the waiting list. If the patient should undergo surgery within 2 weeks according to the NZA, it will get a basic priority value of 164, this is 147 for surgery within 1 month, 117 for surgery within 2 months, 86 for surgery within 3 months and 0 for surgeries that can be performed after more than 3 months. The number of days that the patient is on the waiting list is added to this basic priority value to get the priority value used to optimize. Those basic priority values are chosen in such way that if a patient from priority level within 2 months is on the waiting list for one month, its value is equal to that of a person that just entered the waiting list but has to have surgery within 1 month, as $117 + 30 = 147$. The difference between within 3 months and over 3 months is chosen as this represents slightly less than 3 months of waiting time. The difference between the other categories is a month (30 or 31 days) or 17 days (a month minus a week), as this represents the differences between the time between the different urgency categories of the NZA.

### A.7.4. Constraints

To make sure that this simplified proof of concept gives realistic results, multiple constraints are added to the model. The first constraint makes sure that number of hours planned in the operating room does not exceed a certain maximum. This maximum number of hours is based on the available time for surgeries in the RdGG. As one day is considered, the available hours for a regular Monday are taken. The first surgery starts at 8:00 in the morning, at 12:00 there is a break, at 12:30 the surgeries continue and at 16:30 the last planned surgery ends. Therefore there are 8 hours available for surgery. On Monday there is one afternoon block available for acute surgeries, so one of the ORs has only 4 hours available for planned surgery, this will be included in both the 4 and 8 ORs plannings.

The second constraint makes sure that one patient can be planned only once. It is important to tell the model that if a patient is planned in one OR , it cannot be planned in another OR as well.

The last constraint considers the outflow of patients towards the ICU and the ward. Both in regular times as during COVID-19 there is a maximum amount of beds available in those departments. The maximum outflow values chosen are 17 patients per day during regular times and 5 patients per day during COVID-19. The first value is chosen as the average number of patients that went to the ICU or ward after elective surgery during 2019 was 17. The second value is chosen as the average number of patients that went to the ICU or ward after elective surgery during week 12 and 13 in 2020 was 5.

## A.8. Testing the model on simplified input

This appendix shows how the articles model of this article performs with artificially made simple patients. The model is run for 20 patients with a decreasing priority value from 100 to 5, for 2 ORs with both 4 hours of surgical time available. Three different durations are applied to see how the model performs. This appendix does not have the regular introduction, method, results, discussion, conclusion setup, so conclusions can be found with all three patient sets.

In Table A.7, one can see the outcome of a model run where all surgeries have a duration of 1 hour. The table shows patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and similar duration. Looking at which patients are planned one can see that all patients with a high priority are planned until the OR is fully planned. This is what one would expect to happen, as patients with high priorities should be planned first.

In Table A.8, one can see the outcome of a model run where all surgeries have a different random duration declining in value. The table shows patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and similar duration. Looking at which patients are planned one can see that all highest priority patients are planned until the next highest priority patient does not fit in the OR anymore, then the next highest prioritized patient that fits is planned and so on. This is what should be done, as highest priority patients are planned first and the leftover time is filled with patients with a priority as high as possible.

In Table A.9, one can see the outcome of a model run where all surgeries have a different random duration declining in value. The table shows patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and similar duration. Looking at which patients are planned one can see that all highest priority patients are planned, however the model skips patient 16, which does fit in the OR, to plan patient 17. The result is that the OR is more efficiently planned. If patient 16 was planned, there would have been 0.45 hours available in OR 2 which could not have been filled. However, now that patient 17 is planned, there is only 0.02 hours left in OR 2. This shows that this optimization model not only takes patient priority into account, but also OR utilization.

There might be a situation where prioritizing an urgent patient is way more important than using the available OR time. When the priority of the patient is squared, this will make patient priority more important than duration as can be seen in Table A.10. This shows that patient 16 which was skipped in the previous planning, is now planned. This results in an undertime of 0.39 and 0.23 hours in OR 1 and OR 2 respectively.

## A.9. Checking normality for the results of part 3

In this section the distributions of all data of part 3, Section 12.2, is visualized and the results of the Kolmogorov-Smirnov tests is shown. If the p-value of this test is smaller than 0.05, the distribution is significantly different from a normal distribution.

### A.9.1. Distributions of values

In Figures A.8, A.9, A.10, A.11, A.12, and A.13 all the distributions of the runs for all the performance measures are visualized. In table A.11 all the p-values of the Kolmogorov-Smirnov tests can be seen. All distributions are significantly different from the normal distribution.

Table A.7: Patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and **similar** duration.

| | **Patient 1** | **Patient 2** | **Patient 3** | **Patient 4** | **Patient 5** | **Patient 6** | **Patient 7** | **Patient 8** | **Patient 9** | **Patient 10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 100 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 |
| Duration | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Planned OR 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| Planned OR 2 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| Planned hours OR 1 | 0 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 4 | 4 |
| Planned hours OR 2 | 1 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 |
| Hours left OR 1 | 4 | 3 | 3 | 2 | 2 | 2 | 1 | 0 | 0 | 0 |
| Hours left OR 2 | 3 | 3 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Sum of planned prio*duration** | **100** | **95** | **90** | **85** | **80** | **75** | **70** | **65** | **0** | **0** |

| *Continuation* | **Patient 11** | **Patient 12** | **Patient 13** | **Patient 14** | **Patient 15** | **Patient 16** | **Patient 17** | **Patient 18** | **Patient 19** | **Patient 20** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 | 5 | |
| Duration | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| Planned OR 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Planned OR 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Planned hours OR 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | |
| Planned hours OR 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | |
| Hours left OR 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Hours left OR 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| **Sum of planned prio*duration** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **660** |

Table A.8: Patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and a **decreasing** duration.

| | **Patient 1** | **Patient 2** | **Patient 3** | **Patient 4** | **Patient 5** | **Patient 6** | **Patient 7** | **Patient 8** | **Patient 9** | **Patient 10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 100 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 |
| Duration | 2.61 | 2.54 | 2.19 | 1.63 | 1.2 | 0.96 | 0.95 | 0.64 | 0.57 | 0.55 |
| Planned OR 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Planned OR 2 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Planned hours OR 1 | 2.61 | 2.61 | 2.61 | 2.61 | 3.81 | 3.81 | 3.81 | 3.81 | 3.81 | 3.81 |
| Planned hours OR 2 | 0 | 2.54 | 2.54 | 2.54 | 2.54 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Hours left OR 1 | 1.39 | 1.39 | 1.39 | 1.39 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Hours left OR 2 | 4 | 1.46 | 1.46 | 1.46 | 1.46 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Sum of planned prio*duration** | **261** | **241.3** | **0** | **0** | **96** | **72** | **0** | **0** | **0** | **0** |

| *Continuation* | **Patient 11** | **Patient 12** | **Patient 13** | **Patient 14** | **Patient 15** | **Patient 16** | **Patient 17** | **Patient 18** | **Patient 19** | **Patient 20** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 | 5 | |
| Duration | 0.5 | 0.42 | 0.34 | 0.32 | 0.26 | 0.25 | 0.14 | 0.14 | 0.1 | 0.04 | |
| Planned OR 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | |
| Planned OR 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Planned hours OR 1 | 3.81 | 3.81 | 3.81 | 3.81 | 3.81 | 3.81 | 3.95 | 3.95 | 3.95 | 3.99 | |
| Planned hours OR 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | |
| Hours left OR 1 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.05 | 0.05 | 0.05 | 0.01 | |
| Hours left OR 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| **Sum of planned prio*duration** | **25** | **0** | **0** | **0** | **0** | **0** | **2.8** | **0** | **0** | **0.2** | **698.3** |

Table A.9: Patients with their priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and a **increasing** duration.

| | Patient 1 | Patient 2 | Patient 3 | Patient 4 | Patient 5 | Patient 6 | Patient 7 | Patient 8 | Patient 9 | Patient 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 100 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 |
| Duration | 0.04 | 0.1 | 0.14 | 0.14 | 0.25 | 0.26 | 0.32 | 0.34 | 0.42 | 0.5 |
| Planned OR 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Planned OR 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Planned hours OR 1 | 0 | 0.1 | 0.1 | 0.24 | 0.49 | 0.75 | 1.07 | 1.41 | 1.83 | 2.33 |
| Planned hours OR 2 | 0.04 | 0.04 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Hours left OR 1 | 4 | 3.9 | 3.9 | 3.76 | 3.51 | 3.25 | 2.93 | 2.59 | 2.17 | 1.67 |
| Hours left OR 2 | 3.96 | 3.96 | 3.82 | 3.82 | 3.82 | 3.82 | 3.82 | 3.82 | 3.82 | 3.82 |
| **Sum of planned prio*duration** | **4** | **9.5** | **12.6** | **11.9** | **20** | **19.5** | **22.4** | **22.1** | **25.2** | **27.5** |

| *Continuation* | Patient 11 | Patient 12 | Patient 13 | Patient 14 | Patient 15 | Patient 16 | Patient 17 | Patient 18 | Patient 19 | Patient 20 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Prio value | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 | 5 | |
| Duration | 0.55 | 0.57 | 0.64 | 0.95 | 0.96 | 1.2 | 1.63 | 2.19 | 2.54 | 2.61 | |
| Planned OR 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Planned OR 2 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | |
| Planned hours OR 1 | 2.88 | 2.88 | 2.88 | 3.83 | 3.83 | 3.83 | 3.83 | 3.83 | 3.83 | 3.83 | |
| Planned hours OR 2 | 0.18 | 0.75 | 1.39 | 1.39 | 2.35 | 2.35 | 3.98 | 3.98 | 3.98 | 3.98 | |
| Hours left OR 1 | 1.12 | 1.12 | 1.12 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | |
| Hours left OR 2 | 3.82 | 3.25 | 2.61 | 2.61 | 1.65 | 1.65 | 0.02 | 0.02 | 0.02 | 0.02 | |
| **Sum of planned prio*duration** | **27.5** | **25.65** | **25.6** | **33.25** | **28.8** | **0** | **32.6** | **0** | **0** | **0** | **348.1** |

Table A.10: Patients with their **squared** priority value, duration of surgery, planned or not in OR 1 or 2, the total number of planned hours up to that patient and the hours left on OR 1 and 2 up to that patient for a decreasing priority value and a **increasing** duration.

| | **Patient 1** | **Patient 2** | **Patient 3** | **Patient 4** | **Patient 5** | **Patient 6** | **Patient 7** | **Patient 8** | **Patient 9** | **Patient 10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Squared prio value | 10000 | 9025 | 8100 | 7225 | 6400 | 5625 | 4900 | 4225 | 3600 | 3025 |
| Duration | 0.04 | 0.1 | 0.14 | 0.14 | 0.25 | 0.26 | 0.32 | 0.34 | 0.42 | 0.5 |
| Planned OR 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Planned OR 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Planned hours OR 1 | 0.04 | 0.04 | 0.18 | 0.32 | 0.57 | 0.83 | 1.15 | 1.49 | 1.91 | 2.41 |
| Planned hours OR 2 | 0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Hours left OR 1 | 3.96 | 3.96 | 3.82 | 3.68 | 3.43 | 3.17 | 2.85 | 2.51 | 2.09 | 1.59 |
| Hours left OR 2 | 4 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 |
| **Sum of planned prio*duration** | **400** | **902.5** | **1134** | **1011.5** | **1600** | **1462.5** | **1568** | **1436.5** | **1512** | **1512.5** |

| *Continuation* | **Patient 11** | **Patient 12** | **Patient 13** | **Patient 14** | **Patient 15** | **Patient 16** | **Patient 17** | **Patient 18** | **Patient 19** | **Patient 20** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Squared prio value | 2500 | 2025 | 1600 | 1225 | 900 | 625 | 400 | 225 | 100 | 25 | |
| Duration | 0.55 | 0.57 | 0.64 | 0.95 | 0.96 | 1.2 | 1.63 | 2.19 | 2.54 | 2.61 | |
| Planned OR 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | |
| Planned OR 2 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | |
| Planned hours OR 1 | 2.41 | 2.41 | 2.41 | 2.41 | 2.41 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | |
| Planned hours OR 2 | 0.65 | 1.22 | 1.86 | 2.81 | 3.77 | 3.77 | 3.77 | 3.77 | 3.77 | 3.77 | |
| Hours left OR 1 | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | |
| Hours left OR 2 | 3.35 | 2.78 | 2.14 | 1.19 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | |
| **Sum of planned prio*duration** | **1375** | **1154.25** | **1024** | **1163.75** | **864** | **750** | **0** | **0** | **0** | **0** | **18870.5** |

Table A.11: P-values of the Kolmogorov-Smirnov tests performed on the datasets of the article's objective function and the objective function of Ozkarahan [18] for all performance measures

| **Performance measures** | **P-value article's objective function** | **P-value Ozkarahan [18]** |
|---|---|---|
| Number of planned patients | p<0.001 | p<0.001 |
| Assigned priority value of planned patients | p<0.001 | p<0.001 |
| Assigned priority of planned patients per hour | p<0.001 | p<0.001 |
| Position on the waiting list of planned patients | p<0.001 | p<0.001 |
| Number of patients per NZA priority | p<0.001 | p<0.001 |
| Time on the waiting list of planned patients | p<0.001 | p<0.001 |

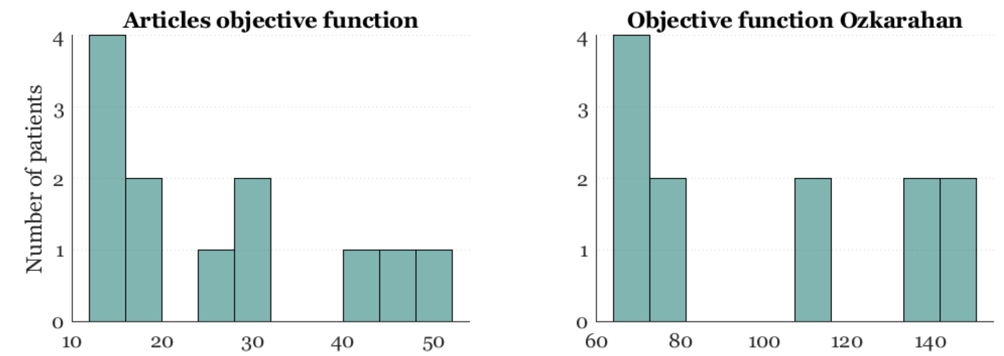


Figure A.8: The distribution of the number of planned patients per run for the article's objective function and the objective function of Ozkarahan [18].

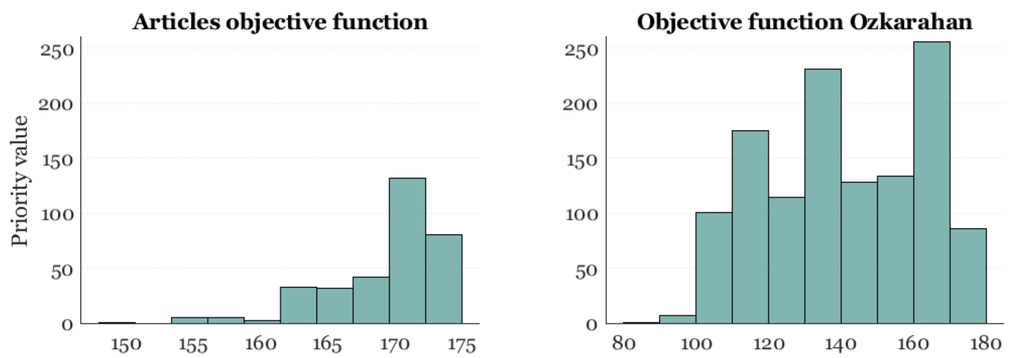


Figure A.9: The distribution of the assigned priority value of planned patients for the article's objective function and the objective function of Ozkarahan [18].

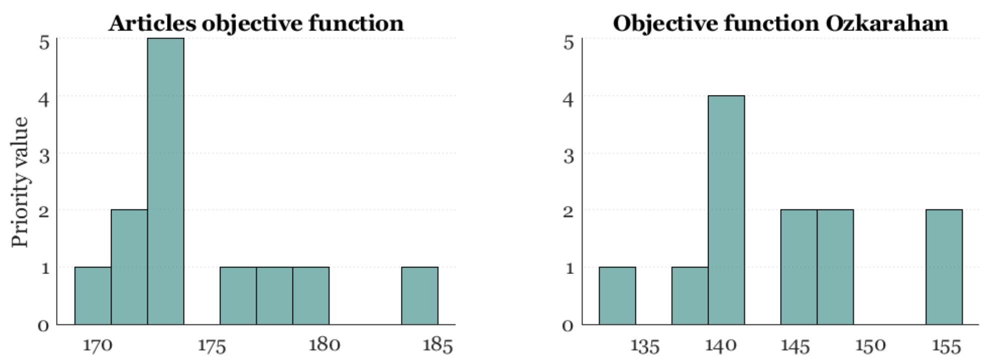


Figure A.10: The distribution of the assigned priority of planned patients per hour for the article's objective function and the objective function of Ozkarahan [18].

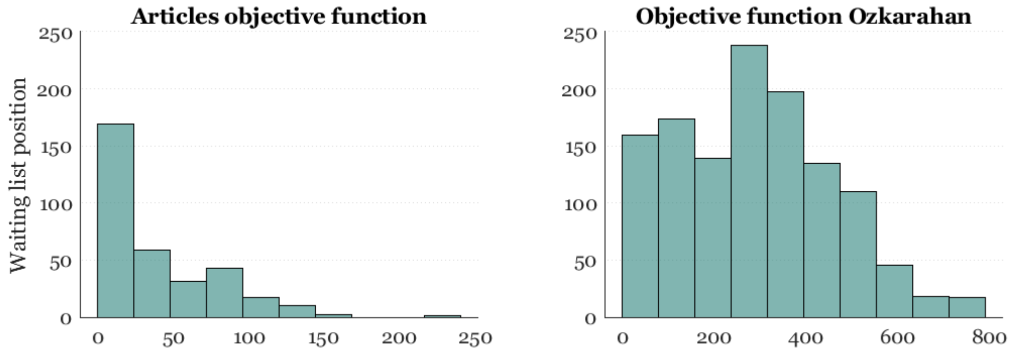


Figure A.11: The distribution of the position on the waiting list of the planned patients for the article's objective function and the objective function of Ozkarahan [18].

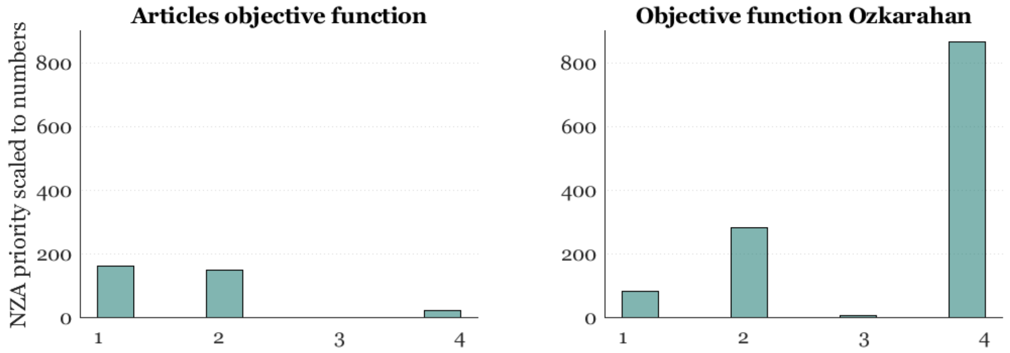


Figure A.12: The distribution of the NZA priorities scaled to numbers where C is 1 and G is 5 for the planned patients for the article's objective function and the objective function of Ozkarahan [18].

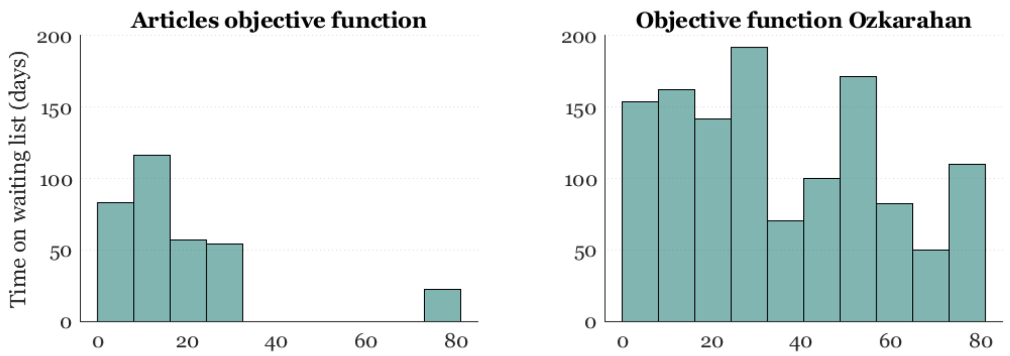


Figure A.13: The distribution of the time on the waiting list of planned patients for the article's objective function and the objective function of Ozkarahan [18].

## A.10. Elaborate results for all situation runs of part 3

This appendix shows the elaborate analysis of the proof of concept for all the 24 different situations. The comparisons are made between the two objective functions, the three waiting lists, the OR availabilities, and the different outflows towards the ICU and ward. The results are displayed in two tables; first, the differences between the two objective functions are shown, and next, the differences between the situations per objective functions are shown. Three different p-values are comparing the situations with the three different waiting lists to each other. The p-value for comparing the short and regular waiting list is called $p_{SR}$, the p-value for comparing the short and long waiting list is called $p_{SL}$, and the p-value for comparing the regular and long waiting list is called $p_{RL}$. The average value of the different tested outcomes is notated as $\bar{x}$. The outflow is abbreviated to "OF".

### A.10.1. Number of planned patients

In Table A.12 the planned number of patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow.

Table A.13 shows that for the article's objective function the number of planned patients is not significantly different ($p_{SR} = 0.5, p_{SL} = 0.5, p_{RL} = 0.25$) between the different waiting lists ($\bar{x}_{shorterWL} = 26.5$, $\bar{x}_{regularWL} = 25.3$, $\bar{x}_{longWL} = 28.3$). The number of planned patients is significantly higher for 8 ORs than for 4 ORs ($p = 0.031$, $\bar{x}_{8ORs} = 38.2$, $\bar{x}_{4ORs} = 15.2$). The number of planned patients is not significantly different (p=0.13) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 22.0$, $\bar{x}_{downscaledOF} = 31.3$).

For the objective function by Ozkarahan [18], also in Table A.13 the number of planned patients is not significantly different ($p_{SR} = 0.13, p_{SL} = 0.13, p_{RL} = 0.13$) between the different waiting lists ($\bar{x}_{shortWL} = 90.8$, $\bar{x}_{regularWL} = 113.0$, $\bar{x}_{longWL} = 113.0$). The number of planned patients is significantly higher for 8 ORs than for 4 ORs ($p = 0.031$,$\bar{x}_{8ORs} = 134.5$, $\bar{x}_{4ORs} = 70.7$). The number of planned patients is not significantly different (p=1) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 102.5$, $\bar{x}_{downscaledOF} = 102.7$).

Table A.12: Number of patients planned per situation

| | | **Article's objective function** | | | **Objective function by Ozkarahan [18]** | | |
|---|---|---|---|---|---|---|---|
| | | Short WL | Regular WL | Long WL | Short WL | Regular WL | Long WL |
| 8 ORs | Regular OF | 31 | 27 | 29 | 113 | 139 | 151 |
| | Downscaled OF | 47 | 43 | 52 | 114 | 139 | 151 |
| 4 ORs | Regular OF | 15 | 15 | 15 | 68 | 69 | 75 |
| | Downscaled OF | 13 | 16 | 17 | 68 | 69 | 75 |

Table A.13: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the number of planned patients and its averages.

| Difference between | P-value article's objective function | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.50 | 0.50 | 0.25 | 26.5 | 25.3 | 28.3 |
| 8 and 4 Ors | 0.031 | | | 38.2 | 15.2 | - |
| Regular and downscaled outflow | 0.13 | | | 22.0 | 31.3 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.13 | 0.13 | 0.13 | 90.8 | 113.0 | 113.0 |
| 8 and 4 Ors | 0.031 | | | 134.5 | 70.7 | - |
| Regular and downscaled outflow | 1.00 | | | 102.5 | 102.7 | - |

### A.10.2. Utilization

In Table A.14 the OR utilization per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow.

Table A.15 shows that for the article's objective function the OR utilization is not significantly different ($p_{SR} = 1.00, p_{SL} = 0.38, p_{RL} = 0.25$) between the different waiting lists ($\bar{x}_{shorterWL} = 89.1$, $\bar{x}_{regularWL} = 89.2$, $\bar{x}_{longWL} = 87.9$). The OR utilization is not significantly different between planning 8 or 4 ORs ($p = 0.438$, $\bar{x}_{8ORs} = 87.4$, $\bar{x}_{4ORs} = 90.0$). The OR utilization is not significantly different (p=0.13) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 90.7$, $\bar{x}_{downscaledOF} = 86.7$).

For the objective function by Ozkarahan [18], also in Table A.15 the OR utilization is not significantly different ($p_{SR} = 0.13, p_{SL} = 0.13, p_{RL} = 0.13$) between the different waiting lists ($\bar{x}_{shortWL} = 49.4$, $\bar{x}_{regularWL} = 43.6$, $\bar{x}_{longWL} = 38.5$). The OR utilization is significantly higher for 8 ORs than for 4 ORs ($p = 0.031$,$\bar{x}_{8ORs} = 47.2$, $\bar{x}_{4ORs} = 40.4$). The OR utilization is not significantly different (p=0.25) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 43.9$, $\bar{x}_{downscaledOF} = 43.8$).

### A.10.3. Assigned priority value of planned patients

In Figure A.14 the assigned priority value of planned patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow. In Figure A.15 the same can be seen in percentages.

Table A.14: OR utilization per situation

| | | **Article's objective function** | | | **Objective function by Ozkarahan [18]** | | |
|---|---|---|---|---|---|---|---|
| | | Short WL | Regular WL | Long WL | Short WL | Regular WL | Long WL |
| 8 ORs | Regular outflow | 90.4% | 92.1% | 91.2% | 56.2% | 45.4% | 40.4% |
| | Downscaled outflow | 83.7% | 85.4% | 81.7% | 55.8% | 45.3% | 40.4% |
| 4 ORs | Regular outflow | 90.2% | 90.2% | 90.2% | 42.9% | 41.9% | 36.6% |
| | Downscaled outflow | 92.0% | 89.3% | 88.4% | 42.9% | 41.6% | 36.6% |

Table A.15: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the OR utilization.

| Difference between | P-value article's objective function | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 1.00 | 0.38 | 0.25 | 89.1 | 89.2 | 87.9 |
| 8 and 4 Ors | 0.438 | | | 87.4 | 90.0 | - |
| Regular and downscaled outflow | 0.13 | | | 90.7 | 86.7 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.13 | 0.13 | 0.13 | 49.4 | 43.6 | 38.5 |
| 8 and 4 Ors | 0.031 | | | 47.2 | 40.4 | - |
| Regular and downscaled outflow | 0.25 | | | 43.9 | 43.8 | - |

The top part of Table A.16 shows that for the article's objective function, the assigned priority value of planned patients is only significantly lower for the short waiting list compared to the regular and the long one ($p_{SR} < 0.001, p_{SL} < 0.001, p_{RL} = 0.76$, $\bar{x}_{shortWL} = 168$, $\bar{x}_{regularWL} = 172$, $\bar{x}_{longWL} = 172$). The assigned priority value of planned patients is not significantly different (p=0.16) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 170$, $\bar{x}_{4ORs} = 171$). The assigned priority value of planned patients is not significantly different (p=0.79) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 172$, $\bar{x}_{downscaledOF} = 172$).

For the objective function by Ozkarahan [18], in the bottom part of Table A.16, the assigned priority value of planned patients is significantly lower for the short waiting list opposed to the regular and long one, and for regular waiting list opposed to the long one ($p_{SR} < 0.001, p_{SL} < 0.001, p_{RL} < 0.001$, $\bar{x}_{shortWL} = 116$, $\bar{x}_{regularWL} = 135$, $\bar{x}_{longWL} = 150$). The assigned priority value of planned patients is not significantly different (p=0.51) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 137$, $\bar{x}_{4ORs} = 137$). The assigned priority value of planned patients is not significantly different (p=0.65) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 137$, $\bar{x}_{downscaledOF} = 143$).

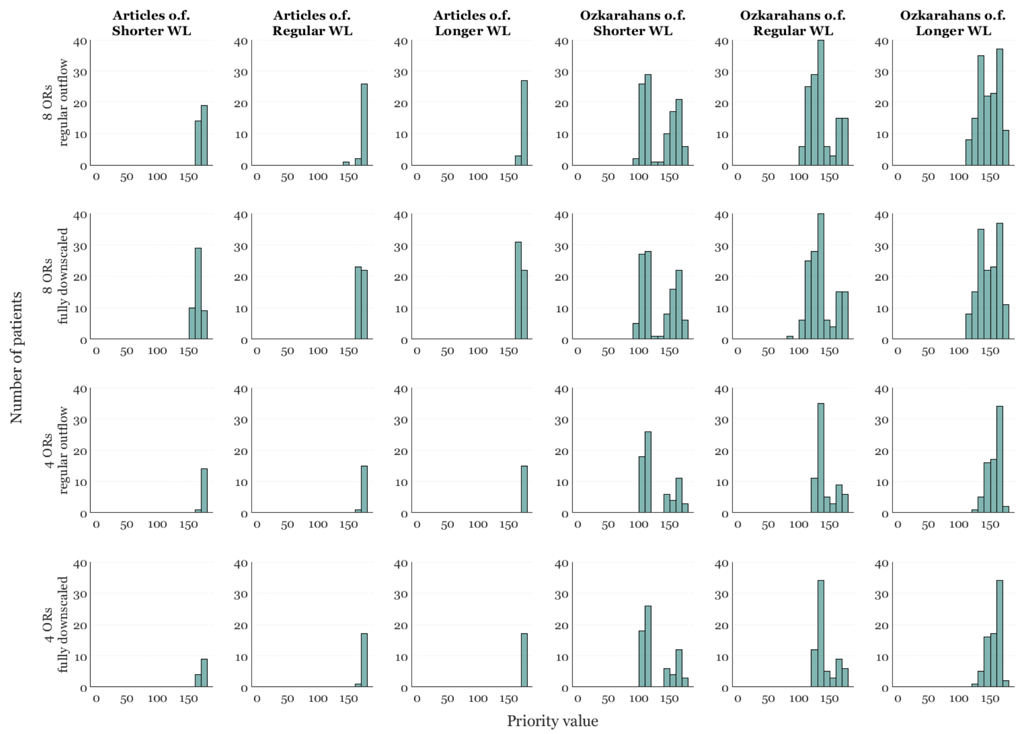


Figure A.14: Assigned priority value of planned patients

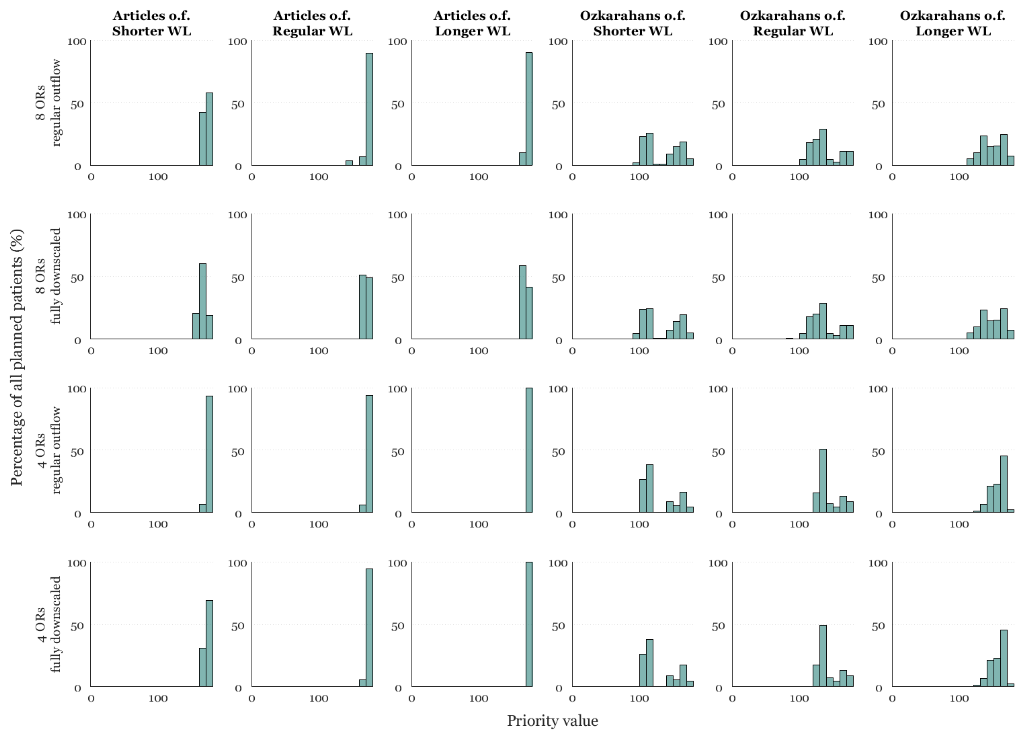


Figure A.15: Assigned priority value of planned patients in percentages

Table A.16: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the assigned priority value of planned patients and its averages.

| Difference between | P-value article's o.f. | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | 0.760 | 168 | 172 | 172 |
| 8 and 4 Ors | 0.160 | | | 170 | 171 | - |
| Regular, downscaled outflow | 0.791 | | | 172 | 172 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | <0.001 | 116 | 135 | 150 |
| 8 and 4 Ors | 0.510 | | | 137 | 137 | - |
| Regular and downscaled outflow | 0.649 | | | 137 | 143 | - |

### A.10.4. Assigned priority of planned patients per hour

In Figure A.16 the assigned priority of planned patients per hour per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow.

Table A.17 shows that for the article's objective function, the assigned priority of planned patients per hour is not significantly different ($p_{SR} = 0.34$, $p_{SL} = 0.89$, $p_{RL} = 0.11$) between the different waiting lists ($\bar{x}_{shortWL} = 172.8$, $\bar{x}_{regularWL} = 176.7$, $\bar{x}_{longWL} = 173.3$). The assigned priority of planned patients per hour is not significantly different (p=1) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 173.5$, $\bar{x}_{4ORs} = 173.5$). The assigned priority of planned patients per hour is not significantly different (p=0.67) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 175.0$, $\bar{x}_{downscaledOF} = 173.8$).

For the objective function by Ozkarahan [18], also in Table A.17, the assigned priority of planned patients per hour is significantly lower for the short waiting list as opposed to the regular and the long one ($p_{SR} = 0.057$, $p_{SL} = 0.029$, $p_{RL} = 0.029$, $\bar{x}_{shortWL} = 139.0$, $\bar{x}_{regularWL} = 142.7$, $\bar{x}_{longWL} = 152.0$). The assigned priority of planned patients per hour is not significantly different (p=0.94) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 141.1$, $\bar{x}_{4ORs} = 141.2$). The assigned priority of planned patients per hour is not significantly different (p=0.99) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 142.7$, $\bar{x}_{downscaledOF} = 144.2$).

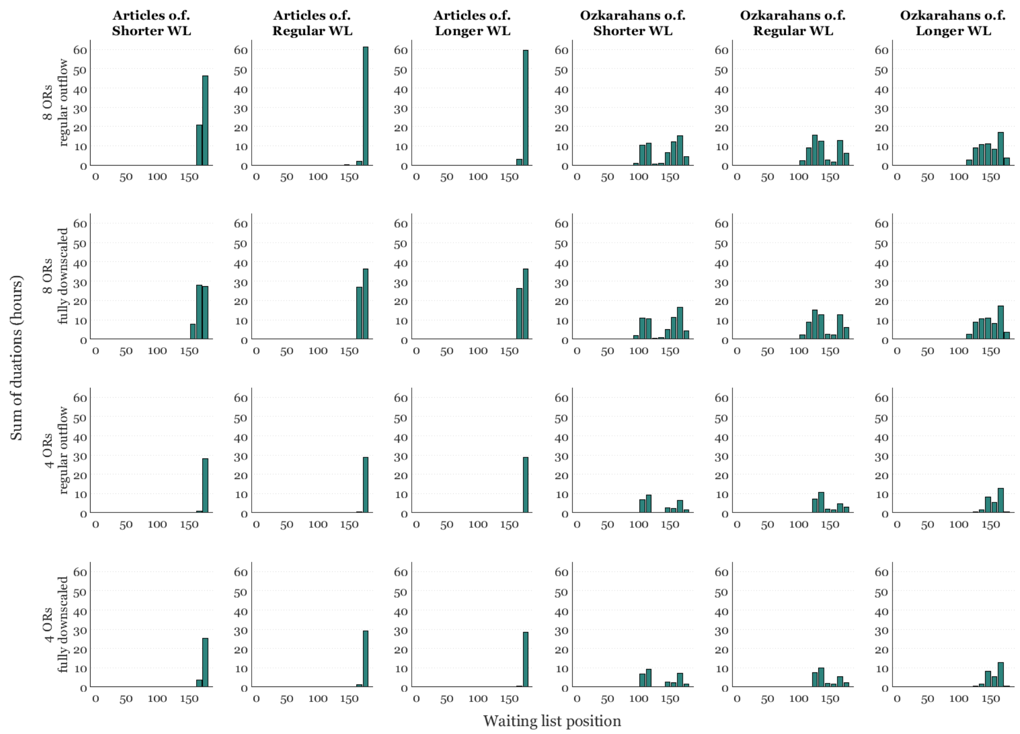


Figure A.16: Assigned priority of planned patients per hour

Table A.17: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the assigned priority of planned patients per hour and its averages.

| Difference between | P-value article's o.f. | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.343 | 0.886 | 0.114 | 172.8 | 176.7 | 173.3 |
| 8 and 4 Ors | 1.000 | | | 173.5 | 173.5 | - |
| Regular, downscaled outflow | 0.674 | | | 175.0 | 173.8 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.057 | 0.029 | 0.029 | 139.0 | 142.7 | 152.0 |
| 8 and 4 Ors | 0.944 | | | 141.1 | 141.2 | - |
| Regular and downscaled outflow | 0.992 | | | 142.7 | 144.2 | - |

## A.10.5. Position on the waiting list of planned patients

In Figure A.17, the position on the waiting list of planned patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow.

Table A.18 shows that for the article's objective function, the position on the waiting list of planned patients is not significantly different ($p_{SR} = 0.88, p_{SL} = 0.40, p_{RL} = 0.51$) between the different waiting lists ($\bar{x}_{shortWL} = 21.0$, $\bar{x}_{regularWL} = 22.5$, $\bar{x}_{longWL} = 24.0$). The position on the waiting list of planned patients is not significantly different (p=0.18) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 35.0$, $\bar{x}_{4ORs} = 30.0$). The position on the waiting list of planned patients is not significantly different (p=0.64) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 13.5$, $\bar{x}_{downscaledOF} = 15.5$).

For the objective function by Ozkarahan [18], also in Table A.18, the position on the waiting list of planned patients is significantly lower for the short waiting list as opposed to the regular and the long one ($p_{SR} < 0.001, p_{SL} < 0.001, p_{RL} < 0.001$, $\bar{x}_{shortWL} = 237.0$, $\bar{x}_{regularWL} = 311.0$, $\bar{x}_{longWL} = 326.0$). The position on the waiting list of planned patients is not significantly different (p=0.20) between planning 8 or 4 ORs ($\bar{x}_{8ORs} =$

307.5, $\bar{x}_{4ORs} = 299.0$). The position on the waiting list of planned patients is not significantly different (p=0.36) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 290.0$, $\bar{x}_{downscaledOF} = 282.0$).

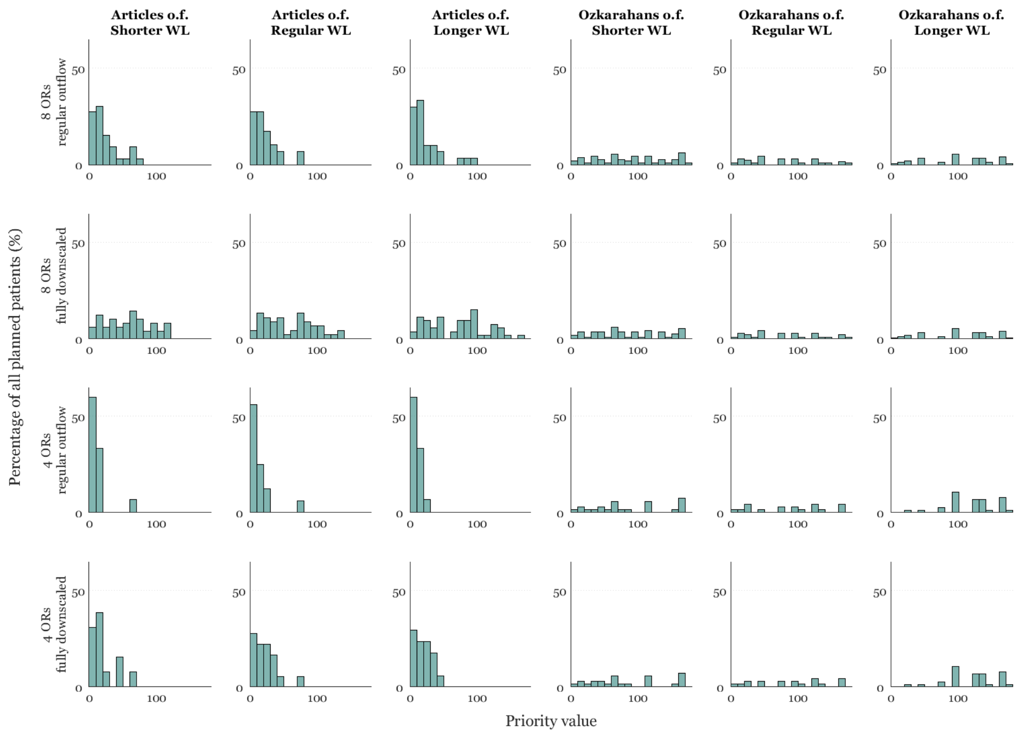


Figure A.17: Position on the waiting list of planned patients

Table A.18: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the position on the waiting list of planned patients and its averages.

| Difference between | P-value article's o.f. | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.881 | 0.398 | 0.513 | 21.0 | 22.5 | 24.0 |
| 8 and 4 Ors | | 0.184 | | 35.0 | 30.0 | - |
| Regular, downscaled outflow | | 0.645 | | 13.5 | 15.5 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | <0.001 | 237.0 | 311.0 | 362.0 |
| 8 and 4 Ors | | 0.195 | | 307.5 | 299.0 | - |
| Regular and downscaled outflow | | 0.363 | | 290.0 | 282.0 | - |

### A.10.6. NZA priority

In Figure A.18, the NZA priority of the planned patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow. The NZA priorities are approximated by the numbers 1 to 5 in which refers to category C to G respectively.

Table A.19 shows that for the article's objective function, the NZA priority of the planned patients is significantly higher, the longer the waiting list gets ($p_{SR} = 0.018, p_{SL} < 0.001, p_{RL} = 0.024$, $\bar{x}_{shortWL} = 1.4$, $\bar{x}_{regularWL} = 1.5$, $\bar{x}_{longWL} = 2.0$). The NZA priority of the planned patients is not significantly different (p=0.38) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 1.8$, $\bar{x}_{4ORs} = 1.7$). The NZA priority of the planned patients is not significantly different (p=0.72) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 1.3$, $\bar{x}_{downscaledOF} = 1.3$).

For the objective function by Ozkarahan [18], also in Table A.19, the NZA priority of the planned patients is significantly higher, the longer the waiting list gets ($p_{SR} < 0.001$, $p_{SL} < 0.001$, $p_{RL} < 0.001$, $\bar{x}_{shortWL} = 3.0$, $\bar{x}_{regularWL} = 3.3$, $\bar{x}_{longWL} = 3.6$). The NZA priority of the planned patients is not significantly different (p=0.91) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 3.3$, $\bar{x}_{4ORs} = 3.3$). The NZA priority of the planned patients is not significantly different (p=0.93) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 3.3$, $\bar{x}_{downscaledOF} = 3.3$).

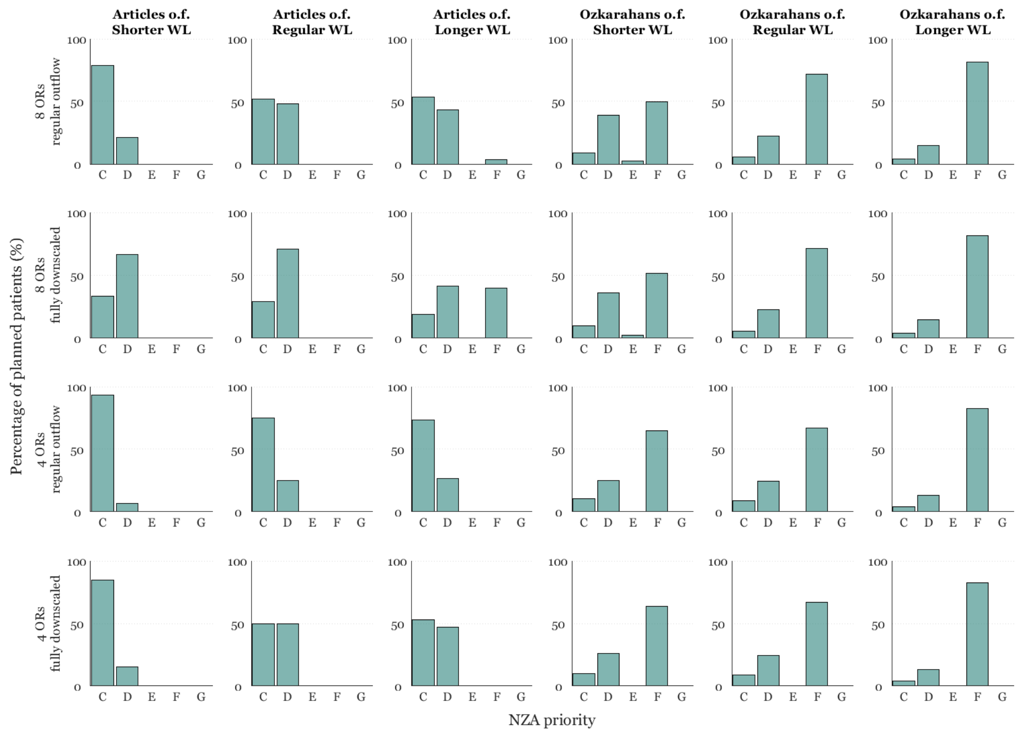


Figure A.18: The NZA priority of the planned patients

Table A.19: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the NZA priority of the planned patients and its averages.

| Difference between | P-value article's o.f. | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | 0.018 | <0.001 | 0.024 | 1.4 | 1.5 | 2.0 |
| 8 and 4 Ors | 0.381 | | | 1.8 | 1.7 | - |
| Regular, downscaled outflow | 0.719 | | | 1.3 | 1.3 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | <0.001 | 3.0 | 3.3 | 3.6 |
| 8 and 4 Ors | 0.908 | | | 3.3 | 3.3 | - |
| Regular and downscaled outflow | 0.934 | | | 3.3 | 3.3 | - |

## A.10.7. Time on the waiting list of planned patients

In Figure A.19, the time on the waiting list of planned patients per situation is shown, in which situation refers to all the different combinations of objective functions, waiting lists, ORs, and outflow.

Table A.20 shows that for the article's objective function, selected patients had a significantly longer waiting time when the waiting list got longer ($p_{SR} < 0.001$, $p_{SL} < 0.001$, $p_{RL} = 0.003$, $\bar{x}_{shortWL} = 10.0$, $\bar{x}_{regularWL} =$

16.5, $\bar{x}_{longWL} = 23.0$). The time on the waiting list of planned patients is not significantly different (p=0.82) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 16.0$, $\bar{x}_{4ORs} = 15.0$). The time on the waiting list of planned patients is not significantly different (p=0.78) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 10.0$, $\bar{x}_{downscaledOF} = 10.0$).

For the objective function by Ozkarahan [18], also in Table A.20, selected patients had a significantly longer waiting time when the waiting list got longer ($p_{SR} < 0.001, p_{SL} < 0.001, p_{RL} < 0.001$, $\bar{x}_{shortWL} = 18.0$, $\bar{x}_{regularWL} = 37.0$, $\bar{x}_{longWL} = 57.0$). The time on the waiting list of planned patients is not significantly different (p=0.50) between planning 8 or 4 ORs ($\bar{x}_{8ORs} = 29.0$, $\bar{x}_{4ORs} = 30.0$). The time on the waiting list of planned patients is not significantly different (p=0.65) between a regular and a downscaled outflow ($\bar{x}_{regularOF} = 30.0$, $\bar{x}_{downscaledOF} = 30.0$).

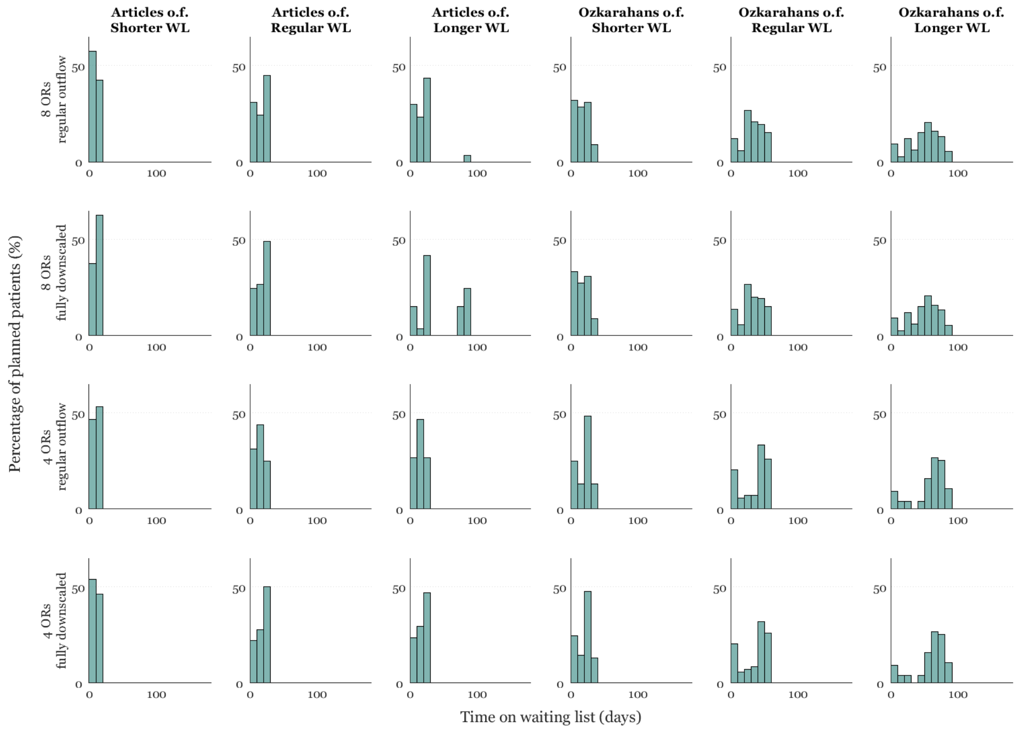


Figure A.19: Time on the waiting list of planned patients

Table A.20: P-value of the Wilcoxon signed rank-test to compare the different waiting lists, number of ORs and the different ORs for the article's objective function and the objective function by Ozkarahan [18] separately for the time on the waiting list of planned patients and its averages.

| Difference between | P-value article's o.f. | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | 0.003 | 10.0 | 16.5 | 23.0 |
| 8 and 4 Ors | 0.824 | | | 16.0 | 15.0 | - |
| Regular, downscaled outflow | 0.776 | | | 10.0 | 10.0 | - |

| Difference between | P-value Ozkarahan [18] | | | $\hat{x}$ var 1 | $\hat{x}$ var 2 | $\hat{x}$ var 3 |
|---|---|---|---|---|---|---|
| Waiting lists | <0.001 | <0.001 | <0.001 | 18.0 | 37.0 | 57.0 |
| 8 and 4 Ors | 0.503 | | | 29.0 | 30.0 | - |
| Regular and downscaled outflow | 0.650 | | | 30.0 | 30.0 | - |

# B

# Matlab script proof of concept

```
clear all
close all
clc

%% Load the needed data
load('F:\Model maken\dataset_model.mat')

%% Select which situation is implemented
% create a for loop to select the right situation
% 2 different OR availabilities
for ORA = 1:2
    if ORA ==1
        OR_availability = '8 ORs available'
    elseif ORA ==2
        OR_availability = '4 ORs available'
    end

    % 3 different waiting lists
    for WL = 1:3
        if WL ==1
            waiting_list = 'Regular'
        elseif WL ==2
            waiting_list = 'Longer'
        else
            waiting_list = 'Shorter'
        end

        % 2 different ward availabilieties
        for WA = 1:2
            if WA ==1
                Ward_ICU_availability = 'Regular'
            else
                Ward_ICU_availability = 'Fully downscaled'
            end

            for opt = 1:2
                if opt ==1
                    Optimization_method = 'Own'
                else
                    Optimization_method = 'Article'
                end
tic
diary command_window_run


%% Select the right patients (make a waiting list)
% Different waiting lists will be created to check the performance of the
% model in different situations. One waiting list will be of a "regular"
```

```
% week, another of a week with less elective patients (as might be the case
% during covid), one with a lot of patients <2 weeks, and one with only a
% few patients <2 weeks. The waiting lists will be created without acute
% care as future plannings are always made with acute care.

% "Regular" waiting list - taking data from 2019 week 13 as the number of
% ORs that are open and the number of surgical hours is average.
RegularWeek = 201913;

% Next we find the elective care of this week
% (multiple of weeks, bec more logical with planning. Amount of weeks is
% based on time within planning should happen.

if strcmp(waiting_list,'Regular')==1
    % For prio C: last 2 weeks
    % For prio D: last 4 weeks
    % For prio E: last 7 weeks
    % For prio F & G: last 9 weeks
    WLRegularWlElective = data(...
        ((strcmp(data.NZAPrioriteit,'C') & ...
        (data.OperatieJaarWeek == RegularWeek |...
        data.OperatieJaarWeek == RegularWeek-1))) ...
        | ...
        (strcmp(data.NZAPrioriteit,'D') & ...
        (data.OperatieJaarWeek >= RegularWeek - 3 & ...
        data.OperatieJaarWeek <= RegularWeek)) ...
        | ...
        (strcmp(data.NZAPrioriteit,'E') & ...
        (data.OperatieJaarWeek >= RegularWeek - 5 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        | ...
        ((strcmp(data.NZAPrioriteit,'F') | strcmp(data.NZAPrioriteit,'G')) & ...
        (data.OperatieJaarWeek >= RegularWeek - 7 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        ,:);
elseif strcmp(waiting_list,'Longer')==1
    % For prio C: last 2 weeks
    % For prio D: last 4 weeks
    % For prio E: last 8 weeks
    % For prio F & G: last 12 weeks
    WLRegularWlElective = data(...
        ((strcmp(data.NZAPrioriteit,'C') & ...
        (data.OperatieJaarWeek == RegularWeek |...
        data.OperatieJaarWeek == RegularWeek-1))) ...
        | ...
        (strcmp(data.NZAPrioriteit,'D') & ...
        (data.OperatieJaarWeek >= RegularWeek - 3 & ...
        data.OperatieJaarWeek <= RegularWeek)) ...
        | ...
        (strcmp(data.NZAPrioriteit,'E') & ...
        (data.OperatieJaarWeek >= RegularWeek - 7 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        | ...
        ((strcmp(data.NZAPrioriteit,'F') | strcmp(data.NZAPrioriteit,'G')) & ...
        (data.OperatieJaarWeek >= RegularWeek - 11 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        ,:);

elseif strcmp(waiting_list,'Shorter')==1
    % For prio C: last 2 weeks
    % For prio D: last 3 weeks
    % For prio E: last 4 weeks
    % For prio F & G: last 5 weeks
    WLRegularWlElective = data(...
        ((strcmp(data.NZAPrioriteit,'C') & ...
        (data.OperatieJaarWeek == RegularWeek |...
        data.OperatieJaarWeek == RegularWeek-1))) ...
        | ...
        (strcmp(data.NZAPrioriteit,'D') & ...
        (data.OperatieJaarWeek >= RegularWeek - 2 & ...
        data.OperatieJaarWeek <= RegularWeek)) ...
```

```
        | ...
        (strcmp(data.NZAPrioriteit,'E') & ...
        (data.OperatieJaarWeek >= RegularWeek - 3 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        | ...
        ((strcmp(data.NZAPrioriteit,'F') | strcmp(data.NZAPrioriteit,'G')) & ...
        (data.OperatieJaarWeek >= RegularWeek - 4 & ...
        data.OperatieJaarWeek <= RegularWeek))......
        ,:);
end

%Calculate how long patient has been on waiting list, counted from the
%patient that is there the shortest
WLRegularWlElective.DaysOnWaitingList = max(WLRegularWlElective.WanneerOpWachtlijst) - ...
    WLRegularWlElective.WanneerOpWachtlijst;

% Calculate priority value based on NZA priority combined with how long
% this patient has been on the waiting list.
WLRegularWlElective.Priority = WLRegularWlElective.NZAprioValue + WLRegularWlElective.DaysOnWaitingList;

%% Set-up of the model
% Sorting the waiting list based on priority, this doesn't change anything
% in the model itself but makes it easier to interpret the results in the
% end.
patients_temp = WLRegularWlElective;
patients = sortrows(patients_temp,'Priority','descend');

%% Create the parameters
% Number of patients
nPatients = height(patients);

if OR_availability == '8 ORs available'
    nORs = 8;
elseif OR_availability == '6 ORs available'
    nORs = 6;
elseif OR_availability == '4 ORs available'
    nORs = 4;
end

% Number of variables
nvars = nPatients*nORs;

%% Set up the constraint matrix A
% CI - OR utilization restriction
p_temp = patients.Operatieduur + 0.25; %Duration of operation i in hours including
                                       %15 minutes clean up and set up time
surgical_time = repmat(p_temp,nORs,1);
p_temp_vec = {p_temp',p_temp',p_temp',p_temp',p_temp',p_temp',p_temp',p_temp'};
p = blkdiag(p_temp_vec{1:nORs}); %Create a matrix with vector p_temp, with the nr
                                 %of rows same as ORs and 0's for the unselected ORs

% CII - Unique assignment restriction
q=[];
for i = 1:nORs
    q = [q, diag(ones(1,nPatients))]; %Only one OR per patient constraint
end

% CIII - Outflow restriction
r_temp = patients.Opname; %Are patients going to the ICU or ward after surgery?
r=[];
for i=1:nORs
    r = [r r_temp'];
end

% Full constraint matrix A
A = [p;q;r]; %Constraint matrix

%% Set up the constraint vector b

% CI - OR utilization restriction
% Regular day is from 8 to 16:30, excluding 30 minutes break time, so 8 hours. Every
```

```
% surgery has an additional switching time of 15 minutes added to this, so
% 8.25 hrs for a regular OR. One OR has 4hrs emergency OR, so 4.25 hrs
Tors = [4.25;8.25;8.25;8.25;8.25;8.25;8.25;8.25]; %Amount of time OR is available per
            %day in hours - based on a Monday, so 1 afternoon reserved for acute care
T = Tors(1:nORs);

% CII - Unique assignment restriction
U = ones(nPatients,1); %Maximum amount of times a patient is in an OR, only 1

% CIII - Outflow restriction
if strcmp(Ward_ICU_availability,'Regular')
    V = 17; %Maximum allowed nr of patients going to ICU/ward
elseif strcmp(Ward_ICU_availability,'Fully downscaled')
    V = 5; %Maximum allowed nr of patients going to ICU/ward
end

% Full constraint vector b
b = [T;U;V];

%% Create patient priority vector
if strcmp(Optimization_method,'Own')==1
    % Own way
    Z1 = patients.Priority'; %patient priority, where the highest number is the most
                             %important patient.
    Z = [];
    for i = 1:nORs
        Z = [Z,Z1]; %Create vector of patient priority
    end

elseif strcmp(Optimization_method,'Article')==1
    % As in article
    Zart_temp = linspace(nPatients,1,nPatients);
    Z_artikel = [];
    for i = 1:nORs
        Z_artikel = [Z_artikel,Zart_temp]; %Create vector of patient priority
    end
end
%% Run the optimization

% The Objective functions
if strcmp(Optimization_method,'Own')==1
    FitFcn = -Z.*surgical_time';
elseif strcmp(Optimization_method,'Article')==1
    FitFcn = -Z_artikel;
end

% Define the lower and upper bound, maximum once planned
% and minum 0.
lb = zeros(1,nvars);
ub = ones(1,nvars);

%Select options: Primal simplex and maximum of 2 hrs
options = optimoptions('intlinprog','RootLPAlgorithm','primal-simplex','MaxTime',14400);

try
    X=intlinprog(FitFcn,1:nvars,A,b,[],[],lb,ub,[],options);
catch me
    continue
end

%% Save the relevant parameters
elapsed_time = toc
X2 = reshape(X,nPatients,nORs)';
all_vars = {patients,X2,p_temp,Z1,r_temp,elapsed_time};
save(join([waiting_list,' waiting list, ',OR_availability, ', ', Ward_ICU_availability,...
    ' ICU and ward, ', Optimization_method, ' optimization method.mat']),'all_vars')
diary off
            end
        end
    end
end
```