MASTER

Handling urgent patients in operation room scheduling using a flexible emergency-OR

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Contents

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Abstract

This report develops a new method of handling emergency patients in operating room (OR) departments at an operational off-line level. The method is called 'Flexible Emergency-OR (from here on referred to as FEOR)' and is implemented and tested in combination with four ''different'' methods of slack allocation for anticipating urgent surgery on a tactical level: (1) no built-in slack for urgent surgery (No slack), (2) concentrated slack in a single dedicated operating room (Emergency OR), (3) allocated slack to a subset of the operating rooms (White spots) and (4) allocated slack to all operating rooms (Department wide slack). This results in a total of eight different ways of anticipating urgent surgery which will be tested in four different scenarios.

Before the testing is conducted, a standard back-of-the-envelope analysis is performed. Not only do the results of this BoE predict the simulation results, large differences in the two will help identify flaws in either of the methods.

The actual testing is done using a discrete-event simulation and a comparison of the different combinations is made based on among others the following key performance indicators (KPI's): urgent surgery waiting time, overtime and OR utilization. Simulation results show a trade-off between utilization rate and waiting times. Depending on which of the two is higher on the priority list of hospital management, using the FEOR method can either improve or decrease the efficiency of the OR planning.

Keywords: Emergency patients, Non-elective patients, Operating room utilization, Discrete-event simulation, BoE analysis

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This Master thesis was written over a notable period of time in which my life changed from being a student living in a student home, to being an employee of a big firm, an husband and a soon-to-be dad. Due to all these happy events taking place, finishing my master Thesis was not always on top of my mind. Luckily I was, and still am, blessed with a group of great people around me of which at least the following subset have my eternal gratitude.

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1 Introduction

OR's and the personnel working in the OR's are very expensive assets for a hospital, which is why it is important to make efficient use of them. The amount of staffed OR's (OR capacity) available to a hospital is usually just enough to cover the demand of care that the particular hospital receives on a yearly basis (having more would be a waste). A remodeling of the OR department that decreases capacity for a while therefore can be a major problem and a serious concern for the OR-department.
A similar occurrence was the reason for a group of KPMG advisors to get into OR-scheduling. During their research, these advisors were looking for ways to handle the arrivals of emergency-patients and found out that allocating slack on a subset of the OR's is an alternative for using a dedicated emergency-OR. The waiting time for urgent surgery however was a disadvantage, which led to the idea of the FEOR method (Figure 1).
Before the performance of FEOR will be investigated using both mathematical analysis and simulation, this chapter will first clarify the context of the problem. First the case study conducted by the KPMG advisors, which triggered this project, will be described in more detail. Subsequently more information will be given around the need for efficiency in hospitals and more precisely, in OR-departments. Literature concerning modeling and simulation methods relevant to the problem will be summarized after which literature will be discussed more focused on handling emergency patients. The last section of this chapter will set the focus for the remaining part of this master thesis.

1.1 Case study as origin

Due to remodeling the OR department, an Academic Medical Center in the Netherlands (from here on referred to as "S.T.A.R. labs") had to deal with a notable decrease in OR capacity, while maintaining their normal production. As a solution, they decided to remove their dedicated emergency-OR and to extend business hours on 3 of their ORs. As a replacement solution for the emergency-ORs they allocated slack (known as white spots) for urgent surgery to a subset of the operating rooms.
Although the total amount of time reserved for the different specialisms was unchanged, there was a lot of discussion whether or not the new schedule would suffice. Furthermore the waiting time of emergency patients within the new schedule was a big concern to many of the specialists. It was clear that more certainty was needed concerning traditional KPI's such as utilization, overtime, amount of cancellations and average waiting time for emergency patients.
Commissioned by S.T.A.R. labs, a group of KPMG RC ITA and KPMG PLEXUS consultants performed the needed research to answer the questions of the professionals and take away the concerns regarding the new schedule for the period of remodeling. Using a simulation in which almost every uncertainty was taken into account (the stochastic processes surrounding the OR department were not ignored, but recognized and modeled), they concluded that the schedule would indeed suffice (Matthijssen & Vlieger, 2013).
The allocation of slack for urgent surgery turned out to be a sufficient way of handling emergency patients. Although the waiting time increased, it was only by a small margin and still within the norm. Besides this sufficient result, the method also showed some very positive unexpected incidentals. On traditional KPI's such as utilization, overtime and the amount of cancellations, the new schedule performed better than the old schedule. These findings raised

the question why the operation department would ever go back to a dedicated emergency-OR. The simulation results suggested that it would be better to stick with the white spots, even after the transition period.
Further researching the usage of white spots seemed a logical next step, but as within many commercial companies the advisors lacked spare time to do so, while S.T.A.R. labs did not order them to further pursue the matter. This provided a perfect opportunity for a master thesis student as myself to step in.
Notable, but not exceptional is that the research was conducted following a renovation of the OR-department. Another example where this was the case is the master thesis of Dibbits, a mathematics student at the TU/e (Dibbits, 2012) . Here a change in housing was the reason for the hospital to take a closer look at their usage of operation rooms and thus at their scheduling method.

1.2 Hospital efficiency

For years, the costs of healthcare have been increasing with a much faster rate than the budget. As a result, working efficiently to cut costs gets more and more important (Ministerie van VWS, PLEXUS, 2010). A major portion of the health care expenditure is spent in hospitals. Hospital efficiency and management is, therefore, receiving an increasing amount of attention in practice and in the literature (Houdenhoven, 2007). Since the operation room department is one of the bigger expenses for a regular hospital, working efficiently here is of big impact. High utilization rate of the costly ORs is therefore aspired by many, although the pressure of delivering quality stays. Patient well-being is at the top of the list for most hospitals. Long waiting times, high cancellation rates and overtime are important drivers for patient dissatisfaction. Using operational research techniques, hospitals are looking for ways to comply with both requirements in the best possible way.
Both utilization rates and the earlier mentioned drivers for patient dissatisfaction are derived from the way surgeries are scheduled. Therefore, appointment scheduling in health care brings many challenges (Gupta & Denton, 2008). High utilization rates can be achieved by a tight and full schedule, but this brings a lot of drawbacks. Duration of a certain type of surgery varies a lot and is very unpredictable. In case a surgery gets delayed for whatever reason in a tight schedule, this immediately results in expensive overtime or even cancellation of the patients planned later in the afternoon on the same OR. Both cases are best avoided as much as possible when creating a surgery schedule. Developing an effective OR schedule often happens in a three-stage procedure: allocation of OR time to surgical specialties at strategic level, development of a master surgery schedule at tactical level and scheduling individual (emergency) patients at operational level (Demeulemeester & Beliën, 2007). The question of how to develop a robust tactical plan and how to translate that into an operational plan is one that challenged many researchers.
As might be clear by now, when creating an OR-schedule a lot of different factors have to be taken into account. Therefore it is a difficult task which is mathematically challenging. It is the subject of a large number of research projects focusing on many different aspects of the problem. Naturally, a lot of literature exists concerning the scheduling of surgery or operation room scheduling. This can be concluded from multiple literature reviews on the topic. Where some summarize the research done on OR scheduling with the hope that it will stimulate further investigation (Przasnyski, 1986), others focus on significant trends in research on operating room planning and scheduling and identify the lack of research concerning for example emergency patients, wishing more research would be focused towards the specific

topic (Cardoen, Demeulemeester, & Beliën, 2010). The lack of research concerning emergency patients is a recurring topic (Lans et al., 2006). This report will partly fill in the mentioned gaps. Given the complexity of OR planning, not all factors will be taken into account within this research. Although walk-in seasonality (regular and emergency) is an interesting research area (Cayirli & Veral, 2003) with a practical bearing on certain practices such as radiology (summer fractures and winter colds) and pulmonary specialties (seasonal asthma and allergy agents), the impact of this will be ignored for example.

1.3 Modeling and simulation

OR departments and their patient streams are ideal subjects to model using queueing theory (Denton, 2013). Queues form when entities that request service arrive at a server and cannot be served immediately upon arrival. In OR departments, patients (both elective and urgent) are typically the ones requesting service while ORs together with the medical teams are the servers. Modeling the OR department using queueing theory can provide managers with insights into, for example, the causes for excessive wait times and the relationship between wait times and capacity (Patrick & Puterman, 2008). It is shown that the quality of service at a hospital emergency department can be improved by utilizing simulation (Yeh & Lin, 2007). If only for these reasons, operational research should be the input for nearly every discussion around surgery planning, but sadly this is not the case most of the times (Delesie, 1998).
Modeling and/or simulating the events occurring in an OR department brings many challenges. Accurate prediction of medical operation times for example is crucial when researching OR planning, but this factor alone depends on many surgeon factors like age, experience, gender, and team composition (Stepaniak, Heij, and de Vries 2010, Strum et al. 2000). A log-normal model for predicting surgical procedure times seems to be the best choice in most cases (Strum, May, & Vargas, 2000), but in this report another approach will be used as is explained later.
As could be apparent for the reader by now, scheduling elective surgeries on available ORs in an optimal way, is finding the balance between high utilization rates while maintaining a certain level of patient satisfaction. This optimization problem is, as suggested above, often solved by a computer simulation where the uncertainties are modeled mathematically. Within the available literature a wide range of different simulation and modeling techniques can be found, varying from a stochastic dynamic programming model (Gerchak, Gupta, & Henig, 1996) to a Markov chain probability model that uses maximum likelihood regression (Broyles, Cochran, & Montgomery, 2010) to mixed integer programming (Adan et al. 2011, Dellaert and Jeunet 2013, Lamiri et al. 2008) to column generation (Lamiri, Xie, & Zhang, 2008) to using the Bailey–Welch rule combined with a neighborhood search heuristic (Sickinger & Kolisch, 2009). After having decided which surgeries are performed in which OR on which day, the order in which the surgeries are performed is also of importance. For example when emergency patients arriving mid-day is a possibility (more on emergency patients in section 1.4), optimizing the spread of Break-In-Moments (BIM's) turns out to be very useful (Lans et al., 2006). Furthermore, scheduling the short procedures first improves on-time performance and decreases overtime expense without reducing surgical throughput (Lebowitz, 2003). Sorting the requests for a particular day on the basis of block restrictions and historical data is also very common (Ozkarahan 2000, Hans et al. 2008)
Ignored in most research on the topic is nonoperative time (room turnover time plus anesthesia induction and emergence time) (Drenth, Jong, & Koster, 2012). A coordinated multidisciplinary process redesign can significantly reduce this driver for low utilization rates (Harders, Malangoni, Weight, & Sidhu, 2006). While reducing nonoperative time is not in

scope for this master thesis, it is taken into account when creating and simulating the schedule.

1.4 Emergency surgery as an extra challenge

Emergency patients provide for an extra challenge in the already complex operation room planning. Main reasons for emergency patients to be challenging is their unpredictable time of arrival and the very short time span in which they need surgery (which is basically the reason why they are called “emergency patients”).
How to serve these unpredictable jobs within the OR department is the topic of several but an inadequate amount of research projects (Cardoen, Demeulemeester, and Beliën 2010, Lans et al. 2006). To deal with the arrivals of emergency patients, they should already be taken into account when creating a schedule on a tactical level. As it were, time should already be reserved in case an emergency patient arrives. In the literature, three different methods of making these time reservations for urgent surgeries are described:

(1) Freeing a single or multiple ORs for the complete day to serve as dedicated emergency-O’s. These ORs are not taken into account when creating a roster for the elective patients, so are not used at all in case no emergency patients arrive. Emergency patients are treated on the dedicated ORs as much as possible. Only in unusual circumstances, an emergency patient is treated on a regular OR. As a result, the planning of elective patients is seldom disturbed by the arrival of an emergency patient.

(2) Reserving a certain amount of time (white spots) on one or several ORs. Emergency patients are preferably treated on the ORs with allocated slack. Only when the expected duration of the planned urgent surgeries exceeds the amount of time reserved, urgent surgery will be performed on ORs without allocated slack.

(3) Allocating a certain amount of slack to every OR. Urgent surgery will be performed on no OR in particular, but thanks to the allocated slack the overtime will be limited.

Here, (2) and (3) are variations of the same idea, using an OR to perform both types of surgeries (elective and urgent). White spots are nothing but a reduction of the amount of time available when scheduling elective patients. This reserves some time for urgent surgery in case that is needed. (2) chooses to allocate this slack to a subset of the available ORs, (3) allocates slack to every OR.
The idea of one or more dedicated emergency-ORs has existed for quite some time now and is used in six out of eight academic hospitals in the Netherlands (Lans et al., 2006). While a dedicated OR for emergency cases improves quality of care by decreasing cancellations and overruns in elective rooms (Heng and Wright 2013, Lovett and Katchburian 1999), it is also known that dedicated emergency-ORs are costly due to the low utilization of the operating room dedicated to emergency patients (Barlow et al. 1993, Brasel, Akason, and Weigelt 1998). With the introduction of methods (2) and (3), the question arose: is it more efficient to reserve ORs dedicated separately for scheduled and emergency surgeries, or is it better to perform both types of surgeries in any available OR using pooled or interchangeable OR arrangement (Kolker, 2012)? Important to note is that in situation (1) there is a non-zero probability that an emergency patient can be treated immediately. Using method (2) or (3) this probability is 0 and there will be always some waiting time involved for emergency patients, which can be a problem in the extremely urgent cases. Minimizing the waiting time of the most urgent

emergency patients is therefore an important topic when using these methods (Lans et al., 2006) and is one of the key futures of the FEOR as will be shown later on in this report.
Results of recent research projects indicate that both methods (2) and (3) (Wullink et al. 2006, Wullink et al. 2007) lead to improvements in waiting times for emergency surgery, reductions of the amount of overtime and an increase of overall OR utilization compared to method (1). Emergency patients are operated upon more efficiently on elective Operating Rooms than on a dedicated Emergency OR. These results led to closing of the Emergency OR in the Erasmus Medical Centre (Rotterdam, The Netherlands).
Where until now the focus was on planning at the tactical level, scheduling of different emergency patients on an operational level can also literally be a matter of live and death when queues of emergency patients occur. However in most of the hospitals this is not the case (Dexter, Macario, & Traub, 1999). In S.T.A.R. labs for example, only 349 emergency patients of the most urgent type arrived in 2012. Therefore the probability of another emergency patient arriving while the first is waiting for surgery is negligible in this case.
Within S.T.A.R. labs (and in most of the Dutch academic hospitals), three types of emergency patients are distinguished:

A. Which according to the standard, may wait a maximum of 2 hours on the start of surgery.
B. Which according to the standard, may wait a maximum of 6 hours on the start of surgery.
C. Which according to the standard, may wait a maximum of 24 hours on the start of surgery.

Priorities between these different types of emergency patients are as expected. Type A patients typically have more priority than patients of type B while type B patients have more priority than patients of type C. Only in rare cases there will be deviation in this matter (Panayiotopoulos & Vassilacopoulos, 1984). Further into this report the different priorities will get clear when the planning rules for the different types are discussed.

1.5 Focus of this study

Specific research concerning the reduction of waiting time of the emergency patients is scarce. An investigated method is minimizing the maximum expected period between the end of two different surgeries. The end of a surgery is called a BIM (Break-In-Moment) since here the treatment of an arrived emergency patient can start. When the time between BIM's is small, automatically the expected waiting time for an emergency patient is small (Lans et al., 2006). In this study an alternative method with the same goal but many helpful side effects is suggested. The new method called FEOR, is the main added value of this thesis and will be researched for the first time. The FEOR method is expected to have a positive impact on certain very important KPI's in OR scheduling while leaving the other KPI's, more or less untouched. Although BIM and the new method share the same purpose, they can co-exist and are complementary. One will not weaken or undo the effects of the other. Therefore the two methods will not be compared, but the working of the new method will be researched by comparing a situation in which FEOR is used, with a situation in which the method is not used. The main idea behind the method is to have an OR ready to start urgent surgery at all times, reducing the average waiting type of an emergency patient of type A to almost 0 (not exactly 0 as will be explained later). Although reserving an OR for the potential arrival of an emergency patient at all times sounds like having a dedicated emergency-OR, there is an important

difference between the two. Which OR is kept free varies throughout the day and is based on the expected end time of today's work at the different ORs. The OR with the earliest end time is kept free for urgent surgery, making sure the extra work is directed to the OR that will receive the least overtime from performing the urgent surgery. Though in total a full day of operation time is not used to treat elective patients, as is the case with a dedicated emergency-OR, here the influence on utilization rate and overtime is expected to be a lot less painful. However, the question remains whether the reduced waiting time for emergency patients is worth the mentioned negative effects (how small they may be).
The method is called 'Flexible Emergency-OR (FEOR)' and will be implemented and tested in combination with the three earlier mentioned methods of "anticipating" urgent surgery on a tactical level plus the situation where no anticipation is performed: (1) no build-in slack for urgent surgery, (2) concentrated slack in a single dedicated operating room, (3) allocated slack to a subset of the operating rooms and (4) allocated slack to all operating rooms. These four methods with and without FEOR (making a grand total of 8 different methods) will be simulated and compared in terms of many of the earlier mentioned KPI's.
Ultimately this study hopes to contribute to the reduction of waiting times of emergency patients while still maintaining an acceptable utilization rate, thereby enriching the research performed by KPMG commissioned by S.T.A.R. labs.

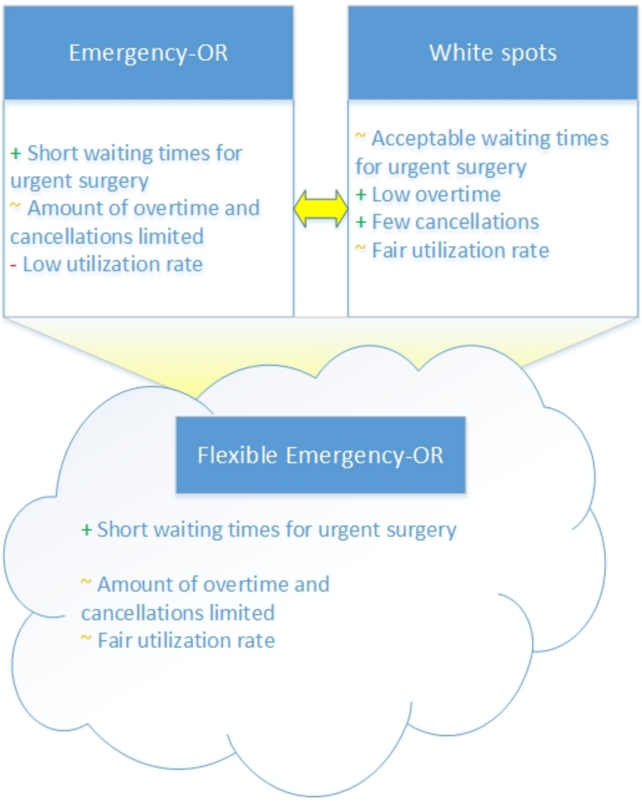


Figure 1 The idea of the FEOR method

2 Model definition

The testing of the FEOR method is done using a mathematical representation of the reality within the OR-department. This particular mathematical representation is called a queueing model and will be defined within this chapter. First of all, the general terminology used within queueing models is given.

2.1 Terminology

Figure 2 shows the building blocks of a basic queueing model. The input source, queue and servers each have their own characteristics. In short:

- **Input Source**
  The size and statistical distribution of arrival are the main characteristics of an input source. The size can be either finite or infinite. In the case of this research, the size of the input source is big enough to model it as being infinite (i.e. the stream of patients requiring treatment will probably never end). The statistical distribution, as the name suggest, defines according to which distribution patients arrive at the hospital.
  It could be for example, that there is a seasonality involved. I.e. depending on the season the stream of patients is higher or lower. This does happen with certain types of patients, such as knee-patients that typically arrive more during the winter sport season or eye-patients that typically arrive more around new-year. Looking at the complete patient stream however, no real seasonality is visible.

- **Queue**
  After his or her arrival, a patient can either be served immediately or wait in line for service. This waiting is done in the queue. A queue can have finite capacity (for example when the input source is impatient and does not wait but rather leaves and gets back later, this is called a zero capacity queue) , but in the case of this research the queue capacity is infinite. Besides the capacity, a queue also has a certain queue discipline which defines in what way patients from the queue are selected to be served. These disciplines are roughly split into two types. The difference between these types is whether or not the service of a lower priority patient may be interrupted when a higher priority patient arrives. In this research, this will not be the case. Queues with this characteristic are called non-preemptive queues. The precise queue disciplines used in this research are shown in the different decision trees given in Appendix D.

- **Servers**
  Servers in this research are the different OR's (including staff) within the OR-department. After a certain waiting time, patients are selected for treatment at an OR. This treatment, or service in a more general context, takes a certain time. This is called the service time. It can depend on the patient, the type of treatment, the server or any combination of those three how the service time is distributed. It is important that a queueing model explicitly states which distribution for the service time is assumed in which situation. In this research, the distributions are based on the measured service times within S.T.A.R. labs and depend mainly on the type of treatment.

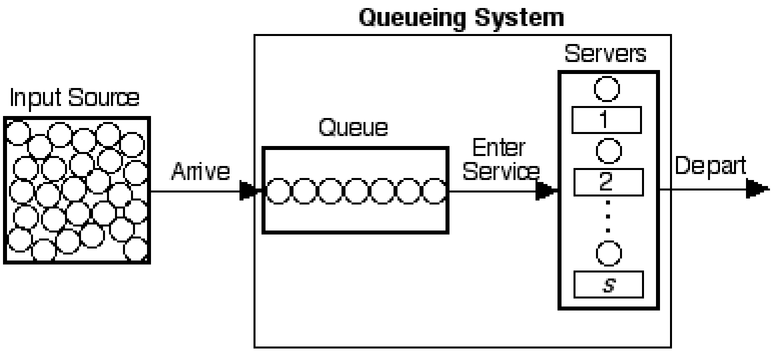


Figure 2 Schematic representation of a queueing model

To reduce the content gap between this section and the next, Figure 3 is an even more schematic representation of a queueing model. Here the typical way of drawing queues (sort of staircase from above) and servers (circles) is shown. λ represents the arrival rate, in which patients leave the input source and arrive at the queues. The P_1, P_2 and P_m represent the possibilities of an arriving patient choosing for a certain queue. The different µ's represent the service rates of the different OR's, which in this case depend on the type of service required. With this schematic in mind, the model used in this research will be defined.

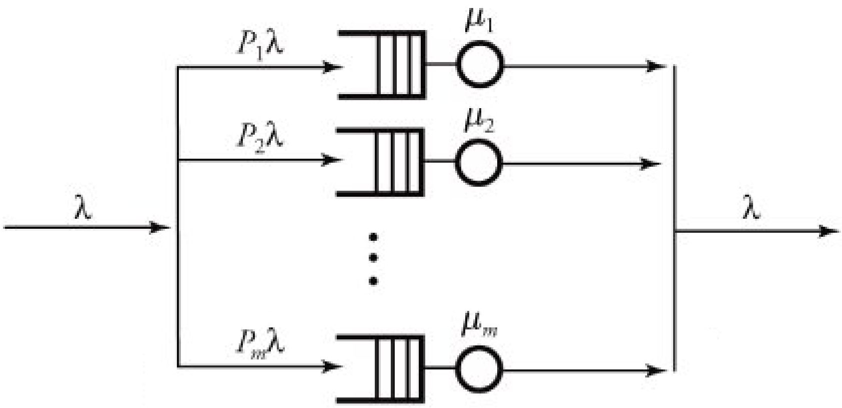


Figure 3 Mathematical representation of a queueing model

2.2 Variables and Parameters

The variables and parameters used in the model (and later on in the mathematical analysis and simulation) are given in Tables 1 and 2. These will be used and further explained during the remainder of this chapter. The values in the base case are derived from the situation in S.T.A.R. labs.

Variables		Representation in the simulation code
T_i	Number of work hours at OR i, for i = 1, … , O	ORHours(i)
S_i	Specialism assigned to OR i, for i = 1, … , O	specialism(i)
h_i	Number of hours slack allocated at OR i, for i = 1, … , O	SlackHours(i)
t_i	Number of hours available at OR i to schedule elective patients, for i = 1, … , O	WorkHours(i)
N_i	Number of scheduled elective patients at OR i, for i = 1, … , O	Scheduled(i)
N'_i	Number of actual performed surgeries at OR i, for i = 1, … , O	Performed(i)
WS_i	Binary variable tracking whether OR i has a white spot allocated to it, for i = 1, … , O	isWITTEVLEK(i)
$DEOR_i$	Binary variable tracking whether OR i is the dedicated Emergency OR, for i = 1, … , O	isSPOEDOK(i)
FER_i	Binary variable tracking whether OR i is currently the FEOR, for i = 1, … , O	isFEOR(i)
FER	Identity number of the current FEOR	CFEOR
$FT_{i,t}$	Planned finish time of the work in OR i at time t, for i = 1, … , O	PlannedFT(i, t)
FT'_i	Actual finish time of the work in OR i, for i = 1, … , O	FT(i)
OT_i	Expected extra time to be worked at OR i at time t, for i = 1, … , O	Overtime(i, t)
OT'_i	Extra time worked at OR i, for i = 1, … , O	Overtime(i)
$Q_{i,t}$	Sum of the X_i's of the patients in queue for OR j at time t, for j = 1, … , O	workToDo(i,t)
$W_{i,k}$	Amount of change time after the k'th patient served at OR i, for i = 1, … , O	wisseltijd(i,k)
$X_{i,k}$	Planned surgery duration for the k'th patient planned for surgery at OR i, i = 1, … , O	serviceTime(i, k)
$X'_{i,k}$	Actual surgery duration for the k'th patient planned for surgery at OR i, i = 1, … , O	actualServiceTime(i, k)
$ST_{i,k}$	Planned start time of the k'th surgery at OR i, for i = 1, … , O	Starttime(i,k)
$ST'_{i,k}$	Actual start time of the k'th surgery at OR i, for i = 1, … , O	aStarttime(i,k)
$EA_{i,k}$	Arrivaltime of the k'th patient at OR i, for i = 1, … , O	arrivalTime(i, k)
$ES_{i,k}$	Specialism of the k'th patient at OR i, for i = 1, … , O	specialism(i, k)
C	Number of cancellations at the end of the day	cancellations

Table 1: Variables used in the model and their representation within the simulation/mathematical analysis

Parameters		Representation in the simulation code	Value in Base case
Sc	Used scenario	Scenario	Base
L	Simulation length in days	SimLength	2600
SAM	Slack allocation Method	SAM	Emergency OR
F	Are we using FEOR? 0 = No, 1 = Yes	FEOR	0
O	Number of ORs	NrOfORs	20
S	Number of different specialisms	S	11
s_i	Probability distribution of an OR housing specialism i, for i = 1, … , S	SpecialismProbOK(i)	Table 3, 3rd column
$es_{i,j}$	Probability of an emergency patient of type j needing surgery of specialism i, for j = 1, … , E and i = 1, … , S	specialismProb(j, i)	Table 5, 2nd, 3rd and 4th column
E	Number of different emergency patient types	EmergencyTypes	3
λ_i	Arrival rate of emergency patients of type i, for i = A, B and C	Lambda(i)	Table 4, 2nd column
n_i	Standard for the time span in which the treatment of a patient of emergency type i should be started, for i = 1, … , E	Norm(i)	Table 4, 3rd column
T	Number of staffed hours per OR per day	ORHours	8
H	Amount of slack allocated per day for emergency patients	Slack	8
M	Number of ORs that have slack allocated to them $0 \leq M \leq O$	NrOfEORs	1
R	Number of times the planner tries to fill the gap at the end of the day	NumberofTries	3
d	Margin of delay elective surgery may cause	DelayMargin	30 minutes
D	Number of OR's in which the margin of delay can be exceeded	AcceptableNrOfDelays	5
W_{ij}	Amount of change time (min) after patient j at OR i, for j =1, … , P_i-1 and i = 1, … , O	wisseltijd(i,j)	~Pois(15)
L_i	Length of late start (min) in OR i, for i = 1, … , O	LateDist(i)	~Pois(15)

Table 2: Model parameters, their representation within the simulation/mathematical analysis and their value in the base case

2.3 Model Input and Assumptions

The research of this master thesis will be conducted in a mathematical environment closely related to the situation within the OR-department of S.T.A.R. labs. This will allow for a validation of the simulation model by comparing the simulation results with the actual results of S.T.A.R. labs. Patient data from S.T.A.R. labs will be taken as input and several assumptions will be made based on the reality of the S.T.A.R. labs OR-department. Parameter values in the base scenario will be such that they mirror the reality within the OR-department of S.T.A.R. labs.

2.3.1 The OR-department

A total of twenty class-one ORs are part of S.T.A.R. labs operation theater. All of these OR's are used eight hours a day plus any possible overtime. Because of this, standard values for parameter O will be twenty and parameter T will be eight. The class-one ORs are in reality numbered: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 21, 22 but will be numbered 1, .., O in the model and together form the

Set of operation rooms: J = {1, … , O}

A class-one OR is an OR that contains the tools needed to perform any type of operation. Therefore every surgery can be performed at any of the twenty class-one OR's. While in reality the same cannot be said for the specialist, in this model the assumption will be made that every specialist is able to perform every type of surgery. They do prefer to perform surgeries of their own specialism though, which follows from the planning rules as pointed out in section 2.7. Later in section 6.2, when the practical application of this research is studied, it turns out that this assumption will be one of the stronger ones.
The first surgery of the day for every OR always starts with a certain delay. The team of KPMG found out that within S.T.A.R. labs the length of this delay is exponentially distributed with an average of fifteen minutes. This will be an assumption throughout this thesis.

2.3.2 Patient mix (elective)

The surgical case mix used in the model is derived from the production of S.T.A.R. labs in the year 2012. Surgeries are divided over S different specialisms, together forming the

Set of specialisms: I = { 1, .. , S}

The value of parameter S at S.T.A.R. labs is 11, standard value is therefore 11. Specialisms distinguished are: cardiothoracic surgery (CAC), general surgery (CHI), plastic surgery (CHP), gynecology (GYN), oral surgery (MND), neurosurgery (NEC), vascular surgery (VAT), otolaryngology (KNO), ophthalmology (OOG), orthopedics (ORT), and urology (URO).

Table 3 shows the distribution of the surgery duration spent on elective patients over the different specialisms. The percentages are used to define parameter s_i which is the probability of an OR housing specialism i, for i = 1, … , S. Since the percentages add up to 100, $\sum_{i=1}^{S} s_i = 1$. By deciding on a specialism for each OR for each day using the probabilities s_i, it divides the available surgery time over the different specialism in the same way as the actual surgery time spent on each specialism was divided at S.T.A.R. labs in 2012.

Specialism	Sum of Actual surgery duration 2012 (minutes)	% Of total surgery duration 2012
Cardiothoracic surgery (CAC)	251765	17,103647
General Surgery (CHI)	235967	6,0304104
Plastic surgery (CHP)	74752	5,0782747
Gynecology (GYN)	79607	5,4080989
Otolaryngology (KNO)	129906	8,8251599
Oral surgery (MND)	90675	6,1600032
Neurosurgery (NEC)	180804	12,2829138
Ophthalmology (OOG)	171795	11,6708877
Orthopedics (ORT)	114061	7,7487303
Urology (URO)	50631	3,4396153
Vascular surgery (VAT)	92033	6,2522588
Total	**1471996**	**100**

Table 3: Total amount of minutes spend on the different specialisms in 2012 in minutes and as percentages of total surgery duration

2.3.3 Cancellation policy

Cancelling emergency patients is not a possibility at S.T.A.R. labs and thus neither in the model used. Emergency transferring (Litvak, Van Rijsbergen, Boucherie, & Van Houdenhoven, 2008) as a way to manage patient overflow is also not accepted within S.T.A.R. labs so will not be included in the model either. Urgent surgeries are always performed independent of the amount of overtime or the amount of OR's that already are expecting overtime.
Elective patients however can be cancelled in case the amount of overtime gets out of hand. When a planned surgery is cancelled this often results in extra costs and patient dissatisfaction. Therefore the amount of cancellations should be kept at a minimum. S.T.A.R. labs maintains a margin of thirty minutes overtime that surgeries may cause. Overtime will be tracked using variables OT_i and OT'_i. When this margin is anticipated to be exceeded at five ORs already ($OT_i \geq 30$ minutes for five different values of i, for i = 1, … , O), the next elective surgery that is expected to exceed this margin will not be started but cancelled instead. Within the model standard values for the parameters d and D will therefore be 30 minutes and 5 respectively.

2.3.4 Emergency patients

Within S.T.A.R. labs 4 types of patients are distinguished:

- *Normal, non-urgent or elective patients (type G)*
- *Emergency or non-elective patients* requiring surgery to start within 2 hours (*type A)*
- *Emergency or non-elective patients* requiring surgery to start within 6 hours (*type B*)
- *Emergency or non-elective patients* requiring surgery to start within 24 hours (*type C)*.

In S.T.A.R. labs the patients are distributed over these four types as shown in Figure 4. 91% Of the patients is elective, leaving 9% for non-elective patients which are divided over 3 types. The base value of parameter E is therefore 3.

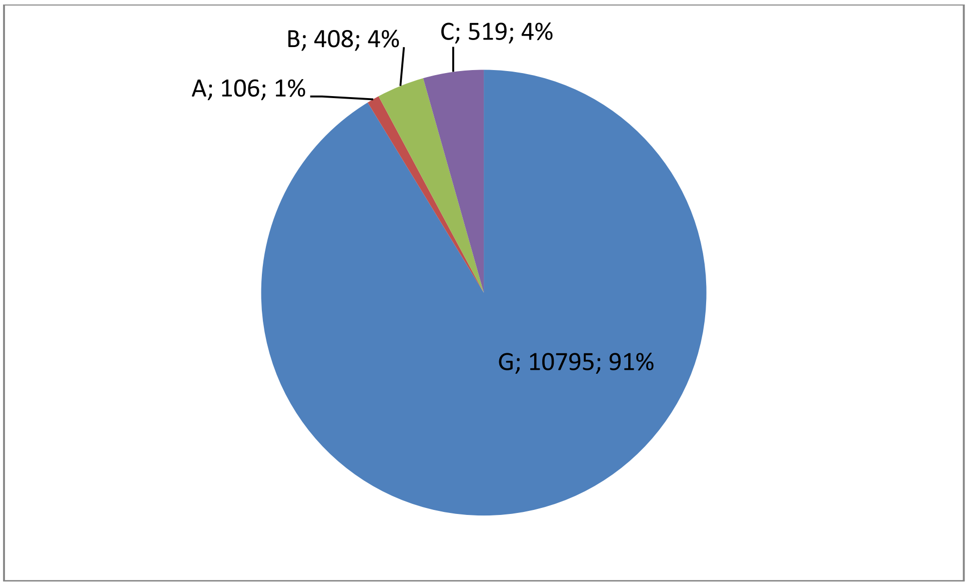


Figure 4: Distribution of the different patient types in S.T.A.R. labs trimmed production of 2012

After plotting the inter-arrival times of patients at S.T.A.R. labs in combination with different distributions, it was visually concluded that fitting the data with a normal or Poisson distribution were good options. Using a Goodness-of-Fit test it was determined that a Poisson distribution process resulted in the best fit.
The probability mass function of the Poisson distribution is as follows:

$$\Pr(X = k) = \frac{\lambda^k e^{-\lambda}}{k!} \qquad \text{for } k \geq 0$$
$$\Pr(X = k) = 0 \qquad \text{for } k < 0$$

Where λ is the only variable that needs to be estimated. Here, λ_i is the amount of emergency patients of type i in that arrived at S.T.A.R. labs in 2012 divided by 260*8*60 (the amount of minutes in the scope of the trimmed production of 2012).

Together, this results in the standard values of λ_i and n_i as shown in Table 4.

Emergency type	Arrival rate λ_i	Norm (n_i)
A	0,000849359	2
B	0,003269231	6
C	0,004158654	24

Table 4: Standard values of the arrival rates and norms for emergency types A, B and C

Within the simulation, the moment an emergency patient arrives in the system, a couple of things need to be registered:

- His emergency type, which also determines the norm
- The type of surgery he needs (specialism)
- His arrival time EA_{ij}

The specialisms of emergency patients are divided differently for each of the emergency types. The percentage of total appearances for each of the combinations specialism/emergency type in the production data 2012 of S.T.A.R. labs are shown in Table 5.

Standard values for the parameters $Es_{i.j}$ are derived from the data in Table 5. The probability of an emergency patient of type j needing surgery of specialism i is given by dividing the percentages by 100, for j = A, B, C and i = CAC, CHI, … , VAT.

Specialism	Emergency type A	Emergency type B	Emergency type C
CAC	26,41509434 %	7,107843137 %	0,963391137 %
CHI	21,69811321 %	32,35294118 %	46,43545279 %
CHP	1,886792453 %	4,656862745 %	4,238921002 %
GYN	4,716981132 %	5,147058824 %	0,385356455 %
KNO	3,773584906 %	6,12745098 %	4,238921002 %
MND	3,773584906 %	3,676470588 %	4,238921002 %
NEC	29,24528302 %	21,32352941 %	16,76300578 %
OOG	0 %	0,735294118 %	0,192678227 %
ORT	0,943396226 %	2,450980392 %	9,248554913 %
URO	0 %	5,882352941 %	8,092485549 %
VAT	7,547169811 %	10,53921569 %	5,202312139 %
Total	**100** %	**100** %	**100** %

Table 5: Distribution of the different emergency types over the specialisms.

2.4 Methods of anticipating urgent surgery

As stated before, literature and the daily practice suggest three different methods of anticipating urgent surgery by slack allocation. All three methods are variations of the same concept, allocating H hours of slack evenly spread over M ORs. Between the methods, M varies between being equal to 1, being a number between 1 and O and being equal to O. Together with the method of not anticipating at all (allocating 0 hours of slack), these are the four methods of allocating slack that will be considered in this thesis. Each method will be simulated with and without the additional use of the FEOR method, resulting in a total of eight different methods of planning. That way, the performance of the FEOR method will be tested in combination with each of the known and used slack allocation methods.
When comparing results of the different methods, the total amount of allocated slack will be kept the same (with the exception of the method where no slack is allocated) and only the number of ORs this slack is allocated to is differentiated between the slack allocation methods. This will ensure that comparing the results of the different methods will be meaningful. Since the dedicated emergency-OR method is widely used, which can be translated into allocating T (a full workday) hours of slack to one OR, the base values for parameters H and T will be the same while M is set to one.
A visualization of the four methods is given in Figure 5. In the following subsections, each of the slack allocation methods will be further explained.

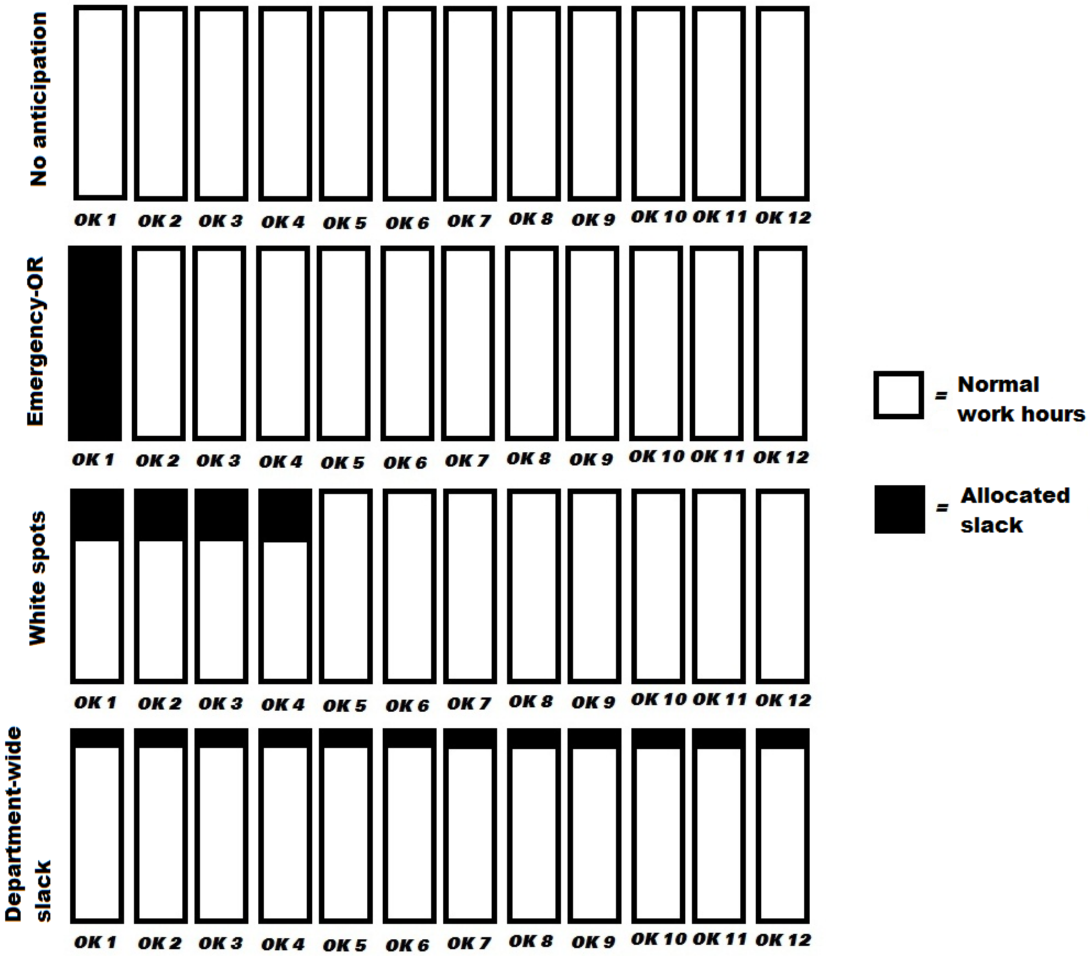


Figure 5 Visualization of the four methods of allocating slack studied in this research (in case O =12)

2.4.1 No anticipation / No slack

The first and most basic method of anticipation that will be discussed is the method of allocating no slack for urgent surgery. Values of the most important parameters for this model are given in Table 6.

Parameters		Value
H	Amount of slack allocated per day for emergency patients (hours)	0
h_i	Amount of slack allocated to OR i, for i = 1, … , O	0, for i = 1, … , O
M	Number of ORs that have slack allocated to them	0

Table 6: Parameter values for method No slack

Expected performance
Since no slack for urgent surgery is allocated, the planner on a tactical level will try to fill up as much of the OR capacity as possible with elective surgeries. OR utilization is therefore expected to be high (close to 1). When an emergency patient arrives the planner on an operational level will immediately have a problem since none of the ORs is prepared to receive extra work. Emergency patients will therefore encounter relatively high waiting times, with a substantial risk of receiving treatment outside the norm. Treatment of elective patients is expected to be pushed into overtime, potentially resulting in a number of cancellations. In

section 5 an analysis of this and other methods will be performed to further investigate the above stated expectations. Simulation results will later on result in a more founded performance description.

2.4.2 Emergency-OR

Reserving a dedicated emergency-OR for urgent surgery is a method often used in hospitals. The method allocates the slack hours to so called dedicated emergency OR's. These OR's are not taken into account when scheduling elective patients. Values of the most important parameters for this model are given in Table 7. Here, T is the representation of the amount of work hours per OR per day. This means that with this method one emergency-OR is created.

Parameters		Value
H	Amount of slack allocated per day for emergency patients (hours)	T
h_i	Amount of slack allocated to OR i, for i = 1, … , O	T if ER_i = 1, 0 otherwise
M	Number of ORs that have slack allocated to them	1

Table 7: Parameter values for method Emergency-OR

Expected performance

One of the O ORs is not considered during the planning on a tactical level, resulting in eight hours of OR capacity which are not being utilized by elective surgery. Since the arrival of emergency patients is not guaranteed, the expected utilization rate is less compared to method No slack. Since urgent surgery is preferably performed on the emergency-OR, elective surgery will be hardly influenced by the arriving emergency patients and overtime and cancellations will be minimal. Emergency patients only have to wait before getting into surgery when arriving closely after another emergency patient. This probability is small as will be shown in section 5.

2.4.3 White spots

When using white spots, none of the ORs is dedicated solely to urgent surgery. Instead, multiple ORs (M in total) will not be fully utilized by elective surgery. A total of T hours of slack is allocated to these M ORs, thereby allocating T/M hours of slack to each of these M ORs.

Parameters		Value
H	Amount of slack allocated per day for emergency patients (hours)	T
h_i	Amount of slack allocated to OR i, for i = 1, … , O	T/M if ER_i = 1, … , M 0 otherwise
M	Number of ORs that have slack allocated to them	$1 \leq M \leq O-1$

Table 8: Parameter values for method White spots

Expected performance

Although the same total amount of slack hours is allocated as in method Emergency-OR, the spreading of the slack is expected to have a less negative impact on the utilization. Because of the allocated slack, overtime caused by elective surgeries is less likely on a subset of the ORs. The waiting time of the urgent patients is the same as in method No slack for the part of the day where even the rooms with allocated slack are still treating elective patients. For the remainder of the day, the waiting time for urgent surgery is the same or even less than in method Emergency-OR.

2.4.4 Department-wide slack

Using department-wide slack means every OR in the OR-department gets the same amount of slack allocated to it (T/O). The total amount of allocated slack remains the same.

Parameters		Value
H	Amount of slack allocated per day for emergency patients (hours)	T
h_i	Amount of slack allocated to OR i, for i = 1, … , O	T/O, for i = 1, … , O
M	Number of ORs that have slack allocated to them	O

Table 9: Parameter values for method Department wide slack

Expected performance

Using the same spreading argument as was used in section 2.4.3, the assumption can be made that utilization will increase and overtime by elective surgery will be reduced even more when spreading the slack over more ORs. The waiting time is constructed the same way as in method White spots although the period in which elective patients are treated is bigger in this situation and very close to the whole day, making it easier for big chunks of surgery time to fit in.

2.5 Flexible emergency-OR

New and central in this research is the FEOR method. The basic idea behind the method is to keep one of the O ORs ready to receive an emergency patient at all times, making sure that even patients with no time to lose can be served without having to interrupt other surgeries. This OR will not always be the same, but will vary throughout the day. This explains the word “Flexible” in the name of the method. The OR waiting for emergency patients is called the FEOR. The main goal is to reduce the expected waiting time for especially the most urgent cases to values very close to zero.

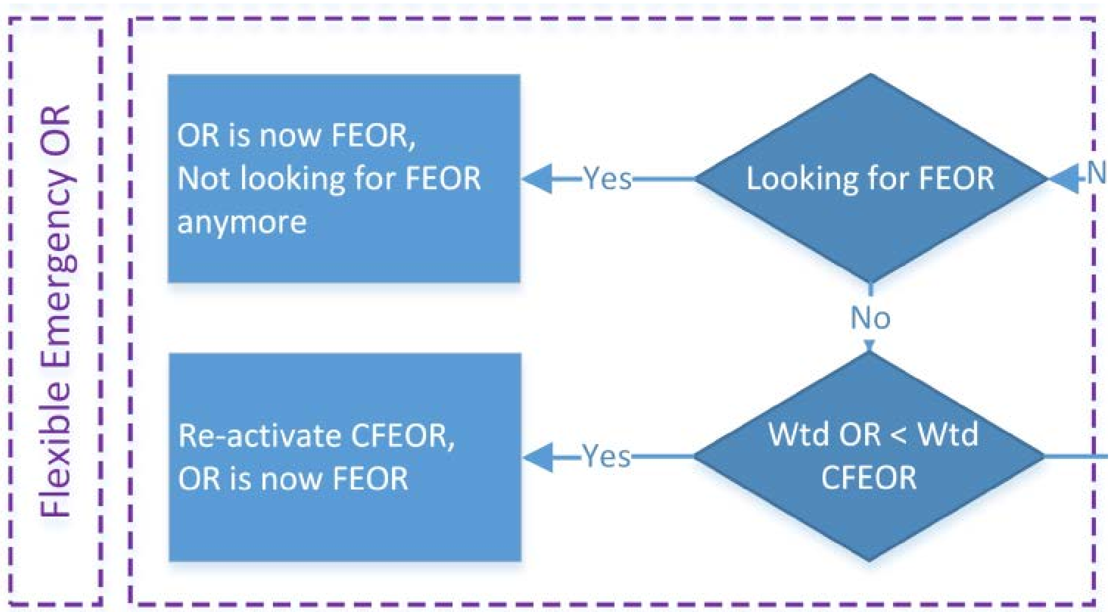


Figure 6 Schematic of the FEOR related part of the decision tree when a surgery is finished at an OR.

Whether or not an OR is the FEOR at a certain time depends mainly on the amount of work that OR has planned for the rest of the day. Being the FEOR could be seen as wearing a label that reads "Current FEOR". This label transfers through the OR-department during the day and is most of the time attached to a particular OR. When an emergency patient arrives and the OR currently wearing the FEOR label gets taken in to service by the emergency patient. The label is removed from that specific OR and needs to be attached to another OR as soon as possible. Therefore the next OR that finishes service receives the label immediately without considering the work that OR has to do. When the FEOR label is attached to an OR and another OR finishes service a consideration is made. The amount of planned work of the OR wearing the FEOR label is compared to the amount of planned work of the OR that just finished service. If the amount of planned work for the OR currently being FEOR exceeds the second value. The FEOR label is reformed from the current FEOR and work at this OR is resumed. The label is then transferred to the just finished OR and all the elective work planned for that OR is temporarily postponed.
To be able to give a mathematical representation of the decisions concerning the FEOR method, some notation needs to be introduced.
For every OR i = 1, … , O, the value of FER_i indicates whether or not this OR is currently the FEOR or in other words, wearing the "current FEOR" label:

$$\mathrm{FER_i} = \begin{cases} 1 \leftrightarrow \text{ OR i is the current variable emergency OR, for i } = 1, \dots, O \\ 0 \leftrightarrow \text{ OR i is currently not the variable emergency OR, for i } = 1, \dots, O \end{cases}$$

The value of parameter *F* indicates whether or not the FEOR method is used. The standard value for *F* is zero, which means the FEOR method is not used. In this case

$$\sum_{i=1}^{O} FER_i = 0$$

and

$$FER_i = 0 \; \forall i = 1, \dots, O$$

at all times. When *F* is set to one, the FEOR method is used. Now

$$\sum_{i=1}^{O} FER_i \leq 1 \; .$$

Most of the time this sum will be equal to one, only when an emergency patient gets assigned to the FEOR it is temporary equal to zero until another OR receives the FEOR label. As mentioned and will be shown in subsection 2.5.1, whether or not an OR receives the FEOR label is based on the amount of work that OR still has to perform compared to the amount of planned work at the current FEOR (in case there is one). An important value therefore is

$$Q_{i,t} = \sum_k X_{i,k}$$

in which *k* represents the patients awaiting surgery at OR *i* at time *t*, $X_{i,k}$ is the planned surgery duration for patient *k* awaiting surgery at OR *i* and $Q_{i,t}$ represents the total amount of work planned for OR *i* at time *t*.

2.5.1 Assigning the FEOR label

Let us assume that $F = 1$, in other words the FEOR method is used. At *t = 0* the day starts and an OR needs to be chosen to fulfill the FEOR role. If

$$Q_{j,0} = \min_{i=1,\dots,O} Q_{i,0}$$

OR j will be selected as the first OR that fulfills the role of FEOR. This means

$$FER_i = \begin{cases} 1 \; if \; i = j \\ 0 \; otherwise \end{cases}$$

From that moment on, the FEOR label will be transferred in the following two cases:

1 An emergency patient of type A or B arrives.

2 Surgery is finished at an OR and the planned amount of work at this OR is less than the planned amount of work at the current FEOR.

Let us consider the first case. Here we assume that the FEOR is currently the only OR up and available. If more than one OR is currently up and available, this means that multiple OR's have finished their planned elective work before the end of the day. Besides this happening on really rare occasions it is also a very non-interesting case.

Based on the planning policy of S.T.A.R. labs (as will be described in section 2.7), arriving type A and B emergency patients are allocated to OR j in case $F = 1 \; and \; FER_j = 1$, OR j will start serving the emergency patient and can therefore no longer wear the FEOR label. As a result:

$$FER_j = 0 \; and \sum_{i=1,\dots,O} FER_i = 0 \; while \; F = 1$$

As soon as $\sum_{i=1,\dots,O} FER_i = 0 \; while \; F = 1$ the first priority of the system, after serving emergency type A patients, becomes appointing a new OR as the FEOR. Therefore if j is equal

to the OR number of the first OR that finishes a surgery, at that moment FER_j is set to 1 and planned work at OR j will be postponed.
The second case springs occasionally from a check that is performed each time an OR finishes serving its patient. Assume $F = 1 \; and \; FER_j = 1$ at the time the procedure in OR k is finished. In case

$$Q_{j,t} = \min_{i=j,k} Q_{i,0}$$

OR k starts serving the first patient inline awaiting surgery at that OR while OR j resumes being the FEOR. The transfer of the FEOR label happens when

$$Q_{k,t} = \min_{i=j,k} Q_{i,0}$$

Now FER_j is set from 1 to 0 and work at OR j is resumed. FER_k is set from 0 to 1 which means that OR k assumes the role of FEOR. Elective work in queue for OR k is postponed.
The amount of times the FEOR label is transferred between OR's during the day, depends heavily on which of the mentioned slack allocation methods in section 2.4 is used. What follows is a short analysis of what impact each of the slack allocation methods is expected to have on the way the FEOR label transitions through the OR-department.

- **No slack & FEOR**

Allocating no slack to any of the OR's in the OR-department means that every OR starts the day with an amount of planned work ($Q_{j,0}$) close to the amount of work hours. There is no obvious candidate for the FEOR label and the label is expected to transfer regularly. OR's will wear the label for short periods of time before another OR finishes service that has a total amount of remaining planned work that is slightly less than that of the current FEOR.

- **Emergency-OR & FEOR**

The use of the FEOR method is expected to have the least impact on the operational plan (section 2.7.3 for more details) combined with the Emergency-OR slack allocation method. Using this slack allocation method results in one OR having no planned work scheduled for that day, so for this OR j we have: $Q_{j,0} = 0$. Meaning that the FEOR label will almost never switch to another OR for the second reason given above. Transfer of the FEOR label happens for reason 1, the arrival of an emergency patient of type A or B in which case the emergency-OR is the OR that will treat this patient. At that point the label will become available and transfer possibly between some other OR's for reason two until the emergency patient in the emergency-OR is served which means by reason two this OR will take over the FEOR label again. This label will stay at that OR until reason one restarts the above pictured process.

- **White spots & FEOR**

Using White spots as the slack allocation method, means there is a subset of the OR's in the OR-department with less planned work than the rest of the OR's. The FEOR label will therefore start at one of these OR's, transferring within this subset throughout the rest of the day. Only later in the afternoon, when by postponing the treatment of elective patients waiting at the OR's with allocated white spots, the amount of planned work at these OR's reaches the same level as the other OR's, it is possible that the label switches to an OR outside the earlier mentioned subset. The impact on the FEOR method is therefore expected to be limited for the elective patients not scheduled at the white spot OR's.

- **Department wide slack & FEOR**

While department wide slack is expected to reduce the “harm” emergency patients cause for the treatment of elective patient compared to no slack, the FEOR label will transfer as much. This situation is very similar to the one where no slack is the slack allocation method.

2.6 Scenarios

To further test the strengths and weaknesses of the FEOR method, the different methods of slack allocation with and without the FEOR method will be tested in four different scenarios. As mentioned the scenario within S.T.A.R. labs will be treated as the base scenario. Three alterations of this base scenario will be used in which the following is tested:

- Two additional scenarios will be tested to get a feel for the impact of the amount of emergency patients on the performance of the different methods.
  - The first of these scenarios will have half the arrival rate for emergency patients of all three types compared to the base case.
  - The second additional scenario will have double the arrival rate for emergency patients of all three types in comparison to the base case.
- The third additional scenario is tested to get a feel for the impact of the size of an OR-department on the performance of different methods. Here the arrival rate for emergency patients and the amount of slack hours allocated stays the same while the amount of OR’s will be half. Therefore the amount of elective patients served will be less than half of the amount in the base case.

All other, not mentioned parameters will be kept equal in all of these scenarios.

Together with the 8 different planning methods (4 slack allocation methods all with and without the use of the FEOR method and in combination with the planning rules used at S.T.A.R. labs) these scenarios form a total of 32 so called configurations. These configurations will all be tested in section 5. An overview of the different configurations is given in Table 13.

2.7 Planning

Choosing a slack allocation method and whether or not to use the FEOR method is just the beginning of OR-planning. What is needed next is a set of planning rules that will guide the process of allocating specialisms, specialists and patients to one of the OR’s in the OR-department. To clarify these different levels of planning, the problem field of operating room planning and scheduling is most of the time divided into three hierarchical decision levels (Demeulemeester & Beliën, 2007). The decision levels and their names, strategic, tactical and operational find their origin in (Anthony, 1965). Each individual decision level has its own problem parameters and results (Vissers & Beech, 2005). Output of one level is the input for the next. When all three levels are completed the OR-schedule is known in every detail.
In short, allocating slack for emergency patients and dividing available OR days over the different specialisms is done at strategic level. Planning elective patients of each specialism in the assigned work hours (also called development of a master surgery schedule) is done at tactical level. The online scheduling during the day including the allocation of arriving emergency patients is subsequently done at operational level. A schematic of this process is given in Figure 7

In the rest of this section the different planning levels will be explained in further detail. Planning rules used at the different levels are in accordance with the rules used at S.T.A.R. labs.

2.7.1 Strategic plan

At the strategic level, the method of slack allocation is chosen. Furthermore the allocation of OR-time among the different specialisms, also referred to as the Case Mix Planning (CMP) problem, is determined.
The slack allocation method used at S.T.A.R. labs is Emergency-OR. 8 Hours of slack are allocated to 1 of the available 20 OR's in the OR-department creating a dedicated emergency-OR. At the rest of the OR's, all 8 hours are available as work hours and elective surgery can be planned during those 8 hours. When using a different slack allocation method, the amount of available work hours at the different OR's could change as is described in section 2.4. What follows is a more mathematical description for this process.
Define:

$$T = number\ of\ staffed\ hours\ available\ per\ OR\ per\ day$$

According to the situation at S.T.A.R. labs T is set to 8 each day for each OR. This is a fixed parameter within this research.

$$H = total\ amount\ of\ slack\ hours\ allocated\ over\ the\ whole\ department\ per\ day$$

According to the situation at S.T.A.R. labs, where a total of 8 hours of slack is allocated, H is set to 8 in case the slack allocation method Emergency-OR, White spots or Department wide slack is used. When method No slack is used, H equals 0.

$$M = number\ of\ OR's\ that\ have\ slack\ allocated\ to\ them, 0 \leq E \leq O$$

M is heavily dependent on the slack allocation method used. Values of M for each of the slack allocation methods are: No slack (0), Emergency-OR (1), White spots (4), Department wide slack (O).

$$ER_i = \begin{cases} 1\ if\ OR\ i\ has\ slack\ allocated\ to\ it \\ 0\ otherwise \end{cases} for\ i = 1, \dots, O$$

For every slack allocation method holds: $\sum_{i=1}^{O} ER_i = M$

$$h_i = number\ of\ hours\ slack\ allocated\ to\ OR\ i\ each\ day, for\ i = 1, \dots, O$$

$$t_i = number\ of\ work\ hours\ allocated\ to\ OR\ i\ each\ day, for\ i = 1, \dots, O$$

For every OR i, it must hold that $h_i + t_i = T$.
Without the loss of generality, for every slack allocation method, slack is allocated to the first M OR's. Therefore $ER_i = 1 \leftrightarrow i \leq M$. It follows that for every OR i

$h_i = \frac{H}{E} * ER_i$ and thus $t_i = T - h_i = T - \left(\frac{H}{E} * ER_i\right)$

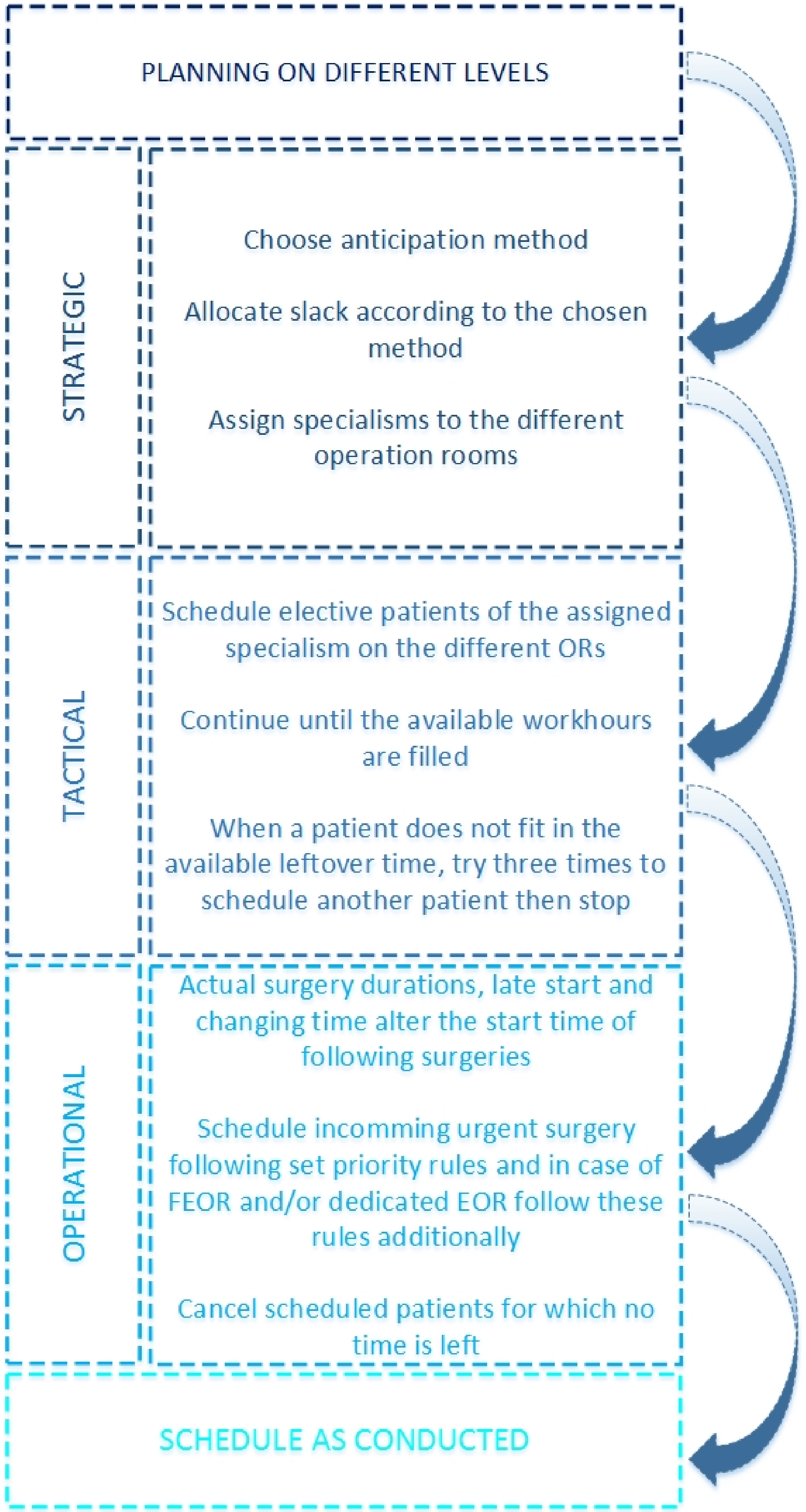


Figure 7 Schematic of the different planning levels

After h_i and t_i are known for every OR I, a specialism has to be assigned to OR i. Available OR time should be divided over the different specialisms according to the expected OR time needed for each of the specialisms. This expected value can be based on production values of the past. For S.T.A.R. labs the production values of 2012 are known. The percentage of actual surgery time spent on each of the different specialisms is shown in Figure 8. This percentage is equal to the total surgery time at S.T.A.R. labs in the production of 2012 divided by the different specialisms. Based on these percentages, each OR has a probability s_i to get assigned specialism i for i = 1, … , S. Therefore

$$S_i = specialism\ assigned\ to\ OR\ i, for\ i = 1, \dots, O$$

and

$$\sum_{i=1}^{O} S_i = 1$$

S_i is equal to specialism j with probability $s_{j,}$ where j = 1,…, 11 represents one of the 11 specialisms.

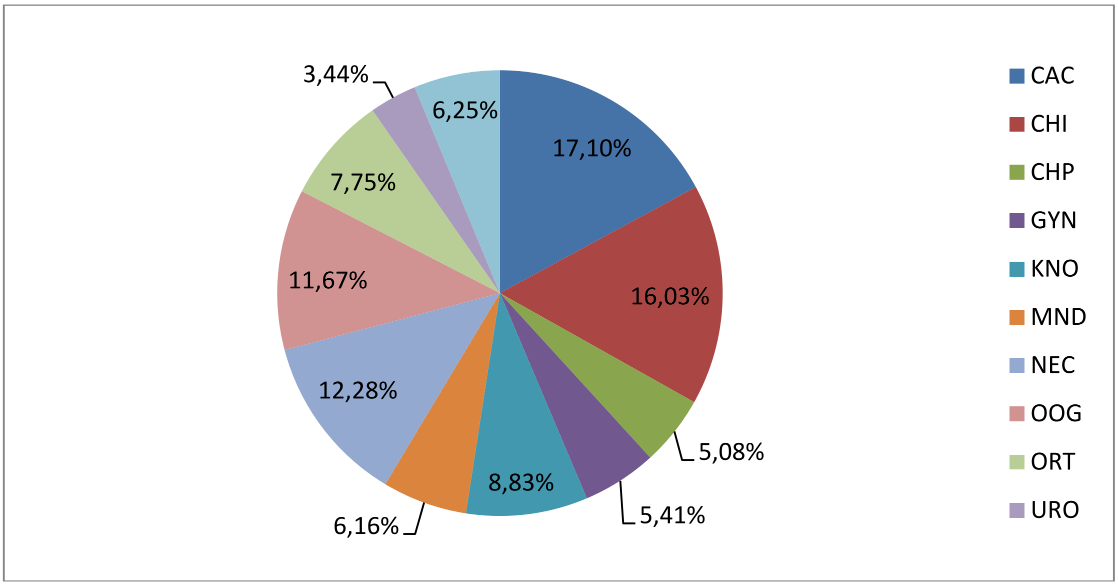


Figure 8 Total surgery time at S.T.A.R. labs in the production of 2012 divided over the different specialisms

The planning horizon at the strategic level normally ranges from 1 up to 2 years (Vissers & Beech, 2005). In this research the planning horizon is set to 260 days which is equal to the total amount of week days in a regular year.

2.7.2 Tactical plan

The problem related to the tactical level is how to best use the allocated OR-time per specialism and translate it into a tactical master plan, also referred to as the Master Surgical Schedule (MSS). A MSS states which sessions at the OT are reserved for which specialism and how these sessions are planned to be used. Therefore, the next step is to fill the reserved sessions with elective patients.
Following from the strategic plan, it is known for each OR i:

- Which specialism is assigned to that OR (S_i) for every of the 260 days (this is not necessarily the same specialism).
- The amount of hours that is available to schedule elective patients per day (t_i).

Optimizing the elective schedule and thereby the usage of t_i is not in the scope of this research. Therefore a pretty straightforward way of assigning elective patients to the different OR's for all 260 days is used. Although straightforward, the chosen method tries to stay close to the reality of S.T.A.R. labs. The following assumptions are made:

- The amount of elective patients awaiting surgery for each specialism is infinite. Meaning that for each specialism there are enough elective patients available to fill the available time t_i.
- These patients are ordered based on "arrival time" and will be scheduled following this order. Therefore this order can be addressed as "First come first served".
- The expected duration of the procedures that the waiting elective patients require are distributed in the same way as the planned time of the procedures in the production of 2012 at S.T.A.R. labs.

More on the distribution of this planned surgery duration can be found in Appendix F. For now let us assume that for every patient we have:

$$X_k = \text{Planned surgery duration for patient k}$$

Within the simulation, filling up t_i for every OR i using elective surgeries is done in a couple of steps. Before these steps are explained a new parameter needs introduction:

$$R = Number\ of\ times\ the\ planner\ tries\ to\ fill\ the\ remaining\ t_i\ (counter\ r)$$

Step 1 Add a patient k of specialism S_i to the queue of OR i. If $X_k < t_i$ the planned surgery duration of this patient "fits" in the remaining available time t_i. Now set $t_i = t_i - X_k$ and repeat Step 1. Else if $X_k > t_i$ continue to Step 2.
Step 2 The patient k triggering this step is set in a queue and will be used later when filling up the available time at another OR with the same specialism. To count the amount of patients tried, we use counter r. Set r = r + 1. If r < R, go back to step 1. If r = R, the elective schedule for OR i is completed.

These two steps are carried out for every OR i with i = 1, … , O. With this, the MSS for the day is finished. At this point, every planned elective procedure has a planned start time

$$ST_{i,k} = Planned\ start\ time\ of\ the\ k'th\ planend\ surgery\ at\ OR\ i, for\ i = 1, \dots, O$$

where

$$ST_{i,k} = \begin{cases} 0\ for\ k = 1 \\ \sum_{j=1}^{k-1} X_j \end{cases} \quad \forall i = 1, \dots, O$$

and every OR in the department has a total amount of work to do for the day

$$Q_{i,0} = \begin{cases} Sum\ of\ the\ X_k^{\prime}s\ of\ the\ elective\ patients\ in\ queue\ for\ OR\ i\ at\ time\ 0, for\ i = 1, \dots, O \\ \sum_{patiens\ k\ in\ queue\ for\ OR\ i\ at\ time\ t} X_k \end{cases}$$

2.7.3 Operational plan

Finally, at the operational level the influence of emergency patients and variable surgery durations (delay) becomes clear. This stage involves a detailed planning of each surgery that can vary during the day. In most hospitals the program coordinator, in consultation with the officiating anesthetist, is responsible for adjusting the schedule.
These adjustments to the elective surgical schedule during an OR-day are needed mainly because of two different events. The first event is the release of an OR after service or downtime (in the form of a late start). This triggers a series of decisions that have to be made after which the system continues. The second type of event is the arrival of an emergency patient (the arrivals of different types of emergency patients will be seen as different events). Again this triggers a series of decisions that have to be made based on the status of the system after which again, the system resumes. Both events and the mentioned series of decisions to be made will be further discussed below.

2.7.3.1 The release of an OR

An OR is released after a period of down time or after the completion of a surgery. Whatever the reason is, it has to be decided what the next job of the OR will be. Possible jobs are taking in the next elective patient for surgery, taking in a waiting emergency patient for surgery or taking on the role of (flexible) emergency-OR. What job has priority over the others, depends on the configuration and state of the system. For each of the different combinations of Slack allocation with and without FEOR method, the decision tree is given in Appendix D. Some of the variables that describe the state of the system and are used within the decision trees are:

$$WS_i = \text{Binary variable tracking whether OR i has a white spot allocated to it, for i} = 1, \dots, O$$

$$DEOR_i = \text{Binary variable tracking whether OR i is the dedicated Emergency OR, for i} = 1, \dots, O$$

$$FER_i = \text{Binary variable tracking whether OR i is currently the FEOR, for i} = 1, \dots, O$$

Each day, the work at an OR starts with a certain delay. Reasons for these are numerous, but can be as simple as the anesthetist oversleeping him- or herself. The length of the late start in the simulation is assumed to be Poisson distributed with an average of 15 minutes. This is based on S.T.A.R. labs data as is described in Appendix F. L_i is independent for different i.

$$L_i = Length\ of\ late\ start\ in\ minutes\ for\ OR\ i, i = 1, \dots, O$$

The late start is one of the reasons that the schedule is not carried out exactly the way it is planned. It causes the first surgery of the day to already start later than planned. This actual start time is important to register, since the difference between planned and actual start time is a performance measure.

$$ST'_{i,k} = Actual\ start\ time\ of\ the\ k'th\ surgery\ at\ OR\ i, for\ i = 1, \dots, O$$

For the surgery itself, a planned duration was derived earlier. This planned duration is an estimate and the actual surgery duration can be different. The ratio actual/planned surgery duration is assumed to follow a certain distribution. More on this is described in Appendix F. A delay in surgery duration is another reason for the schedule to not work out as planned.

$$X'_{i,k} = \text{Actual surgery duration for the k'th patient planned for surgery at OR i, for i} = 1, \dots, \text{O}$$

After a surgery, some time is required to prepare the OR for the next patient. This is called "change time" and in most hospitals this change time is not scheduled. In the simulation this change time will be assumed to be Poisson distributed with an average of 15 minutes. Again, this is based on S.T.A.R. labs data as is described in Appendix F.

$$W_{i,k} = Amount\ of\ change\ time\ in\ minutes\ needed\ to\ clean\ up\ after\ surgery\ of\ the\ k'th\ patient\ at\ OR\ i, for\ i = 1, \dots, \text{O}$$

Together L_i, $X'_{i,k}$ and $W_{i,k}$ of the performed procedures define the actual start times of the following procedures within the OR-department.

$$ST'_{i,k} = \begin{cases} L_i\ for\ k = 1 \\ L_i + \sum_{j=1}^{k-1} X_{i,j} + W_{i,j} \end{cases} \quad \forall i = 1, \dots, O$$

Ultimately defining the actual finish time of the work and how much (if any) overtime will be made at OR i, in case no emergency patients are assigned to OR i.

$$FT_{i,t} = \text{Planned finish time of the work in OR i at time t, for i} = 1, \dots, \text{O} \\ \text{(this values varies troughout the day)}$$

$$FT'_i = \begin{cases} \text{Finish time of the work in OR i, for i} = 1, \dots, \text{O} \\ L_i + \sum_{patients\ served\ at\ OR\ i} X_{i,j} + W_{i,j} \end{cases}$$

$$OT_{i.t} = \text{Expected overtime to be worked at OR i at time t, for i} = 1, \dots, \text{O} \\ \text{(this values varies troughout the day)}$$

$$OT'_i = \text{Overtime worked at OR i, for i} = 1, \dots, \text{O}$$

Based on the amount of expected overtime at the different OR's, elective surgery can be cancelled. The policy for this is explained in section 2.3.3.

In the case that emergency patients do get assigned to OR i, this creates difficulties for the schedule depending on how much these emergency patients were anticipated. The next subsection covers the decisions made at the arrival of an emergency patient.

2.7.3.2 The arrival of an emergency patient

Recall that the non-elective patient class consists of patients who arrive randomly on a daily basis. It is therefore impossible to schedule their surgeries in advance. Surgeries for this type of patient need to be scheduled at operational level even though slack for these emergency surgeries, if any, was already allocated at strategic level. This slack is either allocated to a dedicated emergency-OR, or spread over different OR's that have elective procedures scheduled as well. These last OR's with both elective work and slack scheduled for the day are called flexible. In case of a dedicated emergency-OR, there is no specialism assigned to the OR, meaning that emergency surgery of every specialism is as welcome. Flexible OR's however are staffed with personnel of a certain specialism, making it preferable to perform surgeries of their own specialism over surgeries of the other specialism. This preference is reflected in the decision trees displayed in Appendix D. Within the simulation it is assumed that even though this preference exists, every type of surgery could be performed by every specialist. As will be discussed in section 6.2, this turns out to be a strong assumption.
To handle the arrivals of emergency patients at operational level, a scheduling procedure for these non-elective patients has been formulated. During regular working hours a program coordinator is present in most hospitals, who is responsible for the planning and scheduling of non-elective patients. During these regular working hours, the demand for non-elective patients interferes with the elective surgical schedule. Because non-elective patients have priority over elective patients in most of the cases, elective surgeries can be postponed or even cancelled when there is insufficient capacity to treat all non-elective patients in timely order.
As mentioned in section 2.3.4, three types of emergency patients are distinguished within S.T.A.R. labs. Their arrivals, although of the same category and thus closely related, trigger different series of decisions and will therefore be discussed separately below. In short, two types of waiting lists are being generated within the simulation. The first type of waiting lists contain the elective patients. One of these waiting lists is created for each OR, for which they represent the scheduled elective work following from the tactical plan for the day. Of the second type of waiting lists there are twice as many as there are emergency types E. These lists contain arrived emergency patients that did not receive treatment yet. For each type of emergency there are two of these lists since distinction is made between patients requiring a specialism that is assigned to an OR that day and specialisms that are not. As will be described below, an emergency patient is placed on these lists when there is either no OR available to immediately treat this patient or the urgency is just not high enough and other work is given priority. As can be derived from the decision trees displayed in Appendix D, an OR checks these lists for work in a certain order when in need of a new job. In most of the OR-departments the list of emergency type A is checked first. If there is a patient on this list, it will be taken into service immediately. What list is checked secondly already depends on the configuration of the department.

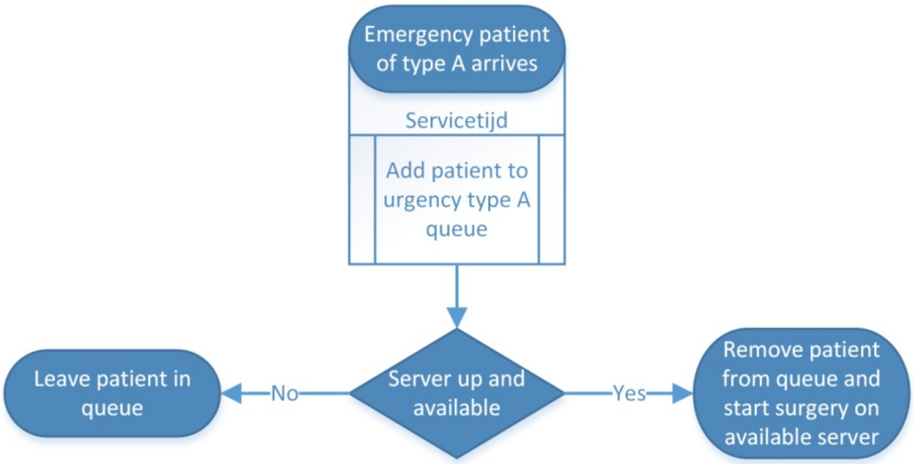


Figure 9 Decision tree in case an emergency patient of type A arrives

Arrival of a type A emergency patient

Type A emergency patients are the most "simple" type when it comes to the allocation of these patients. The allocation is the same for any of the different configurations covered in this research. Because of the high urgency involved, there is no time to waste and the first emergency room to be available will treat the patient. Therefore, at the arrival of an emergency type A patient the simulation will check for an available OR. If an OR is available, this OR will immediately start treating this newly arrived type A emergency patient. When no OR is available at the time, the patient is placed in the appropriate waiting list as was just described. A schematic of this is given in Figure 9. As soon as an OR is released, the first priority is to see if any type A emergency patients are waiting to be treated. If so, the OR will start treating the first patient in the list (again FCFS).
As described in section 2.5, the idea of the FEOR method is to have an OR available to serve any arriving type A or B emergency patient immediately.

Arrival of a type B emergency patient

Although not as urgent as type A, emergency patients of type B require surgery within 6 hours. Therefore, the priority for these patients is relatively high in most configurations. A summary of the planning rules for each of the slack allocation methods is given in Table 10.

Slack allocation method	Placement preference for type B emergency patients
No slack	First available OR of appropriate specialism if existing, else First available OR
Emergency-OR	First available OR of appropriate specialism if existing or emergency-OR, else First available OR
White spots	First available WSOR with unused slack of appropriate specialism if existing, else First available OR of appropriate specialism if existing, else First available OR
Department wide slack	First available OR of appropriate specialism if existing, else First available OR

Table 10 Placement preferences for type B emergency patients

For each of the slack allocation methods, the addition of the FEOR method changes the placement preferences in the same way. To the first preference needs to be added "or FEOR".

This way the FEOR functions the same way as the EOR. Without taking into account the specialism of the OR currently having the FEOR label. A schematic of the decision tree used at the event of an arrival of a type B emergency patient is given in Figure 10.

Arrival of a type C emergency patient
Emergency patients of type C are the least urgent emergency patients known at S.T.A.R. labs. Therefore, they experience a less preferred treatment as is shown in Figure 11. Emergency patients of type C are in most cases treated after the elective work is done, preferably in an OR of corresponding specialism. Again, when no OR is assigned to the specialism of the emergency patient the treatment is done in any of the OR's.

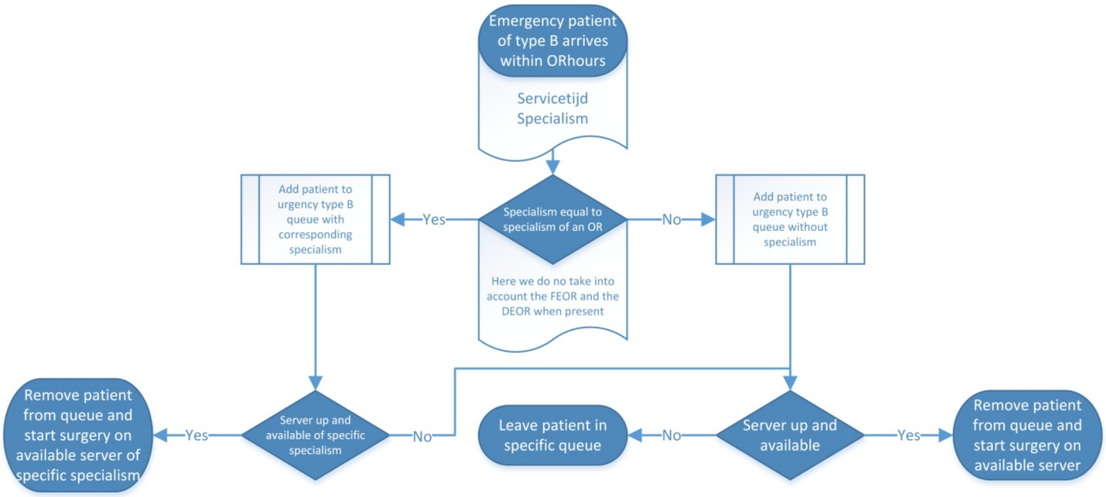


Figure 10 Decision tree in case an emergency patient of type B arrives

Difference between elective work and emergency patients type C, is that elective surgery gets cancelled when it would result in too much overtime. For emergency patients this is never the case. Whatever the resulting overtime would be, they are always served.
As soon as an OR finishes the elective work scheduled on that OR for the day, it starts serving emergency C patients of the corresponding specialism. When none of these are awaiting treatment, emergency patients of type B and C of different specialisms are dealt with. This way, the system strives to a fair distribution of overtime over the different teams. During the interviews performed to discuss the results of this thesis with experts as listed in Appendix B, this turned out to be different in practice at most of the visited hospitals. Here other specialisms do not treat emergency patients of another specialism, but rather end early, leaving a lot of work for a small group of colleagues.

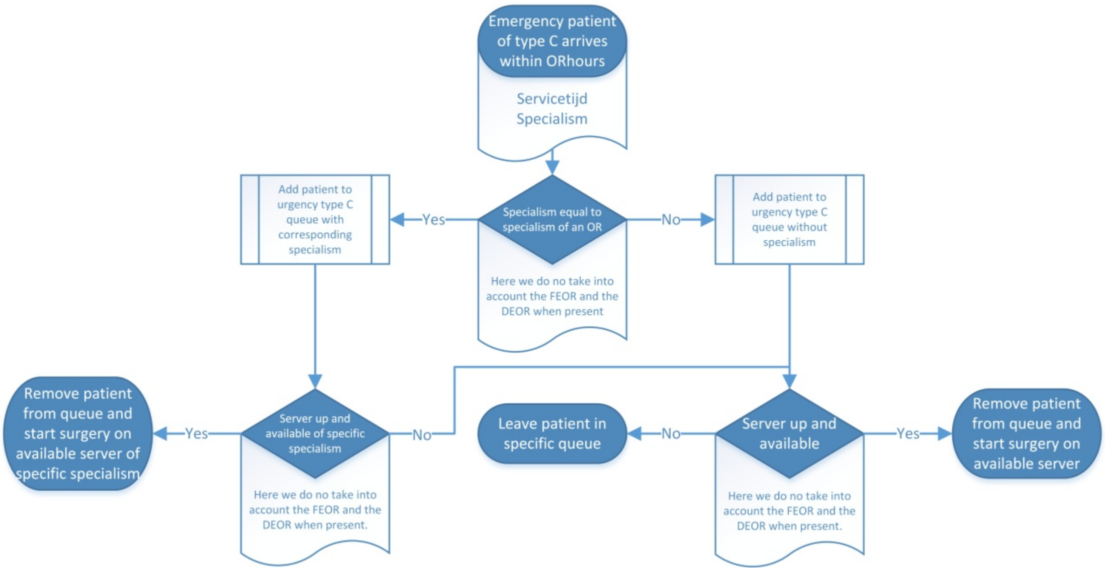


Figure 11 Decision tree in case an emergency patient of type C arrives

In certain situations it is possible for emergency patients to accumulate. Multiple emergency patients of different types are waiting for OR's to be released and take them into service. In these cases type A emergency patients always have priority over type B and C. For type B and C this is not the case. Patients of type C with corresponding specialism receive preferential treatment over patients which have a specialism that corresponds to another OR in the department.

During the day, the operational plan constantly adjusts the MSS to newly received information. At the end of the day, it is fully clear how everything turned out and the schedule of the day is finalized. This schedule reflects all the actual start- and finish times, the actual durations of the different surgeries and a list of all the performed treatments.
The amount of cancellations, the number of surgeries performed, the amount of waiting time and the average surgery duration become clear and are registered. These are used to get an idea of the performance of the system as will be discussed in section 2.8.

2.8 Key performance indicators

The four methods of slack allocation mentioned in section 2.4 combined with the planning decisions used at S.T.A.R. labs with or without the FEOR method applied, yield for a total of 8 different ways of planning. These different ways of planning applied in four different scenarios make up for a total of 32 different configurations as shown in Table 13. Comparing the performance of these different ways of planning in the different scenarios is done based on a set of key performance indicators (short KPI's). What performance indicators are key differs per queueing system and is heavily dependent on the type of business. In the case of this research, the application is OR-department planning and therefore performance indicators concerning patient well-being and utilization of the OR's are "key".
What follows is a list of the KPI's that will be the focus of the data-analysis performed in section 5. Based on the results of this data-analysis, an assessment of the FEOR method will be given in section 6.

<u>Concerning emergency patients:</u>

Average waiting time of urgency patients per type

This KPI, the average waiting time, is an expected value calculated by dividing the total amount of waiting time of a certain type of emergency patient by the total number of patients treated of this particular emergency type.

This KPI's relevance is probably clear from the term 'urgency' patients. These patients require urgent surgery and should not have to wait a substantial amount of time before going into surgery.

$$\frac{Cumulative\ waiting\ time\ of\ urgency\ patients\ of\ type\ A}{Number\ of\ urgency\ patients\ of\ type\ A\ treated}$$

$$\frac{Cumulative\ waiting\ time\ of\ urgency\ patients\ of\ type\ B}{Number\ of\ urgency\ patients\ of\ type\ B\ treated}$$

$$\frac{Cumulative\ waiting\ time\ of\ urgency\ patients\ of\ type\ C}{Number\ of\ urgency\ patients\ of\ type\ C\ treated}$$

Number of urgency patients treated outside norm per type

The number of urgency patients treated outside norm during a given simulation time is a stochastic variable whose value is subject to a lot of variations. As discussed, the norm time differs per emergency type.

This KPI's relevance lies in the same reasons as for the above mentioned average waiting time of urgency patients

$$Number\ of\ urgency\ patients\ of\ type\ A\ with\ a\ waiting\ time\ longer\ then\ 2\ hours$$

$$Number\ of\ urgency\ patients\ of\ type\ B\ with\ a\ waiting\ time\ longer\ then\ 6\ hours$$

$$Number\ of\ urgency\ patients\ of\ type\ C\ with\ a\ waiting\ time\ longer\ then\ 24\ hours$$

<u>Concerning elective patients:</u>

Number of cancellations

This KPI represents the total amount of treatments that is cancelled for any possible reason. Most cancellations occur at the end of the day, when the treatment is expected to cause to much overtime for the OR staff. The number of cancellations during a simulation run is a stochastic variable.

Cancellations cause patient dissatisfaction and can result in serious fines, which explains the relevance of this KPI.

$$Number\ of\ planned\ elective\ surgeries\ not\ performed$$

Difference between realized and planned starting time of elective surgery

This KPI is a stochastic variable with probability distribution that looks almost normal at first sight (Figure 13). Although some patients get treatment earlier than planned, mostly (Figure 13) this will be a possible value (which means patients get served later than planned).

Again patient dissatisfaction is the main driver for this KPI's relevance.

$$Realized\ starting\ time - planned\ starting\ time$$

<u>Concerning overtime:</u>

Overtime in practice is received less negatively than cancellations by patients. However, it is one of the main drivers for dissatisfaction of the OR staff.

Total amount of overtime
The total amount of overtime is a stochastic variable, calculated by summing the overtime for each OR during each simulation day.

$$Cumulative\ overtime\ of\ all\ OR's\ over\ all\ simulated\ days$$

Average amount of overtime per OR, per day
The average amount of overtime per OR is an expected value calculated by dividing the total amount of overtime by the number of OR's and amount of days simulated.

$$\frac{Cumulative\ overtime\ of\ all\ OR's\ over\ all\ simulated\ days}{Simulated\ days * Number\ of\ OR's}$$

Number of OR's working overtime
The number of OR's working overtime is a stochastic variable representing the number of OR's used after closing time during the simulated period. How long the different OR's are used after overtime remains unclear given only this KPI.

$$Sum\ of\ the\ number\ of\ OR's\ working\ overtime\ during\ the\ simulated\ days$$

Number of OR's working more overtime than the set norm
The OR-staff can work overtime, but it becomes really problematic when the amount of overtime exceeds the norm (30 minutes). Therefor it is interesting to calculate the number of OR's where this takes place over de simulated period. This KPI is a stochastic variable.

$$Number\ of\ all\ OR's\ over\ all\ simulated\ days\ working\ more\ \ than\ 30\ minutes\ overtime$$

<u>Concerning productivity:</u>

Productivity drives hospital profits. There is no way to explain the relevance of below KPI's any shorter.

Net utilization
The net utilization is an expected value calculated by dividing the total surgery time by the total time in the simulation. This total consists of every open minute of each OR.

$$\frac{Cumulative\ surgery\ duration\ of\ all\ surgeries\ performed}{Total\ time\ take\ into\ account}$$

Total number of surgeries performed
The total number of surgeries performed is a stochastic variable equal to the sum of the amount of elective and emergency patients served during the full simulation.

$$Elective\ surgeries\ performed + emergency\ patients\ served$$

The interviews listed in Appendix B revealed that besides the above listed KPI's some more simulation output is of interest for practical concerns. One of these concerns is covered in Appendix G.

3 Back-Of-The-Envelope analysis

Now that the model is defined and KPI's are set up, the next step would be to calculate how the different settings of the OR perform. As it turns out the model simply contains too many parameters and variables to make an explicit mathematical analysis doable. Therefore, instead of an in-depth mathematical analysis, in this section a back-of-the-envelope (BOTE) analysis will be performed. The BOTE analysis aims to gain some sense of the way the use of the different slack allocation methods and FEOR method influence the waiting time of emergency patients, the amount of cancellations, the utilization rate of the OR-department and the overtime. By conducting a rough analysis for the expected values of these KPI's, it should already become clear what the strengths and weaknesses of the different methods are. As it turns out, even when using a very simplified model, the mathematics are already 'complex'. The next section will introduce a simulation program ,to be able to further investigate the performance of the different methods.
The actual BOTE analysis for each of the planning methods is given below. First the steps taken to simplify the model will be explained.

3.1 Simplification

The model described in section 2 will be further simplified before the BOTE-analysis is performed. The following simplification steps are conducted:

- The number of specialisms is reduced to one.
- The surgery duration for this specialism is assumed to be exponentially distributed with parameter μ.
- The number of emergency patient types is set to one. The arrival process of this emergency patient type is assumed to be Poisson with parameter λ.
- The arrival rate of emergency patients is such that the probability of multiple emergency patients awaiting surgery is negligible.
- Late start and changing times are completely ignored.

Since the FEOR method is quite a game-changer for some slack allocation methods, the BOTE-analysis is separately performed for each slack allocation method with and without the FEOR method. KPI's that will be analyzed are:

- Expected waiting time for emergency patients
- Expected number of cancellations per day
- Expected amount of overtime for the OR-department per day
- Utilization rate of the available OR-time per day

3.2 Method No slack

3.2.1 Without FEOR

The **waiting time** for an emergency patient is 0 when the patient in question finds an OR empty and ready at his/her arrival. When using method No slack, this only happens when an OR finished all its planned elective work. Given the way elective work is planned, this only happens close to the end of the workday and therefore with a negligible probability. Due to this fact, for now it is assumed that an arriving emergency patient has to wait for one of the O OR's in the department to finish its current surgery. Since every surgery duration is exponentially distributed with parameter μ, the time for the first OR to finish surgery is the minimum of a sum of O exponentials. This is again exponentially distributed with parameter O * μ.

$$\min_{i=1,\dots,O} B_i \sim \exp(O * \mu)$$

Hence the expected waiting time of an arriving emergency patient when using No slack without FEOR can be approximated/expressed as follows.

$$E[W_{emergency}] = E\left[\min_{i=1,\dots,O} B_i\right] = \frac{1}{O * \mu}$$

Approximating the **number of cancellations** is already a bit harder. An elective operation is cancelled when it is expected to end later than T + g minutes after the start of the workday (where T is the amount of minutes in a normal workday and g is the overtime norm in minutes). $\lambda * \mathrm{T}$ emergency patients are expected to arrive each OR-day. For now it will be assumed that this amount is smaller than O, the number of OR's in the OR department. Additionally, the assumption is made that these emergency patients are spread evenly over the different OR's in the department. This means that $\lambda * \mathrm{T}$ OR's have to treat $\lfloor T * \mu \rfloor\ (elective) + 1$ (emergency) patients and O - $\lambda * \mathrm{T}$ OR's have to serve just the $\lfloor T * \mu \rfloor$ planned elective patients. For now we exclude the cases in which the last patient served is the emergency patient (in which case no operation is cancelled). Now the expected number of cancellations is equal to the sum of OR's of both types that spend more time on their assigned surgeries than T + g minutes.

$$\mathrm{E}[\#\mathrm{cancellations}] = (\lambda * \mathrm{T}) * \mathrm{P}(\mathrm{X} > \mathrm{T} + \mathrm{g}) + (\mathrm{O} - \lambda * \mathrm{T}) * \mathrm{P}(\mathrm{Y} > \mathrm{T} + \mathrm{g})$$

where

$$X \sim Erlang(\lfloor T\mu \rfloor + 1, \mu)$$

$$Y \sim Erlang(\lfloor T\mu \rfloor, \mu)$$

So

$$
\begin{aligned}
\mathrm{E}[\#\mathrm{cancellations}] \\
&= (\lambda \mathrm{T}) * \left(1 - \left(1 - \sum_{n=0}^{\lfloor T\mu \rfloor + 1} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\right)\right) \\
&+ (O - \lambda \mathrm{T})\left(1 - \left(1 - \sum_{n=0}^{\lfloor T\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\right)\right) \\
&= \lambda \mathrm{T} * e^{-\mu(T+g)} * \frac{\mu(T+g)^{\lfloor T\mu \rfloor + 1}}{(\lfloor T\mu \rfloor + 1)!} + O \sum_{n=0}^{\lfloor T\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}
\end{aligned}
$$

Overtime and utilization rate will turn out to be the harder KPI's to analyze. This is caused by the fact that the planned surgery duration is strongly related with the expected surgery duration. Basically they are one and the same. When elective patients are planned in such a way that the OR is expected to be utilized close to 100%, the utilization rate is expected to be the same. Due to this fact using No slack, where no slack is allocated so the available hours are all used for planning elective surgeries, the expected utilization rate without taking in to account emergency patients is equal to:

$$\text{E[Utilization rate]} = \frac{\lfloor T\mu \rfloor * \frac{1}{\mu}}{T} * 100\%$$

However, emergency patients have to be taken into account. In most cases their arrival will increase the workload and with that the utilization rate. The above given expression is therefore assumed a lower bound for the utilization rate.
The expected **amount of overtime** is especially hard to determine since at a certain amount of overtime a surgery gets cancelled thereby reducing the overtime back to 0. To work overtime an OR needs to be finished in-between T and T + g minutes after the start of the OR-day. Calculating for how many OR's this is the case and what the average overtime in that case is, turns out to be complex. Therefore the assumption is made that the workload in minutes is spread evenly between all the OR's and cancellations are ignored. That way the expected amount of overtime can be expressed in the following way:

$$E[Overtime] = \max(0, |OT - (O\lfloor T\mu \rfloor + \lambda \mathrm{T})\mathrm{E[B]}|)$$

For the remaining seven planning methods the values for this most simple planning method will serve as a benchmark in case no accurate expression can be found.

3.2.2 Using FEOR

Although the FEOR role is passed on through the OR-department throughout the day, the FEOR itself can be seen as an empty and ready OR whenever it is up. Arriving emergency patients can therefore be treated without any **waiting time** as long as one of the different OR's within the OR-department is fulfilling the role of FEOR. The only times this is not the case is when an emergency patient just took the FEOR into service and the system is waiting for an OR to finish service to take the role of FEOR. The expected time that is needed for an OR to finish service is already calculated in section 3.2.1 and is equal to:

$$E\left[\min_{i=1,\dots,O} B_i\right] = \frac{1}{O * \mu}$$

The probability that the FEOR is taken into account at the arrival of an emergency patient can be seen as the Erlang blocking probability in a system with 1 server and a queue size of 0. This probability is equal to $\frac{\rho}{1+\rho}$ where in this case $\rho = \frac{\lambda}{O * \mu}$. From this can be concluded:

$$E[W_{emergency}] = \frac{\frac{\lambda}{O * \mu}}{1 + \frac{\lambda}{O * \mu}} * \frac{1}{O * \mu} = \frac{\lambda}{O * \mu + \lambda} * \frac{1}{(O * \mu)^2}$$

When the FEOR method works as intended, the **number of cancellations** will hardly rise thanks to the greedy approach used in selecting which OR is the FEOR. However, with the FEOR method some OR's in the OR-department may end up with not just their elective work, but also a certain time period in which they had the FEOR-label and an additional emergency patient.

In this "worst case" scenario λT OR's end up with $\lfloor T * \mu \rfloor + 1$ patients to treat and $\frac{T}{T\lambda} = \frac{1}{\lambda}$ minutes of FEOR time. The expected number of cancellations then becomes:

$$E[\#cancellations] = (\lambda * T) P\left(X > T + g - \frac{1}{\lambda}\right) + (O - \lambda T) P(Y > T + g)$$

where

$$X \sim Erlang(\lfloor T\mu \rfloor + 1, \mu)$$

$$Y \sim Erlang(\lfloor T\mu \rfloor, \mu)$$

So

$$\begin{aligned} E[\#cancellations] &= (\lambda T) * \left(1 - \left(1 - \sum_{n=0}^{\lfloor T\mu \rfloor + 1} e^{-\mu\left(T + g - \frac{1}{\lambda}\right)} * \frac{\mu\left(T + g - \frac{1}{\lambda}\right)^n}{n!}\right)\right) \\ &+ (O - \lambda T)\left(1 - \left(1 - \sum_{n=0}^{\lfloor T\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\right)\right) \end{aligned}$$

$$= \lambda T * e^{-\mu\left(T + g - \frac{1}{\lambda}\right)} * \frac{\mu\left(T + g - \frac{1}{\lambda}\right)^{\lfloor T\mu \rfloor + 1}}{(\lfloor T\mu \rfloor + 1)!} + O \sum_{n=0}^{\lfloor T\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}$$

The derivation of the expected **amount of overtime** in case of No slack can easily be adjusted to No slack & FEOR. Time is now spent on fulfilling the FEOR role (for close to T minutes) besides treating patients. Hence the expected overtime can be approximated by:

$$E[Overtime] = \max(0, |OT - T - (O\lfloor T\mu \rfloor + \lambda T) E[B]|)$$

The **utilization rate** when using the FEOR method is lower than when the FEOR method is not used whenever the sum of the time OR's are unused within the department is less than T minutes. In case of the No slack method this is a safe assumption. Therefore the expression for the expected utilization rate in section 3.2.1 needs to be adjusted to reflect the close to T minutes of total time the OR's in the department that are not used.

$$\text{E[Utilization rate]} = \frac{O\lfloor T\mu \rfloor * \frac{1}{\mu}}{OT+T} * 100\%$$

3.3 Method Emergency-OR

3.3.1 Without FEOR

Since the emergency-OR is in place to instantly treat arriving emergency patients whenever it is up and available, emergency patients only experience **waiting time** when the emergency-OR is in use. The expected waiting time experienced in that case is again related to the expected waiting time in section 3.2.1 and is equal to:

$$E\left[\min_{i=1,\dots,O} B_i\right] = \frac{1}{O * \mu}$$

The probability with which an arriving emergency patient finds to emergency-OR to be in use at arrival can again be seen as an Erlang blocking probability of 1 server with a queue length of 0. This time $\rho = \frac{\lambda}{\mu}$. This results in the expected waiting time for emergency patients being equal to:

$$E[W_{emergency}] = \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \frac{1}{O\mu} = \frac{\frac{\lambda}{O\mu^2}}{1+\frac{\lambda}{\mu}} = \frac{\frac{\lambda}{O\mu}}{\mu+\lambda} = \frac{\lambda}{O\mu^2 + O\mu\lambda}$$

Following from the blocking probability above, only $\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda T$ emergency patients i end up being served on the O-1 non-emergency-OR's. Assuming that two of these patients do not end up on the same OR, but that they are spread over the different OR's, the **number of cancellations** can again be approximated in the same way as is done in section 3.2.1:

$$\text{E[\#cancellations]} = \left(\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda T\right) P(X > T + g) + \left(O - 1 - \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda T\right) P(Y > T + g)$$

where

$$X \sim Erlang(\lfloor T\mu \rfloor + 1, \mu)$$

$$Y \sim Erlang(\lfloor T\mu \rfloor, \mu)$$

so

$$\begin{aligned}
&\mathrm{E[\#cancellations]} \\
&= \left(\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda \mathrm{T}\right) * \left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor + 1} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}\right)\right) \\
&+ \left(\mathrm{O} - 1 - \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda \mathrm{T}\right)\left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}\right)\right) \\
&= \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} \lambda \mathrm{T} * \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\lfloor T\mu \rfloor + 1}}{(\lfloor T\mu \rfloor + 1)!} + (\mathrm{O} - 1) \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}
\end{aligned}$$

As in section 3.2.1, to approximate the **expected overtime** it is assumed that the work done on the O-1 non-emergency-OR's is spread evenly over these OR's. For simplicity the overtime at the emergency-OR is assumed 0, resulting in the following expression for the expected overtime:

$$E[Overtime] = \max(0, \left| (O-1)T - T - \left(O\lfloor T\mu \rfloor + \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda \mathrm{T} \right) \mathrm{E[B]} \right|)$$

The **utilization rate** of the Emergency-OR system is influenced by the emergency-OR in two ways.

1 The emergency-OR has a low utilization rate, thereby lowering the utilization rate of the system as a whole.
2 Emergency patients are mostly treated at the Emergency-OR. Due to this fact, emergency arrivals no longer increase the utilization rate of non-emergency-OR's.

The utilization rate of the emergency OR is equal to the blocking probability calculated earlier:

E[Utilization rate of the emergency-OR] = $\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}}$

For the rest of the OR's in the department the utilization rate can be approximated again by:

E[Utilization rate of the non-emergency-OR's] = $\frac{\lfloor T\mu \rfloor * \frac{1}{\mu}}{T} * 100\%$

This results in an utilization rate for the whole OR-department of:

E[Utilization rate of the whole OR-department] = = $((O+1)\frac{\lfloor T\mu \rfloor * \frac{1}{\mu}}{T} + \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}}) * 100\%$

3.3.2 Using FEOR

Using the FEOR method in combination with Emergency-OR as slack allocation method, is of little impact as described in section 2.4.2. This will become even more clear during the approximation of the different KPI's for this combined planning method.

The **expected waiting time** for emergency patients when using the FEOR method is always the same. This is due to the fact that independently of how slack is allocated over the different OR's, as long as every non-emergency-OR has work to do when the FEOR is taken into use the expected time before another OR finishes service is:

$$E\left[\min_{i=1,\dots,O} B_i\right] = \frac{1}{O * \mu}$$

That every non-emergency-OR has work to do during the OR-day is an assumption that, as mentioned earlier, is acceptable. Even using White spots, the probability of an OR to finish work early is negligible. Using the blocking probability from sections 3.2.2 and 3.3.1 again, the approximation for the expected waiting time is indeed the same:

$$E\left[W_{emergency}\right] = \frac{\lambda}{1 + \mathrm{O}\mu\lambda}$$

The **number of cancellations** in this situation can be derived from sections 3.2.2 and 3.3.1. Both include an addition to the approximation for the number of cancellations made in section 3.2.1. Combining these additions (FEOR and an OR functioning as emergency-OR) results in the approximation for the number of cancellations in the case of Emergency-OR & FEOR:

$$\mathrm{E}[\#\mathrm{cancellations}] = \left(\frac{\frac{\lambda}{\mu}}{1 + \frac{\lambda}{\mu}} * \lambda\mathrm{T}\right) * \mathrm{P}\left(\mathrm{X} > \mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right) + \left(\mathrm{O} - 1 - \frac{\frac{\lambda}{\mu}}{1 + \frac{\lambda}{\mu}} * \lambda\mathrm{T}\right) * \mathrm{P}(\mathrm{Y} > \mathrm{T} + \mathrm{g})$$

where

$$X \sim Erlang(\lfloor T * \mu \rfloor + 1, \mu)$$

$$Y \sim Erlang(\lfloor T * \mu \rfloor, \mu)$$

So

$$
\begin{aligned}
\mathrm{E}[\#\text{cancellations}] \\
&= \left(\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda \mathrm{T}\right) * \left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor +1} \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)^{\mathrm{n}}}{\mathrm{n}!}\right)\right) \\
&+ \left(\mathrm{O} - 1 - \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} * \lambda \mathrm{T}\right)\left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}\right)\right) \\
&= \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} \lambda \mathrm{T} * \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)^{\lfloor T\mu \rfloor +1}}{(\lfloor T\mu \rfloor + 1)!} + (\mathrm{O}-1) \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} \\
&* \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}
\end{aligned}
$$

As with the approximation for the number of cancellations above, approximations for **overtime** and the **utilization rate** for this combined planning method follow from the approximations mate for these KPI's in sections 3.2.2 and 3.3.1. The amount of time lost on being the FEOR within the (O - 1) non-emergency-OR's is $\frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}} T = \frac{\lambda}{\mu+\lambda} T$, which is equal to the amount of minutes the emergency-OR is actually utilized. This value can be recognized in both the approximations given below.

$$
\mathrm{E}[\text{Overtime}] = \max\left(0, \left|(O-1)T - \frac{\lambda}{\mu+\lambda} T - \left(O\lfloor T\mu \rfloor + \frac{\lambda}{\mu+\lambda} * \lambda \mathrm{T}\right) \mathrm{E}[\mathrm{B}]\right|\right)
$$

$$
E[Utilization\ rate] = ((O+1)\frac{O\lfloor T\mu \rfloor * \frac{1}{\mu}}{OT + \frac{\lambda}{\mu+\lambda} T} + \frac{\lambda}{\mu+\lambda}) * 100\%
$$

3.4 Method White spots

As mentioned earlier, the assumption is made that every OR in the department including the OR's with white spots will not finish its work before the end of the day. This is an assumption that heavily simplifies the approximations done below. The assumption is safe since the workload created by emergency patients is assumed to be enough to fill the allocated slack hours.
The number of OR's with a white spot allocated to them within the OR-department is equal to M.

3.4.1 Without FEOR

Due to the above mentioned assumption, the expected waiting time for emergency patients is equal to the expected waiting time in case of No slack.

$$E\left[W_{emergency}\right] = \frac{1}{O *\ \mu}$$

As before, a "worst case" will be assumed to approximate the expected **number of cancellations**. Here this means that it is assumed that all λT emergency patients are treated on the M OR's with slack allocated to them. The expected **number of cancellations** becomes:

$$\mathrm{E[\#cancellations] = M * P(X > T + g) + \ (O - M) * P(Y > T + g)}$$

Where

$$X \sim Erlang\left(\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor, \mu\right)$$

$$Y \sim Erlang(\lfloor T\mu \rfloor, \mu)$$

So

$$\begin{aligned}
\mathrm{E[\#cancellations]} & \\
&= \mathrm{M} * \left(1 - \left(1 - \sum_{\mathrm{n=0}}^{\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor} \mathrm{e}^{-\mu(\mathrm{T+g})} * \frac{\mu(\mathrm{T+g})^{\mathrm{n}}}{\mathrm{n!}}\right)\right) \\
&+ (\mathrm{O - M})\left(1 - \left(1 - \sum_{\mathrm{n=0}}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T+g})} * \frac{\mu(\mathrm{T+g})^{\mathrm{n}}}{\mathrm{n!}}\right)\right) \\
= \mathrm{M} \sum_{\mathrm{n} = \lfloor T\mu \rfloor + 1}^{\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor} & \mathrm{e}^{-\mu(\mathrm{T+g})} * \frac{\mu(\mathrm{T+g})^{\mathrm{n}}}{\mathrm{n!}} + \mathrm{O} \sum_{\mathrm{n=0}}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T+g})} * \frac{\mu(\mathrm{T+g})^{\mathrm{n}}}{\mathrm{n!}}
\end{aligned}$$

The same "worst case" helps approximating the **expected amount of overtime** and **the utilization rate**:

$$\mathrm{E[overtime] = max(0,} \left| OT - \left((O - M)\lfloor T\mu \rfloor + \lambda \mathrm{T} + \mathrm{M} \left\lfloor (T - \frac{T}{M})\, \mu \right\rfloor\right) \mathrm{E[B]} \right|)$$

$$E[Utilization\ rate] = ((O - M)\frac{\lfloor T\mu \rfloor * \frac{1}{\mu}}{T} + M \frac{\lfloor (T - \frac{T}{M})\mu \rfloor * \frac{1}{\mu}}{T}) * 100\%$$

3.4.2 Using FEOR

The **expected waiting time** for emergency patients when using the FEOR method is always the same as is shown in section 3.3.2. So again:

$$E\left[W_{emergency}\right] = \frac{\lambda}{1 + \mathrm{O}\mu\lambda}$$

In the same way as done in section 3.2.2 and 3.3.2, the expected **number of cancellations**, **amount of overtime** and **utilization rate** as approximated in section 3.4.1 can be adjusted to the use of the FEOR method. This results for the number of cancellations in:

$$\mathrm{E[\#cancellations]} = \mathrm{M} * \mathrm{P}\left(\mathrm{X} > \mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right) + (\mathrm{O} - \mathrm{M}) * \mathrm{P}(\mathrm{Y} > \mathrm{T} + \mathrm{g})$$

Where

$$X \sim Erlang\left(\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor, \mu\right)$$

$$Y \sim Erlang(\lfloor T\mu \rfloor, \mu)$$

So

$$\mathrm{E[\#cancellations]} = \mathrm{M} * \left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor} \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right)^{\mathrm{n}}}{\mathrm{n}!}\right)\right) + (\mathrm{O} - \mathrm{M})\left(1 - \left(1 - \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T} + \mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}\right)\right)$$

$$= \mathrm{M} \sum_{\mathrm{n}=\lfloor T\mu \rfloor + 1}^{\lfloor T\mu \rfloor + \left\lfloor \frac{\lambda \mathrm{T}}{M} \right\rfloor} \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)^{\mathrm{n}}}{\mathrm{n}!} + O \sum_{\mathrm{n}=0}^{\lfloor T\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T}+\mathrm{g})^{\mathrm{n}}}{\mathrm{n}!}$$

$$\mathrm{E[Overtime]} = \max(0, \left| OT - T - \left((O - M)\lfloor T\mu \rfloor + \lambda \mathrm{T} + \mathrm{M}\left\lfloor (T - \frac{T}{M})\,\mu \right\rfloor\right) \mathrm{E[B]} \right|)$$

$$E[Utilization\ rate] = ((O - M)\frac{O\lfloor T\mu \rfloor * \frac{1}{\mu}}{OT + T} + M\frac{O\lfloor (T - \frac{T}{M})\mu \rfloor * \frac{1}{\mu}}{OT + T}) * 100\%$$

3.5 Method Department wide slack

As is done in the case of white spots, the assumption is made that every OR in the department will not finish its work before the end of the day, even though there is not enough elective work planned for the full T minutes of work time.

3.5.1 Without FEOR

Due to this assumption, the expected waiting time for emergency patients is again equal to the expected waiting time in case of No slack.

$$E[W_{emergency}] = \frac{1}{O * \mu}$$

Again assuming an even spread of the emergency patients over the available OR's and a total number of arriving emergency patients < O, we can assume that λT OR's within the department get an emergency patient assigned to them. For the expected **number of cancellations** this results in:

$$\mathrm{E[\#cancellations]} = (\lambda * T) * P(X > T + g) + (O - \lambda * T) * P(Y > T + g)$$

where

$$X \sim Erlang\left(\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor + 1, \mu\right)$$

$$Y \sim Erlang\left(\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor, \mu\right)$$

So

$$\begin{aligned}\mathrm{E[\#cancellations]} &= (\lambda T) * \left(1 - \left(1 - \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor + 1} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\right)\right) \\ &+ (O - \lambda T)\left(1 - \left(1 - \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\right)\right) \\ = \lambda T * e^{-\mu(T+g)} * \frac{\mu(T+g)^{\lfloor (T-\frac{T}{O})\mu \rfloor + 1}}{(\lfloor (T - \frac{T}{O})\,\mu \rfloor + 1)!} &+ O \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}\end{aligned}$$

Overtime can again be approximated by the maximum of 0 and the total available OR time (O*T) minus the expected time needed to serve all planned elective patient and the arriving emergency patients.

$$\mathrm{E[overtime]} = \max(0, \left| OT - \left(O \left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor + \lambda T\right) \mathrm{E[B]} \right|)$$

As is the approximation for the overtime, the approximation for the **utilization rate** is closely related to the one associated with slack allocation method No slack.

$$E[Utilization\ rate] = \frac{\lfloor (T - \frac{T}{O})\mu \rfloor * \frac{1}{\mu}}{T} * 100\%$$

3.5.2 Using FEOR

The **expected waiting time** for emergency patients when using the FEOR method is always the same as is shown in section 3.3.2. So again:

$$E[W_{emergency}] = \frac{\lambda}{1 + O\mu\lambda}$$

In the same way as done in section 3.2.2, 3.3.2 and 3.4.2, the expected **number of cancellations**, **amount of overtime** and **utilization rate** as approximated in section 3.5.1 can be adjusted to the use of the FEOR method. This results in:

$$\mathrm{E[\#cancellations]} = (\lambda * \mathrm{T})\mathrm{P}\left(\mathrm{X} > \mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right) + (\mathrm{O} - \lambda\mathrm{T})\mathrm{P}(\mathrm{Y} > \mathrm{T} + \mathrm{g})$$

Where

$$X \sim Erlang\left(\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor + 1, \mu\right)$$

$$Y \sim Erlang\left(\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor, \mu\right)$$

So

$$\begin{aligned}
&\mathrm{E[\#cancellations]} \\
&= (\lambda\mathrm{T}) * \left(1 - \left(1 - \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor + 1} \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right)^{n}}{n!}\right)\right) \\
&\quad + (\mathrm{O} - \lambda\mathrm{T})\left(1 - \left(1 - \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T} + \mathrm{g})^{n}}{n!}\right)\right)
\end{aligned}$$

$$= \lambda\mathrm{T} \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor + 1} \mathrm{e}^{-\mu\left(\mathrm{T}+\mathrm{g}-\frac{1}{\lambda}\right)} * \frac{\mu\left(\mathrm{T} + \mathrm{g} - \frac{1}{\lambda}\right)^{n}}{n!} + (\mathrm{O} - \lambda\mathrm{T}) \sum_{n=0}^{\lfloor (T-\frac{T}{O})\mu \rfloor} \mathrm{e}^{-\mu(\mathrm{T}+\mathrm{g})} * \frac{\mu(\mathrm{T} + \mathrm{g})^{n}}{n!}$$

$$\mathrm{E[Overtime]} = \max(0, \left| OT - T - \left(O\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor + \lambda\mathrm{T}\right)\mathrm{E[B]} \right|)$$

$$E[Utilization\ rate] = \frac{O\left\lfloor (T - \frac{T}{O})\,\mu \right\rfloor * \frac{1}{\mu}}{OT + T} * 100\%$$

3.6 Round-up

To wrap up this chapter concerning the BOTE analysis, this section takes a bird's-eye view and compares the formulas for the different planning methods.

3.6.1 Similarities

As mentioned repeatedly in the previous section, a lot of similarities are visible between the formulas for the KPI's in the different methods. The simplification is in part reason for this, since it brings the different methods closer together.
The biggest similarities are between the expressions for the different methods + FEOR. Apparently, applying the FEOR method brings the methods closer to each other. This is not surprising, since the idea for the FEOR method originates from a combination of other methods and brings the main characteristics of each of them. Therefore the different methods + FEOR are very similar in characteristics, resulting in very similar expressions for the different KPI's.

3.6.2 Gained insights

Looking at the expressions of the different methods for each KPI, predictions on the performance can already made. Table 11 provides an overview of the results of the BOTE-analysis for the different KPI's. This will come in handy when reading the remainder of this section.

	Expected waiting time for emergency patients
No slack	$\frac{1}{O * \mu}$
No slack + FEOR	$\frac{\lambda}{O * \mu + \lambda} * \frac{1}{(O * \mu)^2}$
Emergency-OR	$\frac{\lambda}{O\mu^2 + O\mu\lambda}$
Emergency-OR + FEOR	$\frac{\lambda}{1 + O\mu\lambda}$
White spots	$\frac{1}{O * \mu}$
White spots + FEOR	$\frac{\lambda}{1 + O\mu\lambda}$
Department wide slack	$\frac{1}{O * \mu}$
Dep. wide slack + FEOR	$\frac{\lambda}{1 + O\mu\lambda}$
	Expected amount of cancellations per OR day
No slack	$\lambda T * e^{-\mu(T+g)} * \frac{\mu(T+g)^{\lfloor T\mu \rfloor + 1}}{(\lfloor T\mu \rfloor + 1)!} + O \sum_{n=0}^{\lfloor T\mu \rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^n}{n!}$

No slack + FEOR	$\lambda T * e^{-\mu\left(T+g-\frac{1}{\lambda}\right)} * \frac{\mu\left(T+g-\frac{1}{\lambda}\right)^{\lfloor T\mu\rfloor+1}}{(\lfloor T\mu\rfloor+1)!} + O\sum_{n=0}^{\lfloor T\mu\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
Emergency-OR	$\frac{\lambda}{\mu+\lambda}\lambda T * e^{-\mu(T+g)} * \frac{\mu(T+g)^{\lfloor T\mu\rfloor+1}}{(\lfloor T\mu\rfloor+1)!} + (O-1)\sum_{n=0}^{\lfloor T\mu\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
Emergency-OR + FEOR	$\frac{\lambda}{\mu+\lambda}\lambda T * e^{-\mu\left(T+g-\frac{1}{\lambda}\right)} * \frac{\mu\left(T+g-\frac{1}{\lambda}\right)^{\lfloor T\mu\rfloor+1}}{(\lfloor T\mu\rfloor+1)!} + (O-1)\sum_{n=0}^{\lfloor T\mu\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
White spots	$M\sum_{n=\lfloor T\mu\rfloor+1}^{\lfloor T\mu\rfloor+\left\lfloor\frac{\lambda T}{M}\right\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!} + O\sum_{n=0}^{\lfloor T\mu\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
White spots + FEOR	$M\sum_{n=\lfloor T\mu\rfloor+1}^{\lfloor T\mu\rfloor+\left\lfloor\frac{\lambda T}{M}\right\rfloor} e^{-\mu\left(T+g-\frac{1}{\lambda}\right)} * \frac{\mu\left(T+g-\frac{1}{\lambda}\right)^{n}}{n!} + O\sum_{n=0}^{\lfloor T\mu\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
Department wide slack	$\lambda T * e^{-\mu(T+g)} * \frac{\mu(T+g)^{\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor+1}}{\left(\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor+1\right)!} + O\sum_{n=0}^{\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
Dep. wide slack + FEOR	$\lambda T * e^{-\mu\left(T+g-\frac{1}{\lambda}\right)} * \frac{\mu\left(T+g-\frac{1}{\lambda}\right)^{\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor+1}}{\left(\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor+1\right)!} + O\sum_{n=0}^{\left\lfloor\left(T-\frac{T}{O}\right)\mu\right\rfloor} e^{-\mu(T+g)} * \frac{\mu(T+g)^{n}}{n!}$
	Expected total overtime for an OR day
No slack	$\max(0, \lvert OT - (O\lfloor T\mu\rfloor + \lambda T)E[B]\rvert)$
No slack + FEOR	$\max(0, \lvert OT - T - (O\lfloor T\mu\rfloor + \lambda T)E[B]\rvert)$
Emergency-OR	$\max\left(0, \left\lvert (O-1)T - \left(O\lfloor T\mu\rfloor + \frac{\lambda}{\mu+\lambda} * \lambda T\right)E[B]\right\rvert\right)$

Emergency-OR + FEOR	$\max(0, \left\|(O-1)T - \frac{\lambda}{\mu+\lambda}T - \left(O\lfloor T\mu\rfloor + \frac{\lambda}{\mu+\lambda} * \lambda \mathrm{T}\right)\mathrm{E[B]}\right\|)$
White spots	$\max(0, \left\|OT - \left((O-M)\lfloor T\mu\rfloor + \lambda\mathrm{T} + \mathrm{M}\left\lfloor (T-\frac{T}{M})\,\mu\right\rfloor\right)\mathrm{E[B]}\right\|)$
White spots + FEOR	$\max(0, \left\|OT - T - \left((O-M)\lfloor T\mu\rfloor + \lambda\mathrm{T} + \mathrm{M}\left\lfloor (T-\frac{T}{M})\,\mu\right\rfloor\right)\mathrm{E[B]}\right\|)$
Department wide slack	$\max(0, \left\|OT - \left(O\left\lfloor (T-\frac{T}{O})\,\mu\right\rfloor + \lambda\mathrm{T}\right)\mathrm{E[B]}\right\|)$
Dep. wide slack + FEOR	$\max(0, \left\|OT - T - \left(O\left\lfloor (T-\frac{T}{O})\,\mu\right\rfloor + \lambda\mathrm{T}\right)\mathrm{E[B]}\right\|)$
Expected utilization rate of the OR's in the OR-department	
No slack	$\frac{\lfloor T\mu\rfloor * \frac{1}{\mu}}{T} * 100\%$
No slack + FEOR	$\frac{O\lfloor T\mu\rfloor * \frac{1}{\mu}}{OT+T} * 100\%$
Emergency-OR	$((O+1)\frac{\lfloor T\mu\rfloor * \frac{1}{\mu}}{T} + \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}}) * 100\%$
Emergency-OR + FEOR	$((O+1)\frac{O\lfloor T\mu\rfloor * \frac{1}{\mu}}{OT + \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}}T} + \frac{\frac{\lambda}{\mu}}{1+\frac{\lambda}{\mu}}) * 100\%$
White spots	$((O-M)\frac{\lfloor T\mu\rfloor * \frac{1}{\mu}}{T} + M\frac{\lfloor (T-\frac{T}{M})\mu\rfloor * \frac{1}{\mu}}{T}) * 100\%$
White spots + FEOR	$((O-M)\frac{O\lfloor T\mu\rfloor * \frac{1}{\mu}}{OT+T} + M\frac{O\lfloor (T-\frac{T}{M})\mu\rfloor * \frac{1}{\mu}}{OT+T}) * 100\%$
Department wide slack	$\frac{\lfloor (T-\frac{T}{O})\mu\rfloor * \frac{1}{\mu}}{T} * 100\%$
Dep. wide slack + FEOR	$\frac{O\left\lfloor (T-\frac{T}{O})\,\mu\right\rfloor * \frac{1}{\mu}}{OT+T} * 100\%$

Table 11: Survey of the BOTE-analysis for the different situations

3.6.2.1 Expected waiting time for emergency patients

The expected waiting time for emergency patients decreases for each of the methods with the addition of FEOR. The EOR method is already performing on this KPI, thus the FEOR influence seems to be minimal there.

3.6.2.2 Expected amount of cancellations per OR day

Addition of FEOR seems to increase the amount of cancellations for each of the methods. This can be explained by the amount of time not utilized due to the FEOR. The EOR method seems to be the least influenced method, which can be explained by the fact that this method already includes certain non-utilization of OR's. The expressions for the amount of cancellations are very similar for the Dep. wide slack, no slack and white spot methods.

3.6.2.3 Expected total overtime per OR day

Expressions for overtime are very similar between the different methods.

3.6.2.4 Expected utilization rate of the OR's in the OR-department

The expressions confirm the expectation that addition of the FEOR will reduce utilization. However this reduction seems to be depending on the number of OR's. More specifically, the more OR's in the department the lower impact using the FEOR method has on the utilization. This is due to the smart way in which the algorithm picks the FEOR.

4 Simulation

As was mentioned earlier in section 3, the model simply contains too many parameters and variables to make an explicit mathematical analysis doable. Therefore, instead of an in-depth mathematical analysis, in section 3 a back-of-the-envelope (BOTE) analysis was performed. The BOTE analysis aims to gain some sense of the way the use of the different slack allocation methods and FEOR method influences the waiting time of emergency patients, the amount of cancellations, the utilization rate of the OR-department and the overtime. This section will introduce a simulation program, to be able to further investigate the performance of the different methods.
The simulation program in this research, is a discrete event simulation (short DES). DES is a form of computer-based modeling that provides a flexible and intuitive approach to representing complex systems. DES models the operation of a system as a discrete sequence of events in time, which makes it very suitable to simulate more complex queueing systems.
The simulation program finds its use also beyond this specific research. An example of this can be found in Appendix G.
The simulation program is written in the Java programming language, using NetBeans IDE 8.0. A set of existing packages is used to perform standard tasks such as reading and writing to .csv files, generating random numbers and creating HashMaps.

4.1 Basic strategy

The simulation length (SimLength) represents the number of days that is simulated. Since only weekdays are in scope, 260 days represent a complete year. In order to reduce the influence of variation not just one, but ten years are simulated. Thereafter for most of the variables (except for maxima), the result after ten years is divided by 10. Base value for parameter SimLength is therefore 2600.
Every new day can be viewed as a fresh simulation run that is completely independent of all earlier simulated days. Statistically there is no difference between a Monday and a Friday. Every workday is assumed to be the same.

Every new day the simulation follows the planning steps in the same order as described in section 2.7. So first the strategic plan is made, meaning that based on the slack allocation method used, slack is allocated leaving a certain amount of hours for elective procedures on each of the OR's. After that every OR gets a specialism assigned as described in section 2.3.2. After the strategic plan, follows the tactical plan. For each OR in the department the queue is filled with elective patients that need to be treated that day. This is done as described in section 2.7.2. Now that for each OR a set (sometimes empty) of elective patients is waiting in queue of the specialism that is assigned to the specific OR for that day, the discrete event simulation starts. Each day starts at t=0.

Events distinguished in the simulation are:

Begin of the late start **-** Every OR starts with a certain delay. This delay is called late start and the length of this delay turns out to be Poisson(15) distributed. This event takes place at t=0 and is therefore the first event to happen at each OR. The moment this event takes place, the OR in case is set to be down for the duration of the delay and a new event is generated. This new event will function as the trigger for the end of the delay.

End of the late start **-** After t~Poisson(15) minutes the delay at an OR ends. This appears as the occurrence of an event called "end of the late start". The moment this event takes place the OR is set back up and a departure event at this exact t and with an empty patient is generated.

Arrival of emergency patient type A **-** What this event simulates should be quite clear from just the name. Before the day starts, the time at which the first arrival of emergency patient type A takes place is generated using the distribution described in section 2.3.4. At the occurrence of the event, the time of the following arrival is generated and the new arrival event is created including the specifics of the patient. The arriving patient is either placed in service or placed in a queue depending on the status of the system as described in section 2.7.3.2.

Arrival of emergency patient type B / C - These events are closely related to the event of an emergency patient type A arriving. The distribution for the arrival times is of course different as is the exact way in which the patients are handled. More on these differences can be found in sections 2.3.4 and 2.3.42.7.3.2.

Departure of a patient after surgery **-** The departure of a patient is the most complex event in the simulation. The OR that treated the patient gets released and starts looking for a new job. This new job is not necessarily the next elective patient in line, but can also be treating an emergency patient or taking on the role of FEOR. For each combination of slack allocation method with or without FEOR, the decision tree belonging to this event is given in Appendix D.

End of the workday **-** At t = 480 (8 hours * 60 minutes = 480 minutes) the "End of the workday" event takes place. This event simulates the end of the normal work hours. In case an OR has emptied its elective patient queue (either by cancellation or treatment) for the day and no emergency patients are awaiting service, the OR closes. For the specialist and his team this means not working overtime. This event also triggers the arrival of emergency patients to stop. Emergency patients arriving after work hours are out of scope for this research.

End of the day **-** At t = 1440 (24 hours * 60 minutes = 1440 minutes) not just the work hours, but the complete work day comes to an end. Any OR's still open at that time are closed. Surgeries in progress are assumed to be finished. The only reason for an OR to be open at this time is because the actual surgery duration for the patient in service turned out to be exceptionally large. The way actual surgery durations are calculated, allow for these extreme values. Since the rarity (24 in 10 years on average over all performed simulation runs) of this occurrence it is assumed to not influence the results of this research.

OR's are closed at "end of the day", "end of the workday" and departure events. The simulation run of the day stops as soon as all OR's are closed. At this point, information is stored that is needed to calculate the KPI's as described in section 2.8. For the next day all OR's are set up and running again, each one starting with a new list of elective work to perform.

4.2 Validation

To validate that the simulation works as intended the simulation is configured in such a way that it mirrors the situation at S.T.A.R. labs as good as possible. Subsequently, the results of this simulation run will be compared to the trimmed production data of 2012 from S.T.A.R. labs. Different variables of both productions will be compared. The configuration used to mirror S.T.A.R. labs is configuration 1.2.0 as shown in Table 13. Results for the simulation run together with the according values in the trimmed S.T.A.R. labs production 2012 dataset are shown in Table 12. In the following subsection the content of this table will be discussed and it will be validated that the simulation program works as needed to perform this research.

4.2.1 Comparing simulation results with real life data

The data in Table 12 is roughly divisible into three groups. Data on average surgery durations, data on number of patients served and data on the number of OR days and minutes spent on certain type of activities. This last mentioned data will be discussed first, since it will provide reasons for values in the other groups of data to differentiate.
The number of OR days within the simulation is 5200. This is in accordance with an OR-department of 20 OR’s being operational for 260 weekdays. The 2012 production data of S.T.A.R. labs contains information on 4042 OR days. Apparently not all OR’s were used on every weekday in 2012. Explanations for this phenomenon could be illness of personnel, holidays, reconstruction of the department, etcetera.
This difference in the number of OR days partially explains the difference in total time spent on operations and changing time although here a difference per OR day occurs as well. Looking at the S.T.A.R. labs production data more closely reveals that on average only 303 minutes of planned work is available, only 2,92 surgeries are performed and only 397,40 minutes are spent on operations per OR day. This is a lot less than the on average 3,64 surgeries and 480,02 minutes spent on operations per OR day within the simulation output. These simulation results can easily be explained looking at the assumption that enough patients are available to fill the 480 minutes of every OR day with planned work. Apparently this assumption is not true for S.T.A.R. labs, or there are other reasons for not scheduling in an appropriate amount of elective patients.
The above mentioned difference is also of influence on the amount of patients served per specialism. These numbers are generally higher for the simulation output than for the S.T.A.R. labs data. Looking at the distribution of the performed surgeries over the different specialisms however, gives very similar results. The way OR days are assigned to specialisms described in section 2.3.2 seems to work out as intended. The distributions of emergency patients inter-arrival times are chosen in such a way that the number of emergency patients within the simulation mirrors the same value in the S.T.A.R. labs data. This works out as intended as can be concluded from Table 12. This however, does create a difference in the percentages of patients that is non-elective, since the amount of elective patients served in the simulation is higher than within S.T.A.R. labs.
Average time spent on late start per OR day is very much the same in both the simulation and the S.T.A.R. labs data. This confirms that the chosen value for mu in the Poisson(mu) distribution of the length of the late start was a valid choice.
Average surgery duration per specialism within the simulation run seems to correspond with the same values in the S.T.A.R. labs data. Differences can be explained by a combination of the way actual surgery durations are simulated (the planned/actual ratio can vary between 0,2

and 8 for some specialisms) and the small (some hundreds) number of patients served per specialism per year.
After this comparison, it is safe to assume with a high degree of certainty that the simulation is indeed valid. The program is assumed to work as intended and will therefore be used in the remainder of this research.

	Specialism / patient type	Simulation result	Trimmed S.T.A.R. labs production 2012
Average surgery duration	CAC / All	248,9321	245,8896104
	CHI / All	128,5285	136,2837707
	CHP / All	87,39367	99,74907293
	GYN / All	101,557	106,7092568
	KNO / All	102,945	121,9792793
	MND / All	143,9808	172,6976744
	NEC / All	189,4109	198,3547486
	OOG / All	71,75274	72,69003378
	ORT / All	107,3726	118,1097087
	URO / All	154,0976	163,3903134
	VAT / All	165,1144	166,1634615
Amount of patients served / % of total	CAC / All	1928 / 10,2%	1078 / 9,1%
	CHI / All	3377 / 17,8%	2058 / 17,4%
	CHP / All	1273 / 6,7%	809 / 6,8%
	GYN / All	1306 / 6,9%	767 / 6,5%
	KNO / All	1765 / 9,3%	1110 / 9,4%
	MND / All	1011 / 5,3%	559 / 4,7%
	NEC / All	1830 / 9,7%	1074 / 9,1%
	OOG / All	3251 / 17,2%	2368 / 20, 0%
	ORT / All	1604 / 8,5%	1030 / 8,7%
	URO / All	596 / 3,1%	351 / 3,0%
	VAT / All	1011 / 5,3%	624 / 5,3%
	All / Emergency type A	104 / 0,5%	106 / 0,9%
	All / Emergency type B	400 / 2,1%	408 / 3,4%
	All / Emergency type C	523 / 2,8%	519 / 4,4%
	All / Elective	17925 / 94,6%	10795 / 91,3%
	All / All	18952 / 100%	11828 / 100%
Number of OR days		5200	4046
Average #surgeries / OR days		3,64	2,92
Total time spent on operations		2496106	1607871
Time spent on operations / OR day		480,02	397,40
Total time spent on changing		198460	116727
Time spent on changing / OR day		38,17	28,85
Total time lost with late start		77658	59800
Time spent on late start / OR day		14,93	14,78

Table 12 Values for certain variables resulting from a simulation run compared to the according values from the trimmed S.T.A.R. labs production 2012 data

5 Data analysis

The four methods of allocating slack in combination with or without the FEOR method used in each of the four scenarios make up for a total of 32 different configurations as shown in Table 13. Input variables not mentioned in the table keep their given base values.

Conf. nr.	Scenario	Slack allocation method	FEOR method applied	Nr. of OR's that have slack allocated	Slack hours / day	Arrival rate of patients of urgency type		
						A	B	C
1.1.0	Base	No slack	No	0	0	0,000849359	0,003269231	0,004158654
1.1.1	Base	No slack	Yes	0	0	0,000849359	0,003269231	0,004158654
1.2.0	Base	Emergency OR	No	1	8	0,000849359	0,003269231	0,004158654
1.2.1	Base	Emergency OR	Yes	1	8	0,000849359	0,003269231	0,004158654
1.3.0	Base	White spots	No	4	8	0,000849359	0,003269231	0,004158654
1.3.1	Base	White spots	Yes	4	8	0,000849359	0,003269231	0,004158654
1.4.0	Base	Department wide slack	No	20	8	0,000849359	0,003269231	0,004158654
1.4.1	Base	Department wide slack	Yes	20	8	0,000849359	0,003269231	0,004158654
2.1.0	Double urgency arr. rate	No slack	No	0	0	0,001698718	0,006538462	0,008317308
2.1.1	Double urgency arr. rate	No slack	Yes	0	0	0,001698718	0,006538462	0,008317308
2.2.0	Double urgency arr. rate	Emergency OR	No	1	8	0,001698718	0,006538462	0,008317308
2.2.1	Double urgency arr. rate	Emergency OR	Yes	1	8	0,001698718	0,006538462	0,008317308

Conf. nr.	Scenario	Slack allocation method	FEOR method applied	Nr. of OR's that have slack allocated	Slack hours / day	Arrival rate of patients of urgency type A	B	C
2.3.0	Double urgency arr. rate	White spots	No	4	8	0,001698718	0,006538462	0,008317308
2.3.1	Double urgency arr. rate	White spots	Yes	4	8	0,001698718	0,006538462	0,008317308
2.4.0	Double urgency arr. rate	Department wide slack	No	20	8	0,001698718	0,006538462	0,008317308
2.4.1	Double urgency arr. rate	Department wide slack	Yes	20	8	0,001698718	0,006538462	0,008317308
3.1.0	Half urgency arr. rate	No slack	No	0	0	0,00042468	0,001634616	0,002079327
3.1.1	Half urgency arr. rate	No slack	Yes	0	0	0,00042468	0,001634616	0,002079327
3.2.0	Half urgency arr. rate	Emergency OR	No	1	8	0,00042468	0,001634616	0,002079327
3.2.1	Half urgency arr. rate	Emergency OR	Yes	1	8	0,00042468	0,001634616	0,002079327
3.3.0	Half urgency arr. rate	White spots	No	4	8	0,00042468	0,001634616	0,002079327
3.3.1	Half urgency arr. rate	White spots	Yes	4	8	0,00042468	0,001634616	0,002079327
3.4.0	Half urgency arr. rate	Department wide slack	No	20	8	0,00042468	0,001634616	0,002079327
3.4.1	Half urgency arr. rate	Department wide slack	Yes	20	8	0,00042468	0,001634616	0,002079327
4.1.0	Half amount of ORs	No slack	No	0	0	0,00042468	0,001634616	0,002079327
4.1.1	Half amount of ORs	No slack	Yes	0	0	0,00042468	0,001634616	0,002079327

Conf. nr.	Scenario	Slack allocation method	FEOR method applied	Nr. of OR's that have slack allocated	Slack hours / day	Arrival rate of patients of urgency type A	B	C
4.2.0	Half amount of ORs	Emergency OR	No	1	8	0,00042468	0,001634616	0,002079327
4.2.1	Half amount of ORs	Emergency OR	Yes	1	8	0,00042468	0,001634616	0,002079327
4.3.0	Half amount of ORs	White spots	No	4	8	0,00042468	0,001634616	0,002079327
4.3.1	Half amount of ORs	White spots	Yes	4	8	0,00042468	0,001634616	0,002079327
4.4.0	Half amount of ORs	Department wide slack	No	10	8	0,00042468	0,001634616	0,002079327
4.4.1	Half amount of ORs	Department wide slack	Yes	10	8	0,00042468	0,001634616	0,002079327

Table 13 Simulated scenarios

For each configuration, the OR-department is simulated for a time span of 10 years (2600 days). The output of the simulation model consists of a large set of values as is shown in Appendix A. Not all the output values are relevant for this research. Based on expert opinions (Appendix B) and literature (sections 1), the scope of this data analysis is narrowed down to the list of KPI's as introduced in section 2.8. In the following subsections, the performance of the different configurations is given on each of these KPI's. Conclusions based on these results will be stated in section 6.1.

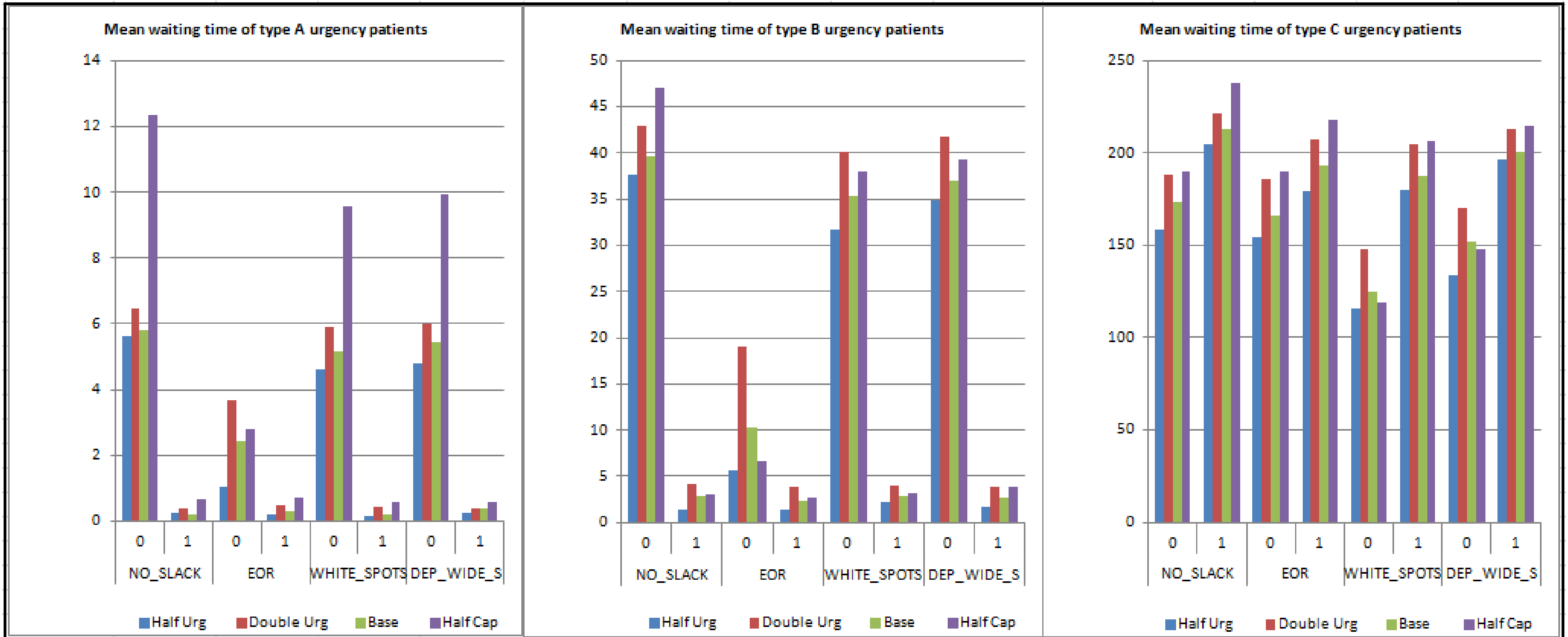
5.1 Performance of the different configurations

This section is divided into seven subsections, each covering a different KPI.

5.1.1 Average waiting time of urgency patients

When an urgency patient arrives at the OR-department, it is important (especially for type A urgency patients) that he or she receives close to immediate care. For some patients a couple of extra minutes waiting time can be life-threatening. The average waiting time of urgency patients therefore is an important KPI when it comes to patient well-being and is one of the main focus points of the FEOR method. By ensuring that an OR is free to receive arriving emergency patients at close to any time during the day, using the FEOR method results in very low mean waiting times for type A and B urgency patients as is shown in Figure 12.

The impact of the FEOR method on the waiting time of type C emergency patients is different than in the case of type A and B. The reason for this is simple. Type C urgency patients are not treated at the FEOR but are scheduled at an OR with preferably the same specialism at the end of the day. Therefore these patients do not enjoy the benefits of the FEOR, but are rather troubled by the time “wasted” on holding the work at one of the available OR’s for possible urgency type A or B arrivals.
What slack allocation method is used in combination with the FEOR method hardly influences the waiting times of type A and B emergency patients. Without the use of the FEOR method there does exist a significant difference between the performance of the different slack allocation methods on this KPI. Especially Emergency-OR stands out in a positive way when it comes to waiting time for emergency patients. The dedicated emergency-OR (DEOR) offers immediate treatment for emergency patients in case it is not in use. Although not as guaranteed as with the FEOR, the DEOR seems to do the job.



NO SLACK 0	5,64956798	6,46533983	5,8242525	12,3270737	NO SLACK 0	37,690075	42,93907	39,6459491	47,08724918	NO SLACK 0	158,348316	188,280603	173,436399	189,99018
NO SLACK 1	0,23848607	0,41509567	0,22931897	0,67983834	NO SLACK 1	1,43413215	4,19706686	2,88262702	2,979055666	NO SLACK 1	204,843561	221,337053	213,078958	237,678683
EOR 0	1,05239799	3,69782861	2,41562658	2,82361414	EOR 0	5,61667858	19,0007407	10,3422807	6,564376829	EOR 0	154,401698	185,627979	165,902382	189,587647
EOR 1	0,21803701	0,48836387	0,28643959	0,70799228	EOR 1	1,33730475	3,91697205	2,34616005	2,658522737	EOR 1	179,605616	207,582989	193,160913	217,736113
WHITE SPOT	4,58988495	5,89547502	5,15384643	9,54428167	WHITE SPOT	31,7926821	40,1824069	35,3813488	37,99211451	WHITE SPOT (	116,080141	147,621775	124,964271	118,942535
WHITE SPOT	0,15798265	0,45148097	0,20859831	0,57541347	WHITE SPOT	2,17476327	3,96681567	2,89706492	3,182596385	WHITE SPOT 1	180,02609	205,239317	187,909015	206,133745
DEP WIDE 0	4,77622931	6,00462189	5,45293211	9,9514677	DEP WIDE 0	34,8350861	41,7275076	36,9524921	39,3218915	DEP WIDE 0	133,67604	170,532958	151,627613	148,294409
DEP WIDE 1	0,25658585	0,38801371	0,37074537	0,57303277	DEP WIDE 1	1,68658828	3,85762004	2,71217505	3,758305335	DEP WIDE 1	196,445298	212,903266	201,101131	214,768726

Figure 12 Mean waiting time of the different types of urgency patients for the different configurations

Effects of the different arrival rates of emergency patients on this KPI are marginal. More arriving emergency patients means more pressure on the OR-department resulting in higher waiting times. This effect can be seen best in combination with the emergency-OR, since this EOR will be in use more often when the arrival rates increase which reduces its positive effect on waiting times.

The waiting times of the different type of patients in the scenarios with half elective capacity are almost double using the No slack, White spots and Department wide slack methods without FEOR. Here, using half the OR's almost doubles the waiting time. This can easily be explained by the function for the expected waiting time given in section 3.

$$E[W_{emergency}] = \frac{1}{O * \mu}$$

When O is more than halved, the expected waiting time automatically is more than doubled.

↓ compared to →	FEOR Yes/No	No slack	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Y/N	-	No	Yes	No	Yes	No	**Yes**	No	Yes
No slack	No	0	+2440	+141	+1933	+13	**+2692**	+7	+1471
No slack	Yes	-96	0	-91	-20	-96	**+10**	-96	-38
EOR	No	-59	+953	0	+743	-53	**+1058**	-56	+552
EOR	Yes	-95	+25	-88	+0	-94	**+37**	-95	-23
White spots	No	-12	+2147	+113	+1699	0	**+2371**	-5	+1290
White spots	**Yes**	**-96**	**-9**	**-91**	**-27**	**-96**	**+0**	**-96**	**-44**
Dep. wide s.	No	-6	+2278	+126	+1804	+6	**+2514**	0	+1371
Dep. wide s.	Yes	-94	+62	-85	+29	-93	**+78**	-93	0

Table 14 Difference in average waiting time for emergency patients type A in terms of percentages (base scenario)

Table 14 shows that slack allocation method White spots combined with using the FEOR method results in the lowest average waiting time for emergency type A patients in the base scenario.

Overall, the waiting times for emergency patients A, B and C are relatively low to the norm time in which each type has to be served, independently of the used configuration. This will be further underlined by the following KPI.

5.1.2 Urgency patients treated outside norm

As is mentioned in section 5.1.1, urgency patients require treatment fast. The degree of urgency determines what amount of waiting time before the treatment starts is acceptable for the patient. Within S.T.A.R. labs, three types of emergency patients are distinguished based on this allowed waiting time. These accepted levels of waiting times are translated into norms as is mentioned in section 2.3.4.

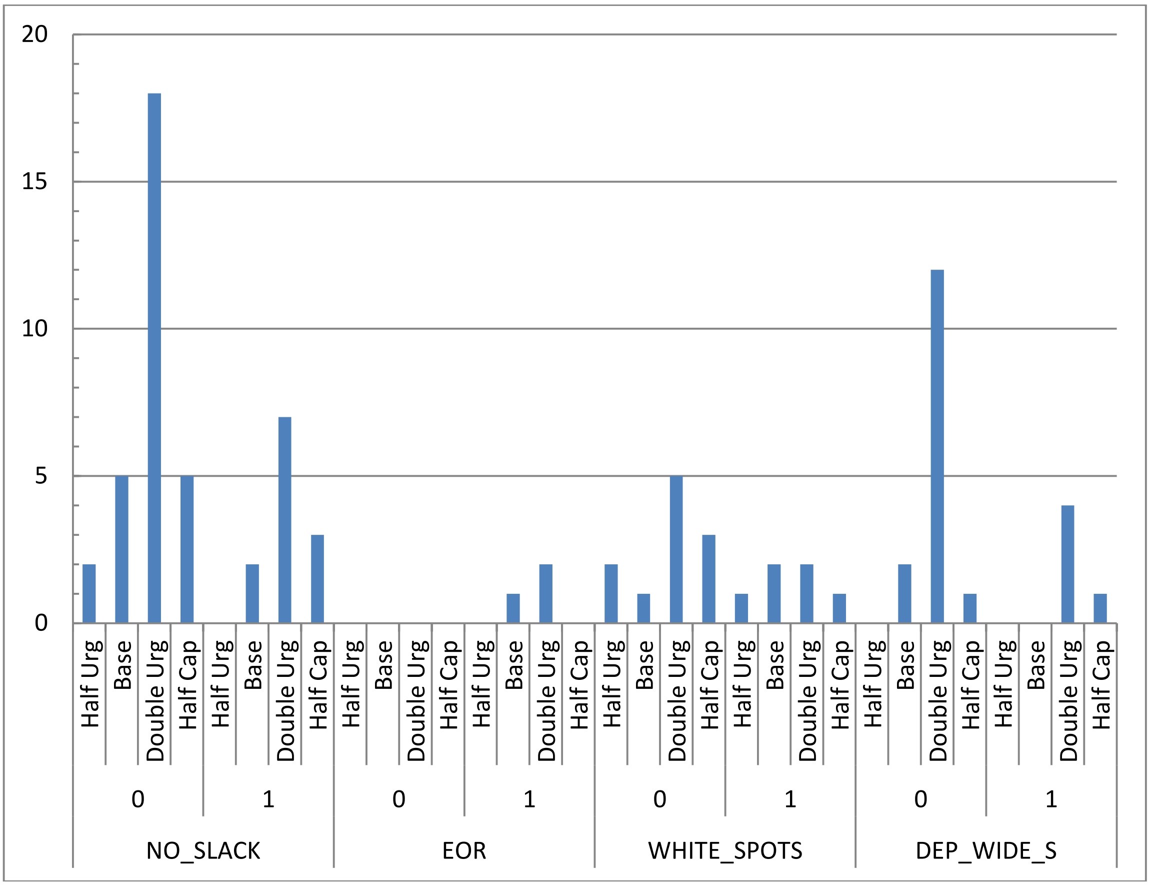


Table 15 Number of emergency patients type B served outside norm

Since the acceptable waiting time is not just a number, but is based on the health of the patient, violating these norms is heavily undesirable. Due to this fact, hospitals strive to treat every emergency patient within his or her norm. This way, keeping the number of patients served outside the norm equal to zero.

Table 15 only shows the number of emergency patients served outside the norm for type B since for none of the configurations an emergency patient of type A or C is served outside the norm. The number of emergency patients of type B that is getting served outside the norm is equal to 18 over 10 years in the worst performing scenario. This worst case is not surprisingly the configuration with the most arriving emergency patients while the hospital is not in any way anticipating these arrivals (No slack without FEOR). Allocating slack to an emergency OR without using FEOR results for every scenario in zero emergency patients type B treated outside the norm in a time span of 10 years. This is the only combination of slack allocation/ FEOR use that does not result in violation of the norm for any type of patient over a time span of 10 years. When allocating slack to white spots or department wide, using FEOR seems to have a positive influence on the value for this KPI. Looking at the different scenarios, more emergency arrivals increase the amount of norm violations.

5.1.3 Cancellations

While getting treated at a different time than expected is already annoying for a patient and his or her relatives, getting his or her surgery cancelled for the day is even worse. The number of cancellations therefore is preferably low.

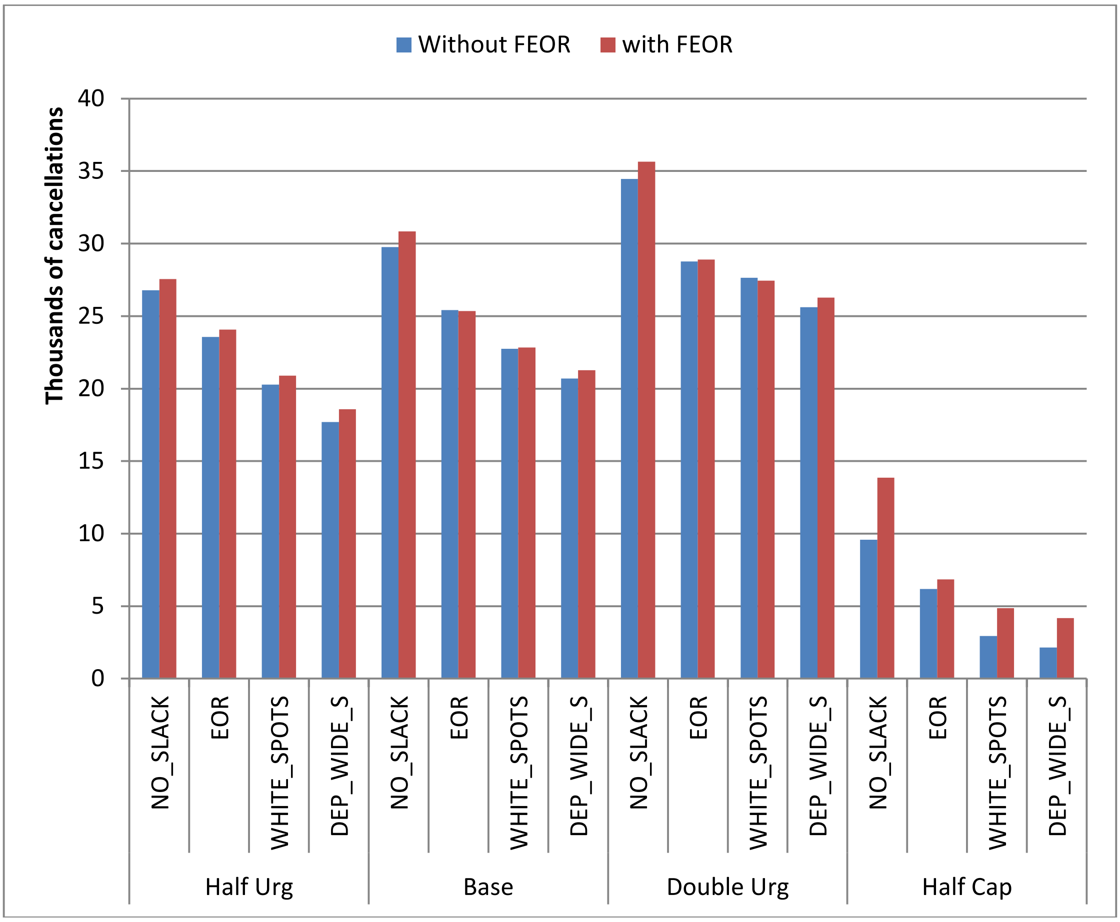


Table 16 Cancellations

Table 16 shows a very clear relationship between the used slack allocation method and the number of cancellations. In each of the scenarios, Department wide slack results in the least cancellations, followed by White spots, Emergency-OR and finally No slack.
The addition of the FEOR method results in the scenarios with the base size OR-department, for small increases and in a very rare occasion for a small decrease. Impact of the FEOR on the number of cancellations is bigger in the smaller size OR-department. Here, the number of cancellations increases more drastically, sometimes even doubles.
From Table 16 it becomes very clear that a higher emergency arrival rate results in more cancellations. Looking at the just the base scenario, Department wide slack without FEOR performs better than all other planning methods (Table 17). Not far behind though is Department wide slack with FEOR, resulting in 2,8% more cancellations.

5.1.4 Delay in elective surgery start times

As is described in section 2.7.3, there are many factors influencing the start times of elective patients. How much influence emergency patients can have on the elective schedule depends heavily on the slack allocation method used and whether or not the FEOR method is implemented. What the impact of the different slack allocation methods and the FEOR method really is, will be researched using this KPI.

↓ compared to →	FEOR Yes/No	No slack	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Y/N	-	No	Yes	No	Yes	No	**Yes**	No	Yes
No slack	No	0,0	-3,5	+17,1	+17,5	+30,9	+30,4	**+43,8**	+39,9
No slack	Yes	+3,6	0,0	+21,3	+21,7	+35,6	+35,1	**+49,0**	+44,9
EOR	No	-14,6	-17,6	0,0	+0,3	+11,8	+11,3	**+22,8**	+19,5
EOR	Yes	-14,9	-17,8	-0,3	0,0	+11,4	+11,0	**+22,4**	+19,1
White spots	No	-23,6	-26,2	-10,5	-10,2	0,0	-0,4	**+9,9**	+6,9
White spots	**Yes**	-23,3	-26,0	-10,2	-9,9	+0,4	0,0	**+10,3**	+7,3
Dep. wide s.	No	**-30,5**	**-32,9**	**-18,6**	**-18,3**	**-9,0**	**-9,3**	**0,0**	**-2,7**
Dep. wide s.	Yes	-28,5	-31,0	-16,3	-16,0	-6,4	-6,8	**+2,8**	0,0

Table 17 Difference in #cancellations of elective patients in terms of percentages (base scenario)

Within the simulation, elective patients are divided into two groups after surgery. The first group received their treatment earlier than planned, while the other group received their treatment later. Subsequently, these patients are divided into subgroups based on the number of minutes their treatment was early or delayed. These subgroups each consist of a 30 minute interval and range from 0 to >450.

Table 18 shows the distribution of the patients over the different subgroups for each of the combinations slack allocation method with or without FEOR in the base scenario. Although not exactly the same, the differences are marginal and from a distance the distributions look very much alike.

A closer look reveals that for every slack allocation method, the addition of the FEOR method results in more delayed elective patients and higher delays over all. This effect becomes even more visible looking at Figure 13. Here it is clear that using the FEOR method tilts the distribution of the patients more to the right, meaning more delay in start times. This negative effect of the FEOR method can be explained due to the fact that through the changing FEOR, many OR's and thus many elective patients are influenced by the (potential) arrivals of emergency patients.

This effect is lowest when using Emergency-OR without FEOR. Here most of the emergency patients are treated at the emergency-OR and only in rare occasions other OR's are involved in the treatment of emergency patients. Due to this fact, only a small percentage of the elective patients experience delays caused by emergency treatment. This is reflected in Table 18.

5.1.5 Number of OR's working (more than the norm) overtime

Overtime is heavily undesirable for both the personnel (specialists, medical assistants) and the management of a hospital. For the first group it means working longer than expected and therefore being home late. For the second group, overtime is above all a very costly business. Not only the operating personnel needs to stay over but related to every surgery are a lot of other resources that have to be used longer than expected as well.

In this subsection, overtime will be measured by the amount of OR's working overtime and the amount of OR's that work even more than the norm in overtime. This overtime norm is set by management and is assumed to be 30 minutes throughout this research (parameter d).

Values	NO_SLACK		EOR		WHITE_SPOTS		DEP_WIDE_S	
	Without FEOR	With FEOR	Without FEOR	With FEOR	Without FEOR	With FEOR	Without FEOR	With FEOR
<-450	0	0	0	0	0	0	0	0
-450_-420	0	2	0	0	0	0	0	1
-420_-390	0	5	0	0	1	1	0	1
-390_-360	0	19	2	1	0	9	0	4
-360_-330	0	7	0	0	1	10	0	7
-330_-300	0	7	0	0	0	2	2	9
-300_-270	3	11	2	0	0	2	0	7
-270_-240	1	8	4	1	2	3	0	12
-240_-210	2	9	2	6	1	6	2	22
-210_-180	7	9	19	6	12	2	4	8
-180_-150	33	5	42	27	33	10	32	12
-150_-120	163	7	166	126	154	40	138	14
-120_-90	642	56	630	488	605	224	544	62
-90_-60	2346	555	2407	1807	2192	1320	2206	595
-60_-30	8144	4222	8127	6874	7741	5794	7935	4068
-30_0	21590	17273	20925	19843	20853	17795	21178	16876
0_30	75330	73085	72548	72262	74015	70295	74103	72487
30_60	32167	36081	31619	32425	31336	31718	30984	34928
60_90	19244	22942	18790	19833	18377	20935	19020	22674
90_120	11612	13759	11302	12029	11644	13972	11751	14237
120_150	6663	7807	6457	6676	6918	8510	7193	8235
150_180	3626	4261	3327	3440	3779	4959	4032	4583
180_210	1921	2090	1578	1709	2063	2604	2171	2269
210_240	971	1131	693	819	1073	1363	1141	1165
240_270	481	533	373	315	514	679	556	564
270_300	239	269	150	148	237	335	312	297
300_330	135	130	60	48	147	187	150	163
330_360	54	60	22	26	91	90	83	73
360_390	36	36	10	13	23	50	48	51
390_420	8	25	3	5	16	22	25	34
420_450	2	15	1	1	14	19	11	12
>450	1	5	0	1	9	17	17	7

Table 18 Distribution of realized - planned start times in the base scenario over a 10 year time span

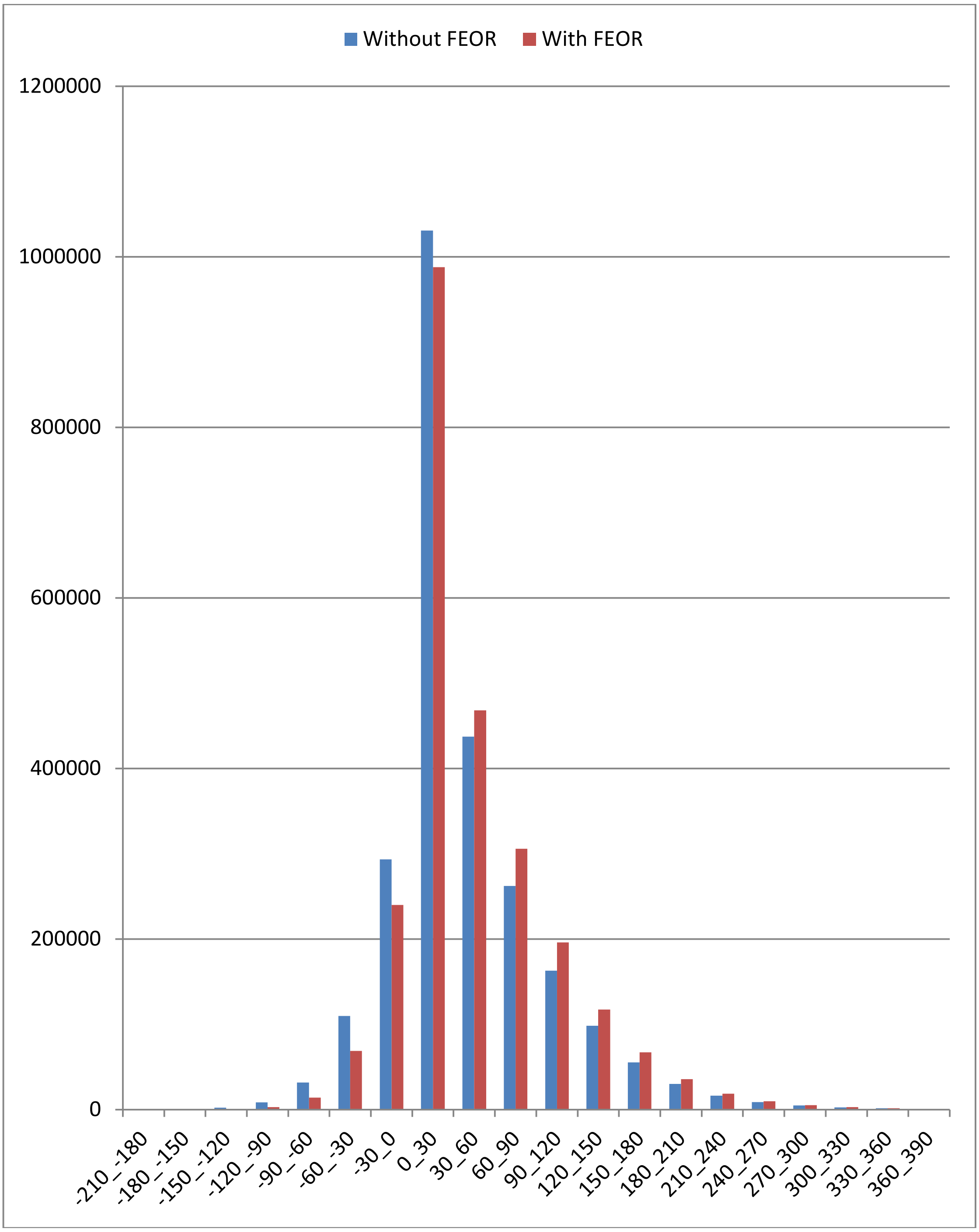


Figure 13 Distribution of realized - planned start times of elective patients in the base scenario over a 10 year time span. The values shown are a sum of the results for the different slack allocation methods. Only with and without FEOR are separated.

Only a certain amount of OR's are allowed to work more overtime than this norm (D = 5 in this research). When D OR's are already expected to work more than the norm in overtime, elective treatment on other OR's is cancelled when it is expected to exceed the norm as well (section 2.3.3). Emergency operations however are never cancelled. Therefore it is possible for more than D OR's to work more than the norm in overtime.

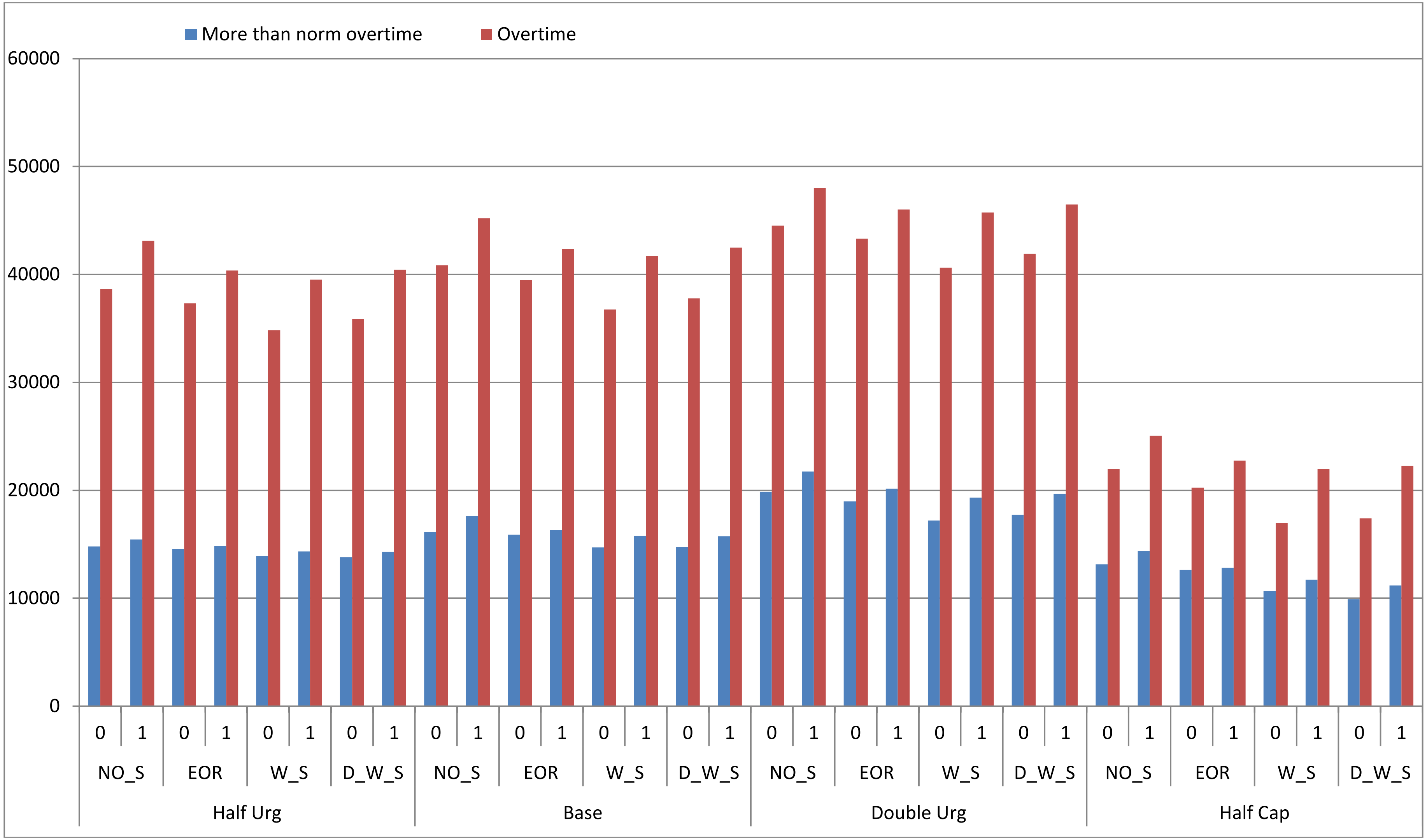


Table 19 Number of OR's with (more than the accepted) overtime for each configuration

Table 19 shows both the number or OR's working overtime and the number of OR's working more than the norm in overtime for each of the configurations.
Taking into account that in the first 3 scenarios at most 20*2600 = 52000 OR's can work overtime while in the 4th scenario only 10*2600 = 26000 OR's can work overtime, a quick look at Table 19 reveals that working overtime is not a rarity but rather common. This is understandable, since only OR's doing nothing at t = 480 are not making overtime. Doing nothing is only possible when all the planned surgeries are finished and no emergency patients are waiting making this, especially in a system focused on effectiveness, a rare occurrence.
Increasing the arrival rate of emergency patients increases the amount of emergency patients to be treated, reducing the probability of an OR able to do nothing even more. This corresponds to the trend visible in Table 19, showing a growth in OR's working overtime with the increase of emergency arrival rate.
Due to the above mentioned facts, the amount of OR's working more than the norm in overtime is much more interesting than just the amount of OR's working overtime. The blue colored bars in Table 19 show this value for the different configurations. Between the different slack allocation methods, White spots and Department wide slack seem to perform best. Spreading slack and with that emergency treatment over different OR's is apparently a good way of reducing the amount of OR's making much overtime. Addition of the FEOR method results in a small increase of OR's making more than the norm overtime. The size of this increase is rather small considering the fact that 8 hours within the OR-department are spent on doing nothing rather than treating patients.

↓ compared to →	FEOR Yes/No	No slack	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Y/N	-	No	Yes	No	Yes	No	**Yes**	No	Yes
No slack	No	0,0	-5,2	+3,0	+1,5	**+7,8**	+4,5	+6,3	+3,4
No slack	Yes	+5,5	0,0	+8,7	+7,2	**+13,8**	+10,3	+12,2	+9,1
EOR	No	-2,9	-8,0	0,0	-1,4	**+4,7**	+1,4	+3,2	+0,4
EOR	Yes	-1,5	-6,7	+1,4	0,0	**+6,2**	+2,9	+4,7	+1,8
White spots	No	**-7,3**	**-12,1**	**-4,5**	**-5,8**	**0,0**	**-3,1**	**-1,4**	**-4,1**
White spots	**Yes**	-4,3	-9,3	-1,4	-2,8	**+3,2**	0,0	+1,7	-1,0
Dep. wide s.	No	-5,9	-10,8	-3,1	-4,5	**+1,5**	-1,7	0,0	-2,7
Dep. wide s.	Yes	-3,3	-8,4	-0,4	-1,8	**+4,3**	+1,0	+2,8	0,0

Table 20 Difference in the total amount of overtime in terms of percentages (base scenario)

5.1.6 Amount of overtime (total and average)

In this subsection the total and average amounts of overtime in minutes will be studied. Table 20 shows the differences in the total amount of overtime in terms of percentages for the base case. White spots without FEOR is here the best performing planning method followed by Department wide slack without FEOR. These two slack allocation methods with FEOR still outperform any of the other planning methods. Again overtime seems best reduced by allocating slack to multiple OR's.
This phenomenon is again visible in Figure 14 for both the total and average overtime, for all of the four different scenarios. The addition of the FEOR method seems to increase the

amount of overtime, although by an acceptable amount compared to the other planning methods.

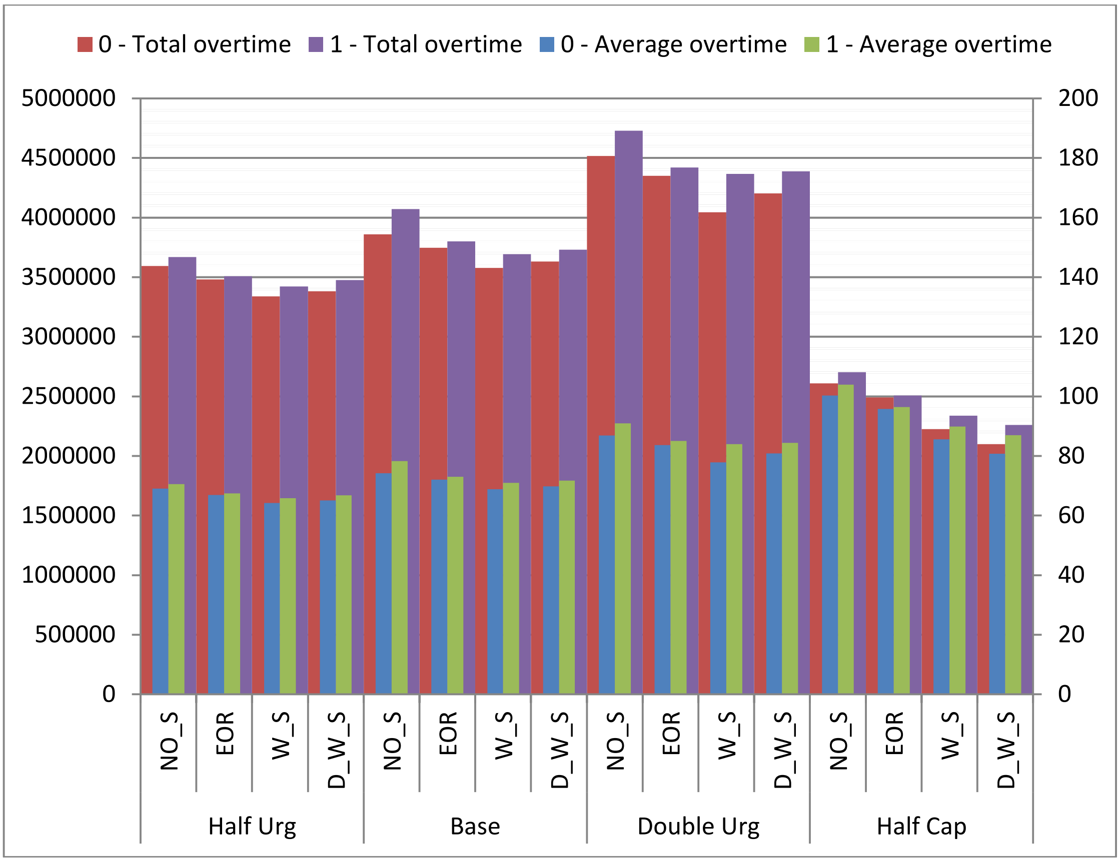


Figure 14 Total and average amount of overtime in minutes for the different configurations.

Figure 15 provides an even clearer image of the influence of the different scenarios on the total and average overtime. Increasing emergency arrival rates, increases the amount of overtime both total and average.

↓ compared to →	FEOR Yes/No	No slack	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Y/N	-	No	Yes	No	Yes	No	**Yes**	No	Yes
No slack	No	**0,0**	**+0,5**	**+3,3**	**+3,5**	**+1,9**	**+2,4**	**+0,9**	**+1,1**
No slack	Yes	**-0,5**	0,0	+2,8	+3,0	+1,4	+1,9	+0,4	+0,6
EOR	No	**-3,2**	-2,8	0,0	+0,2	-1,4	-0,9	-2,3	-2,2
EOR	Yes	**-3,4**	-2,9	-0,2	0,0	-1,6	-1,1	-2,5	-2,3
White spots	No	**-1,8**	-1,4	+1,4	+1,6	0,0	+0,5	-0,9	-0,8
White spots	**Yes**	**-2,3**	-1,9	+0,9	+1,1	-0,5	0,0	-1,4	-1,3
Dep. wide s.	No	**-0,9**	-0,4	+2,4	+2,5	+0,9	+1,5	0,0	+0,1
Dep. wide s.	Yes	**-1,0**	-0,6	+2,2	+2,4	+0,8	+1,3	-0,1	0,0

Table 21 Difference in #surgeries performed in terms of percentages (base scenario)

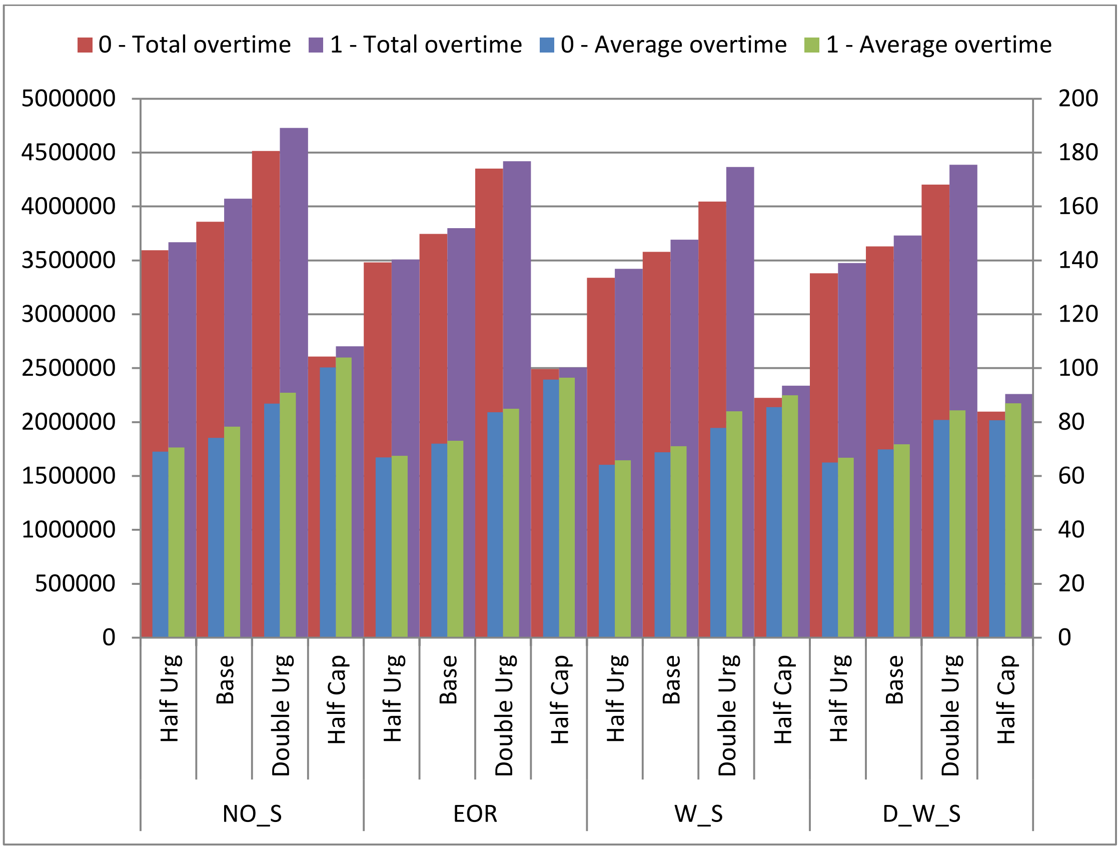


Figure 15 Total and average amount of overtime in minutes for the different configurations.

5.1.7 Utilization and throughput

Last but not least, the KPI's concerning utilization and throughput will be discussed. As shown in section 2.8, utilization is expressed in the percentage of the total time spent on performing actual surgeries. Throughput is expressed by the sum of elective and emergency patients served.

↓ compared to →	FEOR Yes/No	No slack	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Y/N	-	No	Yes	No	Yes	No	Yes	No	Yes
No slack	No	0,0	+0,6	+3,0	+3,2	+1,7	+2,4	+0,9	+1,4
No slack	Yes	-0,6	0,0	+2,4	+2,6	+1,2	+1,8	+0,4	+0,8
EOR	No	-2,9	-2,3	0,0	+0,2	-1,2	-0,6	-2,0	-1,6
EOR	Yes	-3,1	-2,5	-0,2	0,0	-1,4	-0,8	-2,2	-1,7
White spots	No	-1,7	-1,2	+1,2	+1,4	0,0	+0,6	-0,8	-0,4
White spots	Yes	-2,3	-1,7	+0,6	+0,8	-0,6	0,0	-1,4	-1,0
Dep. wide s.	No	-0,9	-0,4	+2,0	+2,2	+0,8	+1,4	0,0	+0,4
Dep. wide s.	Yes	-1,4	-0,8	+1,6	+1,8	+0,4	+1,0	-0,4	0,0

Table 22 Difference in effective use of total time in terms of percentages (base scenario)

Table 21 show the differences in throughput in terms of percentages between the different planning methods in the base scenario. No slack with and without FEOR are here the top performers as can be expected of a slack allocation method with no slack allocated versus slack allocation methods that do allocate slack. More surprising is the observation that department wide slack with FEOR performs only 1% less surgeries than No slack without FEOR and just 0,6% less surgeries than No slack with FEOR. All the benefits of these planning methods seem to come at a “marginal” cost.
Table 22 shows the difference in utilization between the different planning methods in the base scenario. The same observations as described above can be made here. The biggest difference visible is 3,2% utilization, which is smaller than some of the current differences between Dutch UMC’s (E. van Veen-Berkx, 2012). Table 23 and Table 24 demonstrate these small differences again. A slightly growing trend can be observed when the arrival rates of emergency patients is increased in both utilization and throughput. This effect is highest when Emergency-OR is used as a slack allocation method.
Using the FEOR method reduces the utilization as is expected when keeping OR’s unused for 8 hours a day. However, these effects are way smaller than what could be expected when not using 5% (8 hours out of 8*20) of the available OR time.

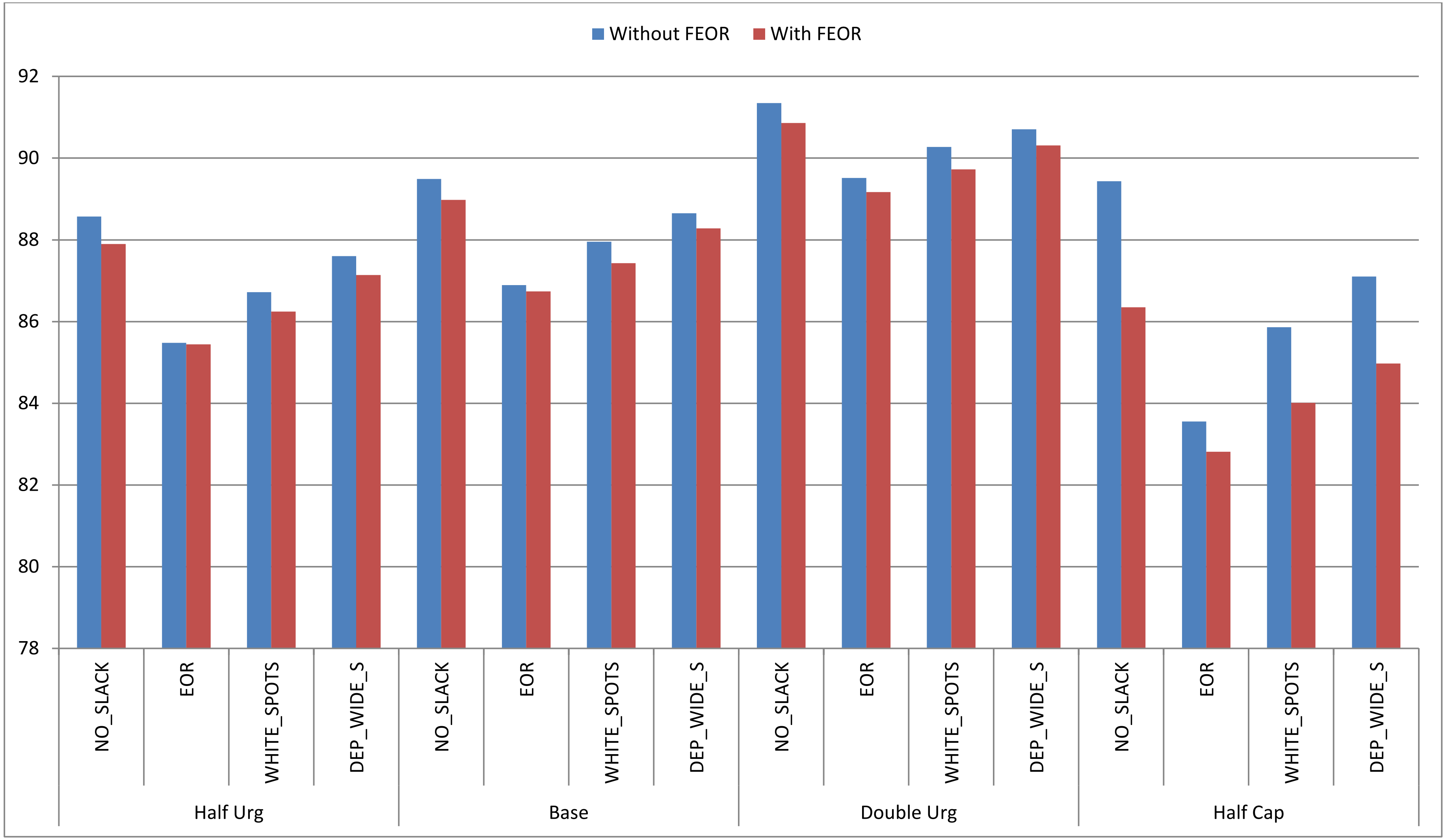


Table 23 Utilization in percentages for each configuration

Table 24 Throughput per configuration in number of performed surgeries

6 Conclusions, discussion and recommendations for further research

6.1 Conclusions

As a summary of the data analysis conducted in section 5, the results for each of the different KPI's of the different configurations is given in Table 26. Instead of values, the results are shown as +, ~ and - signs. The + sign means the score for this configuration at the according KPI is one of the three best performing combinations of slack allocation method with or without FEOR in the given scenario. The – sign represents it is one of the three worst performing configurations in the corresponding scenario for the given KPI. The ~ represents the remaining configurations for the given scenario at the given KPI, the ones with an average performance so to say.
The different KPI's can be subdivided into categories. Here the following categories are distinguished:

- Waiting time for emergency patients
- Number of emergency patients served outside the associated norm
- Number of Cancellations
- Delay in the start times of elective patients
- Overtime related KPI's
- Output related KPI's

For each category the performance on the different KPI's can be summed up. When the category contains more +'s than –'s the sum is a +. In the same way when the category contains more –'s than +'s the sum is a -. When the number of +'s and –'s is equal or the category contains only ~'s the sum is a ~. Performing this summation per category results in a +, ~ or – per category.
Assuming each category has the same weight, the last column represents the overall performance, calculated by summing up the results per category in the following way: Counting a + as the value 1, a – as the value -1 and a ~ as the value 0. Summing those values up results in the total value shown in the last column.
When the total scores of each different planning method are summed over the different scenarios subsequently, Table 25 is the result. Note that:

- Adding the FEOR method has a positive (+8) influence on the No slack method where as it has a very negative influence on the White spots method (-8).
- Using this weight function, marks Emergency-OR without FEOR as the best planning method. Department wide slack with FEOR is a close second.

This is just one way of summarizing the results in the data analysis.

Configuration	*.1.0	*.1.1	*.2.0	*.2.1	*.3.0	*.3.1	*.4.0	*.4.1
Summed total	-8	0	5	-3	1	-2	2	3

Table 25 Summed total scores for the different configurations

Configuration	Average waiting time for emergency patients of type			Number of emergency patients served outside the associated norm of type			Number of cancellations	Delay in the start times of elective surgery	Total amount of overtime	Average overtime /day / OR	Number of OR's with		Utilization	Throughput	Total
	A	B	C	A	B	C					overtime	>norm overtime			
1.1.0	-	-	~	~	-	~	-	+	-	-	~	-	+	+	-2
1.1.1	+	+	-	~	~	~	-	+	-	-	-	-	+	+	1
1.2.0	~	~	+	~	~	~	~	~	~	~	+	~	-	-	1
1.2.1	+	+	-	~	~	~	-	+	-	-	-	-	-	-	-1
1.3.0	-	-	+	~	-	~	+	~	+	+	+	+	~	~	0
1.3.1	+	~	~	~	-	~	~	-	+	+	~	~	-	-	-1
1.4.0	-	-	+	~	~	~	+	-	+	+	+	+	+	+	1
1.4.1	~	+	-	~	~	~	+	-	~	~	-	+	~	~	0
2.1.0	-	-	~	~	-	~	-	+	-	-	~	-	+	+	-2
2.1.1	+	~	-	~	-	~	-	+	-	-	-	-	+	+	-1
2.2.0	~	~	+	~	+	~	-	~	~	~	+	~	-	-	1
2.2.1	~	+	-	~	~	~	~	+	-	-	-	-	-	-	-1
2.3.0	-	-	+	~	~	~	+	~	+	+	+	+	~	~	1
2.3.1	+	+	~	~	-	~	~	-	+	+	~	~	-	-	-1
2.4.0	-	-	+	~	-	~	+	-	+	+	+	+	+	+	0
2.4.1	+	+	-	~	+	~	+	-	~	~	-	+	~	~	2
3.1.0	-	~	~	~	-	~	-	+	-	-	~	-	+	+	-2
3.1.1	+	+	-	~	-	~	-	+	-	-	-	-	+	+	0
3.2.0	~	-	+	~	+	~	~	~	+	+	+	+	-	-	1
3.2.1	+	+	-	~	+	~	-	+	-	-	-	-	-	-	0
3.3.0	-	-	+	~	~	~	~	~	+	+	+	+	~	~	0
3.3.1	+	~	~	~	+	~	+	-	~	~	~	~	-	-	1
3.4.0	-	-	+	~	-	~	+	-	+	+	+	+	+	+	0
3.4.1	~	+	-	~	~	~	+	-	~	~	-	~	~	~	-1
4.1.0	-	-	~	~	-	~	-	+	-	-	~	-	+	+	-2
4.1.1	+	+	-	~	-	~	-	+	-	-	-	-	+	+	0
4.2.0	~	~	+	~	+	~	~	~	~	~	+	~	-	-	2
4.2.1	~	+	-	~	+	~	-	+	-	-	-	-	-	-	-1
4.3.0	-	-	+	~	-	~	+	~	+	+	+	+	~	~	0
4.3.1	+	+	~	~	~	~	~	-	~	~	~	~	-	-	-1
4.4.0	-	-	+	~	~	~	+	-	+	+	+	+	+	+	1
4.4.1	+	~	-	~	~	~	+	-	+	+	-	+	~	~	2

Table 26 Summary of the performance of the different configurations for each of the researched KPI's

Looking at which planning methods perform best at multiple of the more relevant KPI's, the following two stand out:

- No slack & FEOR (Waiting time, Overtime, Utilization, Throughput)
- Department wide slack & FEOR (Waiting time, Cancellations, Delay in start times)

No slack	Without FEOR	With FEOR	FEOR effect
Mean waiting time A min.	5,82	0,23	-96,06%
Mean waiting time B min.	39,65	2,88	-92,73%
Mean waiting time C min.	173,44	213,08	+22,86%
Outside norm A	0	0	0%
Outside norm B	5	2	-60% (-3)
Outside norm C	0	0	0%
#surgeries performed	19580	19489	-0,46%
Cancellations	2976	3084	+3,60%
Overtime min.	385790	407165	+5,54%
Effective use of total time	89,49	88,98	-0,57%
Emergency-OR	Without FEOR	With FEOR	FEOR effect
Mean waiting time A min.	2,42	0,29	-88,14%
Mean waiting time B min.	10,34	2,35	-77,31%
Mean waiting time C min.	165,90	193,16	+16,43%
Outside norm A	0	0	0%
Outside norm B	0	1	(+1)
Outside norm C	0	0	0%
Total surgeries performed	18953	18924	-0,15%
Cancellations	2542	2534	-0,31%
Overtime min.	374656	379915	+1,40%
Effective use of total time	86,89	86,74	-0,18%
White spots	Without FEOR	With FEOR	FEOR effect
Mean waiting time A min.	5,15	0,21	-95,95%
Mean waiting time B min.	35,38	2,90	-91,81%
Mean waiting time C min.	124,96	187,91	+50,37%
Outside norm A	0	0	0%
Outside norm B	1	2	+100% (+1)
Outside norm C	0	0	0%
Total surgeries performed	19222	19125	-0,51%
Cancellations	2274	2283	+0,40%
Overtime min.	357786	369309	+3,22%
Effective use of total time	87,96	87,43	-0,60%
Department wide slack	Without FEOR	With FEOR	FEOR effect
Mean waiting time A min.	5,45	0,37	-93,21%
Mean waiting time B min.	36,95	2,71	-92,66%
Mean waiting time C min.	151,63	201,10	+32,63%
Outside norm A	0	0	0%
Outside norm B	2	0	-100% (-2)
Outside norm C	0	0	0%
Total surgeries performed	19403	19375	-0,14%
Cancellations	2070	2128	+2,79%
Overtime min.	362998	373128	+2,79%
Effective use of total time	88,65	88,28	-0,42%

Table 27 Effect of the FEOR method for different slack allocation methods on different KPI's

No slack & FEOR is standing out in most of the KPI's related to effective use of the OR-department while performing in an acceptable manner on the customer satisfaction related KPI's due to the addition of the FEOR method.
Department wide slack & FEOR is more focused on the customer satisfaction related KPI's while still performing acceptable on the effective use related KPI's due to the smart allocation and usage of the slack time that comes with department wide slack combined with the FEOR method.

6.1.1 Effect of the FEOR method

Table 27 summarizes the effect of the FEOR method on the different slack allocation methods concerning most of the KPI's in scope for this research. It is time to answer the question:

"Is using the FEOR method improving OR-department planning?"

To do so, let us take a closer look at the contents of Table 27:

- Concerning waiting time of the more urgent patients, the FEOR method is a big improvement. Although waiting times are already acceptable, using the FEOR method reduces them to close to 0 for emergency patients type A and B.
- The influence of the FEOR method on the number of patients served outside the norm is not clear. For now it is assumed that the FEOR method is not influencing this value.
- The total number of surgeries performed decreases with a maximum of 0,51% over the different slack allocation methods. This corresponds to a decrease of 90 served patients on a yearly basis.
- The number of cancellations slightly increases which relates partly with the decrease in patients served. If the same number of patients is planned but less patients are served, automatically more are cancelled.
- The amount of overtime increases with a maximum of 5,54% over the different slack allocation methods. This corresponds to an increase of 10.000 - 20.000 minutes of overtime on a yearly basis, which is the equivalent of 2 – 4 minutes of extra overtime per OR per day.
- Following from less served patients combined with more overtime, automatically the utilization rate decreases. Over the different slack allocation methods a maximum of -0,60% utilization can be observed.

As it turns out, whether or not using the FEOR method is a good idea is a tradeoff between efficiency and customer satisfaction. The FEOR method involves reduces waiting times for emergency patients A and B making sure even the most urgent patients can be served in time. The costs at which this advantage comes are 10.000 – 20.000 extra minutes of overtime and 90 less performed surgeries on a yearly basis. Costs for this could be calculated when the cost of overtime and the profit a performed surgery generates would be known. This tradeoff is nothing new, but a well-known phenomenon within healthcare and operations research. It is better known under the name 'multiple-criteria decision-making' or 'multiple-criteria decision analysis (MCDA)'. Figure 16 is a visualization of this tradeoff. Given certain lower bounds for efficiency and customer satisfaction this leaves a certain space to maneuver (orange marked area in Figure 16). The decision to use the FEOR method can be seen as being part of this maneuver space.

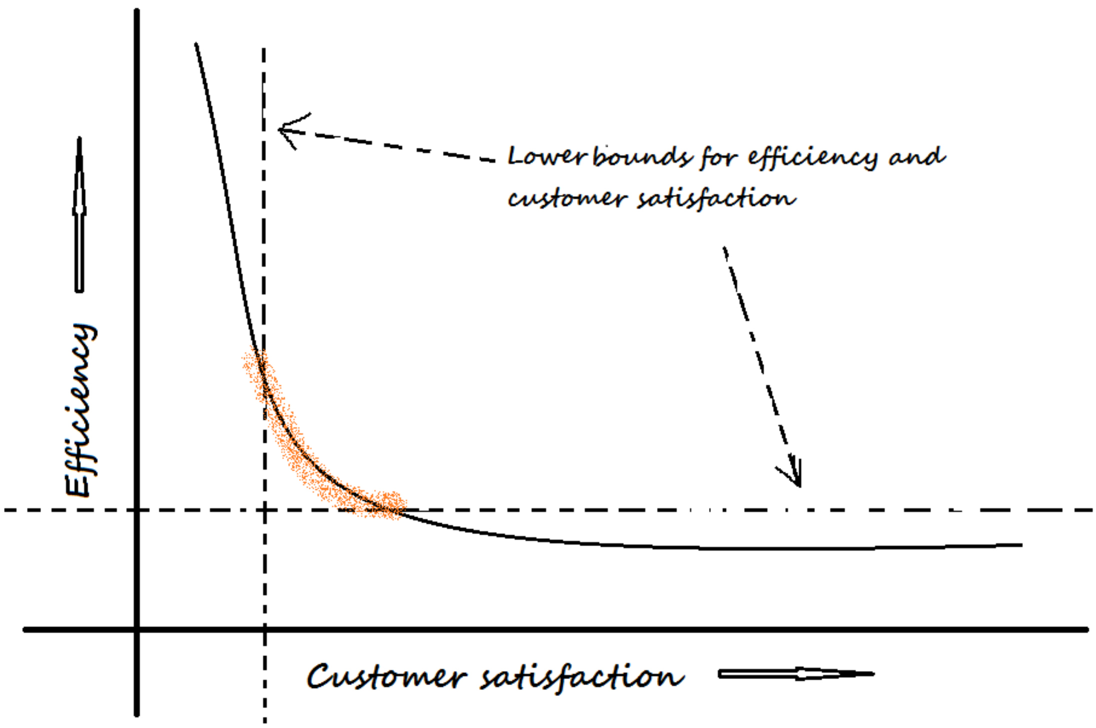


Figure 16 Visualization of the tradeoff between efficiency and customer satisfaction

6.1.2 Room for improvement

Currently No slack without FEOR and Emergency-OR without FEOR are the most used planning methods within Dutch hospitals. Because of this fact, it is interesting to see how the other methods perform in comparison to these methods. To simplify this process, Tables 28 and 29 show the performance differences between the other planning methods in reference to these methods.

	No slack	No slack	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Yes/No	No	Yes	Yes	No	Yes	No	Yes
E[W] type A	+172,07	-89,01	-87,51	+123,39	-90,81	+151,39	-87,30
E[W] type B	+266,87	-75,35	-80,12	+222,27	-77,03	+237,56	-77,40
E[W] type C	+1,44	+26,84	+14,88	-24,70	+12,47	-10,47	+20,71
#Surgeries	+3,54	+3,15	-0,03	+1,74	+1,55	+2,70	+2,10
#Cancellations	+17,00	+21,06	+0,57	-8,45	-9,23	-17,76	-15,81
Overtime	+2,69	+6,66	+1,80	-7,23	-1,91	-4,35	-0,68
Utilization	+3,36	-0,16	-1,55	+1,14	-1,58	+2,16	-0,97

Table 28 Emergency-OR as reference

So let's say a hospital is currently using Emergency-OR as planning method. According to Table 28 there are two directions in which this hospital could improve. The first direction is by

switching to either White spots or Department wide slack (both without FEOR). This choice will result in a higher utilization rate by performing more surgeries in combination with less overtime and less cancellations. This change comes at the cost of higher waiting times but as mentioned in sections 5.1.1 and 5.1.2, the waiting times will still be acceptable and emergency patients will still be treated inside the norm.
The second direction of improvement is by switching to either White spots & FEOR or Department wide slack & FEOR. This change will results in more instant service of arriving emergency patients, less cancellations and less overtime. Additional cost is a decrease in surgeries performed resulting in a lower utilization.
It is up to the management of the hospital in question to decide which, if any direction is more in line with their long term vision for the hospital and whether the benefits are larger than the costs.

	No slack	Emergency-OR	Emergency-OR	White spots	White spots	Department wide slack	Department wide slack
FEOR Yes/No	No	Yes	Yes	No	Yes	No	Yes
E[W] type A	-95,96	-63,25	-95,41	-17,89	-96,62	-7,60	-95,33
E[W] type B	-93,28	-72,74	-94,58	-12,16	-93,74	-7,99	-93,84
E[W] type C	+25,03	-1,42	+13,25	-25,77	+10,88	-11,74	+19,00
#Surgeries	-0,38	-3,41	-3,45	-1,74	-1,92	-0,81	-1,39
#Cancellations	+3,47	-14,53	-14,04	-21,75	-22,42	-29,71	-28,05
Overtime	+3,86	-2,62	-0,87	-9,66	-4,49	-6,86	-3,28
Utilization	-3,40	-3,25	-4,75	-2,14	-4,78	-1,15	-4,19

Table 29 No slack as reference

Now assume a hospital is currently using No slack as their planning method. Again every change will bring costs. This time in the form of surgeries performed and utilization since No slack is absolutely superior in this regard. Good alternative options, bringing only marginal costs, are each and every combination of the slack allocation method (excluding No slack) with or without the addition of FEOR.

6.1.3 BOTE versus Simulation results

So how do the simulation results align with the expectations resulting from the BOTE-analysis? That question will be answered in the remainder of this section. For each of the eight planning methods the mathematically analyzed KPI's will be compared. How does each of the planning methods perform relative to the others? And does this match with the simulation results in the base scenario. Instead of doing this method by method, this will be done per KPI.

6.1.3.1 Waiting time of emergency patients

As shown in Table 11, the expressions for the expected waiting times of the different planning methods are closely related according to the BOTE-analysis conducted in section 3.
Waiting times for any slack allocation method combined with the FEOR method are expected to be the same. Figure 12 shows the same equality between the waiting times within the results of the different slack allocation methods combined with the FEOR method. Both

analyses confirm the great performance of the FEOR method when it comes to waiting times of the emergency patients.
As with the slack allocation methods combined with FEOR, for the methods without FEOR the BOTE-analysis comes up with closely the same expected waiting times. For Emergency-OR however the expression for the expected waiting time deviates from the other three. The BOTE-analysis predicts Emergency-OR to perform better on expected waiting times for emergency patients. All of this is again supported by the simulation results in Figure 12.

6.1.3.2 Cancellations

For each of the slack allocation methods, the BOTE-analysis predicts more cancellations when the FEOR method is added. Furthermore it suggests No slack to have the most cancellations and department wide slack the least.
All of these expectations are confirmed in Table 16 and match the simulation results.

6.1.3.3 Overtime

Assuming that overtime is made, the BOTE-analysis predicts a small increase in overtime when the FEOR method is added. No slack has the highest expected amount of overtime while White spots is here suggested the method with the least overtime. How Emergency-OR and department wide slack relate to each other is hard to say without filling in values for the different variables.
Again, these expectations match the results of the simulation runs. This is shown in Figure 14.

6.1.3.4 Utilization

From the BOTE-analysis it is clear that No slack is expected to result in the highest utilization rate, followed by department wide slack. Again, how Emergency-OR and department wide slack relate to each other is hard to say.
Table 23 confirms the high utilization rates for no slack and department wide slack, visualizing the results of the simulation runs.

6.1.3.5 Bottom line

From the BOTE-analysis it becomes clear that there is no obvious best performing planning method. Which method is best heavily depends on the weight of the different KPI's as is mentioned earlier. Department wide slack & FEOR performs decently on all four of the KPI's discussed and could therefore be a safe pick. This matches with the improvements suggested in section 6.1.2.

6.2 A practical perspective

As soon as the results of the data analysis as conducted in section 5 were clear, they were sent around as a one-pager (Appendix C) to a couple of people who might find them interesting. Following up on positive reactions, multiple interviews with different interviewees were conducted (Appendix B). These interviews were held to shine light on the following issues:

- What is the weight of the different KPI's?
- Which KPI's will be decisive when it comes to choosing a configuration?
- Is the FEOR method an improvement relative to the currently used planning methods?

- What practical hurdles have to be overcome when implementing the FEOR method in an actual OR-department?

In the following subsections these issues will be discussed. Arguments used in these discussions stem from the interviews or literature. In the latter case a reference to the article will be given if possible. Rather than handling them one by one, the first subsection will roughly cover the first three issues. The second subsection is dedicated to the fourth and last issue.

6.2.1 Weight functions

In many related and similar studies the authors come up with a weight function depending on the relative importance of the different KPI’s. This weight function then is used to decide which of the researched methods or configurations works best. The function is often based on interview results (Adan et al., 2011; De Keijzer, 2014) or costs. These weight functions are needed since there is almost never a configuration that performs best at all KPI’s. This research is no exception to this rule as is shown in 6.1.2.
From the conducted interviews it became clear that different hospitals have different focuses when it comes to KPI’s. It depends a lot on how well OR-departments are already performing. As visualized in Figure 16, first a certain lower bound for both effectiveness and customer satisfaction needs to be reached. When one of these lower bounds is not satisfied yet, the hospital will mainly focus on KPI’s that are the cause of this. As soon as both lower bounds are fulfilled, it is up to the management of the hospital where in the “orange” area they want to be. This decision can depend on where other, related hospitals are standing. Does management wants to mirror a certain “example” hospital that has a good reputation or is there some niche in the market in which they want to jump.
All of the above is of influence when deciding whether or not the FEOR method is a good fit for a certain hospitals OR-department. The content of this thesis could and should be a starting point for a similar type of discussion in any hospital.

6.2.2 Practical hurdles

Let’s assume that the FEOR method is going to be implemented in the daily planning of an actual OR-department. This subsection will discuss practical hurdles that have to be taken before such an implementation can be realized.
The FEOR method, in combination with all slack allocation methods but mostly with No slack and Department wide slack, spreads emergency surgeries through the whole OR department. In case of emergency patients of type A and B this is mostly done without taking into account the required specialism for a the emergency surgery in case and whether or not the personnel of a certain OR can perform this surgery. During the interviews this turned out to be the biggest practical hurdle concerning the FEOR method. Especially since the trend in healthcare is going to more and more specialization.
A solution to this problem would be, to have a specialized trauma team follow the FEOR through the OR-department. Taking over the OR that gets marked FEOR to perform possible needed emergency surgeries that cannot be performed by the originally assigned personnel of that particular OR. However, the interviews conducted showed that not the operation rooms, but the assigned staff is the most expensive asset of an OR-department. Therefore having an extra trauma team running around the whole day occasionally performing an emergency surgery that could not be performed by the available s is a very expensive solution.

From this can be concluded that the FEOR method would be a great solution for hospitals where space is the bottleneck. Take for example hospitals that are undergoing construction as did S.T.A.R. labs.
On the other hand, when using an emergency-OR the right specialist for the arrived emergency patient is always called from somewhere. Whether he or she was treating another less urgent patient, finishing up some administrative work or walking his or her round along his or her patients, a specialist for the job can always be found. With the same ease a specialist could be allocated to the FEOR if needed, where the specialist currently occupying the FEOR could even resume the work the needed specialist was conducting.
Another practical hurdle not to be underestimated is the culture change that is needed when implementing the FEOR method. The FEOR method is a strange phenomenon for many people, since precious time is wasted by holding an OR when elective patients could be served. That this has positive effects for the performance of the whole OR-department is hard to explain.

6.3 Suggestions for further research

Within this section, two types of suggestions for further research are given. The first type concerns further research into the FEOR method, such as angles that were out of scope for this project but can further clarify the right conditions in which to use the FEOR method.
The second type of suggestions for further research, are ideas that arose while conducting this research and later during the interviews and are more of a general nature.

6.3.1 Further research into the FEOR method

This research tested the FEOR method in combination with different slack allocation methods, in two different sizes of hospitals and with three levels of emergency arrival rates. This may seem a lot, but there are a lot of variables kept fixed that could be varied. Some of them may have a big effect on the performance of the FEOR method. Although not all of these variations would be as interesting as the ones performed in this research, some of them stand out and would be an addition to the already performed research. Two examples:

- Within this research the patient group is based on the patient group of S.T.A.R. labs. While this patient group is a good representation for the patient group of each of the eight Dutch academic hospitals, it differs a lot from the patient groups treated at for example non-academic hospitals or non-Dutch hospitals. It would be interesting to see how the FEOR method performs within these different configurations, especially since some of the patient groups futures (high complexity of needed surgery resulting in long surgery durations and specialization) seem to be a disadvantage for the FEOR method.
- Another important factor influencing the performance of the FEOR method, is the chosen planning policy. During this research the planning policy of S.T.A.R. labs is used in every configuration (section 2.7). A different planning policy could have major impact on the results.

Although a lot of KPI's are measured, even more are not considered in this research and not measured within the current simulation code. This does not mean they are uninteresting. Most of them are not interesting for the hospital as a whole, but could be interesting for the person responsible for a certain specialism. Some examples:

- What percentage of emergency surgery is performed in the allocated slack time/on the OR's that slack is allocated to. Is allocated slack used for its intended purpose?
- How many emergency surgeries are performed on each OR and how much of the emergency surgeries are performed by each specialism.

The two given examples are related in some sense. They both try to figure out how the emergency patients are distributed over the OR-department and over the OR schedule. Where this research focused more on the slack allocation and less on the actual scheduling of the distinct procedures. A research more in this direction could answer these questions and show the impact of the FEOR method in more detail over the day.

6.3.2 Suggestions of a more general nature

This research is like many of its kind focused at planning optimization within the OR-department as a whole. This "broadness" comes at a price, as assumptions need to be made that quickly reduce the practical viability of the results. The same kind of research but then focused at subsets of the OR-department, such as OR's assigned to the same specialism or to a subset of the specialisms, make most of the earlier mentioned assumptions unnecessary thereby increasing the practical usability.
Related to the suggestion made above is research focused on a single type of emergency patient. Each type of emergency patient may have an own optimal set of planning rules. Research concerning these rules would be of much use for many of the Dutch UMC's.

According to many of the interviewees, the research topic that could impact the effectiveness of OR-scheduling the most is that on planned surgery durations. Currently planned surgery durations are based for example on the average duration of the last ten surgeries of the same type. Some hospitals use specialist opinions for determining a planned surgery duration. Much can be gained by further investigating ways of better predicting these durations (Stepaniak et al., 2010). Not just the type of surgery could be used, but for example age, gender and weight of both patient and specialist could influence this approximation. It is not hard to imagine that experience of the specialist plays a role as well. Much can be gained from more accurate planned surgery durations.

Overall there is much interest in a more mathematical approach to the OR-department. Still too few scheduling decisions within the OR-department are based on mathematics. A simple dashboard of the current state of each ongoing surgery or just the amount of time an OR is ahead or behind its schedule could help these decisions greatly.

Bibliography

Adan, I., Bekkers, J., Dellaert, N., Jeunet, J., & Vissers, J. (2011). Improving operational effectiveness of tactical master plans for emergency and elective patients under stochastic demand and capacitated resources. *European Journal of Operational Research*, *213*, 290–308.

Anthony, R. N. (1965). *Planning and Control Systems: A Framework for Analysis* (p. 180).

Barlow, A. P., Wilkinson, D. A., Wordsworth, M., & Eyre-Brook, I. A. (1993). An emergency daytime theatre list: utilisation and impact on clinical practice. *Annals of the Royal College of Surgeons of England*, *75*, 441–444.

Brasel, K. J., Akason, J., & Weigelt, J. A. (1998). Dedicated operating room for trauma: a costly recommendation. *Journal of Trauma-Injury Infection & Critical Care*, *44*(5), 832–838.

Broyles, J. R., Cochran, J. K., & Montgomery, D. C. (2010). A statistical Markov chain approximation of transient hospital inpatient inventory. *European Journal of Operational Research*, *207*, 1645–1657.

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

Cayirli, T., & Veral, E. (2003). Outpatient Scheduling in Health Care: a Review of Literature. *Production and Operations Management*, *12*(4), 519–549.

De Keijzer, T. (2014). *Operating room planning and scheduling for non-elective patients* (p. 80).

Delesie, L. (1998). Bridging the gap between clinicians and health managers. *European Journal of Operational Research*, *105*, 248–256.

Dellaert, N., & Jeunet, J. (2013). *Pareto optimal strategies for improved operational plans of elective patients under multiple constrained resources* (p. 25).

Demeulemeester, E., & Beliën, J. (2007). Building cyclic master surgery schedules with leveled resulting bed occupancy. *European Journal of Operational Research*, *176*(2), 1185–1204.

Denton, B. T. (2013). *Handbook of Healthcare Operations Management* (p. 536).

Dexter, F., Macario, A., & Traub, R. D. (1999). Optimal sequencing of urgent surgical cases. *Journal of Clinical Monitoring and Computing*, *15*, 153–162.

Dibbits, E. (2012). *Optimalisatie planning dagverpleging Atrium MC*.

Drenth, I. M., Jong, S. De, & Koster, D. M. (2012). *Geen OK-tijd te verliezen*.

E. van Veen-Berkx (projectleider Benchmarking OK), prof. dr. G. K. (voorzitter hoofdredactie Nt. (2012). Benchmarking maakt prestaties op de OK transparant. *Nederlands Tijdschrift Voor Heelkunde*, *21*(4), 177 – 180.

Gerchak, Y., Gupta, D., & Henig, M. (1996). Reservation Planning for Elective Surgery under uncertain demand for emergency surgery. *Management Science*, *42*(3), 321–334.

Gupta, D., & Denton, B. (2008). Appointment scheduling in health care: Challenges and opportunities. *IIE Transactions*, *40*, 800–819.

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

Harders, M., Malangoni, M. A., Weight, S., & Sidhu, T. (2006). Improving operating room efficiency through process redesign. *Surgery*, *140*, 509–516.

Heng, M., & Wright, J. G. (2013). Dedicated operating room for emergency surgery improves access and efficiency. *Canadian Journal of Surgery*, *56*(3), 167–174.

Houdenhoven, M. (2007). *Healthcare logistics: The art of balance* (p. 281).

Kolker, A. (2012). *Healthcare Management Engineering: What does this Fancy term really mean?* (p. 121).

Lamiri, M., Xie, X., Dolgui, A., & Grimaud, F. (2008). A stochastic model for operating room planning with elective and emergency demand for surgery. *European Journal of Operational Research*, *185*, 1026–1037.

Lamiri, M., Xie, X., & Zhang, S. (2008). Column generation approach to operating theater planning with elective and emergency patients. *IIE Transactions*, *40*(9), 838–852.

Lans, M. van der, Hans, E., Hurink, J., Wullink, G., Houdenhoven, M. van, & Kazemier, G. (2006). *Anticipating urgent surgery in operating room departments* (p. 26).

Lebowitz, P. (2003). Schedule the short procedure first, to improve OR Efficiency. *Aorn Journal*, *78*(4), 651 – 659.

Litvak, N., van Rijsbergen, M., Boucherie, R. J., & Van Houdenhoven, M. (2008). Managing the overflow of intensive care patients. *European Journal of Operational Research*, *185*(3), 998–1010.

Lovett, B. E., & Katchburian, M. V. (1999). Emergency surgery: half a day does make a difference. *Annals of the Royal College of Surgeons of England*, *81*, 62–64.

Matthijssen, I., & Vlieger, E.-J. (2013). *Evaluatie OK-planning in het UMCU: Eindrapport* (p. 38).

Ministerie van VWS, PLEXUS, B. (2010). *Werken aan de zorg*. *Brief aan Tweede Kamer november* (p. 55).

Ozkarahan, I. (2000). Allocation of surgeries to operating rooms by goal programing. *Journal of Medical Systems*, *24*(6), 339–378.

Panayiotopoulos, J., & Vassilacopoulos, G. (1984). Simulating hospital emergency departments queuing systems:(GI/G/m(t)):(IHFF/ N/∞). *European Journal of Operational Research*, *18*, 250–258.

Patrick, J., & Puterman, M. L. (2008). Reducing Wait Times through Operations Research: Optimizing the Use of Surge Capacity. *Healthcare Policy*, *3*(3), 75–88.

Pricker, E. (2011). *The allocation of emergency- and elective patients to operating rooms* (p. 85).

Przasnyski, Z. H. (1986). Operating Room Scheduling: A literature review. *Aorn Journal*, *44*(I), 67–82.

Sickinger, S., & Kolisch, R. (2009). The performance of a generalized Bailey–Welch rule for outpatient appointment scheduling under inpatient and emergency demand. *Health Care Management Science*, *12*, 408–419.

Stepaniak, P. S., Heij, C., & de Vries, G. (2010). Modeling and prediction of surgical procedure times. *Statistica Neerlandica*, *64*(1), 1–18.

Strum, D. P., May, J. H., & Vargas, L. G. (2000). Modeling the Uncertainty of Surgical Procedure Times. *Anesthesiology*, *92*, 1160–1167.

Strum, D. P., Sampson, A. R., May, J. H., & Vargas, L. G. (2000). Surgeon and type of anesthesia predict variability in surgical procedure times. *Anesthesiology*, *92*, 1454–1466.

Van Veen-Berkx, E., Bitter, J., Elkhuizen, S. G., Buhre, W. F., Kalkman, C. J., Gooszen, H. G., & Kazemier, G. (2014). The influence of anesthesia-controlled time on operating room scheduling in Dutch university medical centres. *Canadian Journal of Anaesthesia = Journal Canadien D'anesthésie*, *61*(6), 524–532. doi:10.1007/s12630-014-0134-9

Van Veen-Berkx, E., Elkhuizen, S. G., Kalkman, C. J., Buhre, W. F., & Kazemier, G. (2014). Successful interventions to reduce first-case tardiness in Dutch university medical centers: results of a nationwide operating room benchmark study. *American Journal of Surgery*, *207*(6), 949–959. doi:10.1016/j.amjsurg.2013.09.025

Vissers, J., & Beech, R. (2005). *Health Operations Management: Patient Flow Logistics in Health Care*.

Wullink, G., Houdenhoven, M., Hans, E. W., Oostrum, J. M., Van der Lans, M., & Kazemier, G. (2007). Closing Emergency Operating Rooms Improves Efficiency. *Journal of Medical Systems*, *31*, 543–546.

Wullink, G., Van der Lans, M., van Houdenhoven, M., Hans, E., Hurink, J., & Kazemier, G. (2006). Eén spoed-OK is géén spoed-OK. In *Benchmarking OK - Leren van elkaar* (pp. 165–172).

Yeh, J.-Y., & Lin, W.-S. (2007). Using simulation technique and genetic algorithm to improve the quality care of a hospital emergency department. *Expert Systems with Applications*, *32*, 1073–1083.

Appendix A

Simulation output

The simulation output consists of numerous values. A complete overview of the output is given in Table 30.

Value description	Data type
Calculation time in seconds	Integer
Total time spent on procedures of specialism CAC	Integer
Total amount of performed procedures of specialism CAC	Integer
Average duration for surgeries of specialism CAC	Double
Total time spent on procedures of specialism CHI	Integer
Total amount of performed procedures of specialism CHI	Integer
Average duration for surgeries of specialism CHI	Double
Total time spent on procedures of specialism CHP	Integer
Total amount of performed procedures of specialism CHP	Integer
Average duration for surgeries of specialism CHP	Double
Total time spent on procedures of specialism GYN	Integer
Total amount of performed procedures of specialism GYN	Integer
Average duration for surgeries of specialism GYN	Double
Total time spent on procedures of specialism KNO	Integer
Total amount of performed procedures of specialism KNO	Integer
Average duration for surgeries of specialism KNO	Double
Total time spent on procedures of specialism MND	Integer
Total amount of performed procedures of specialism MND	Integer
Average duration for surgeries of specialism MND	Double
Total time spent on procedures of specialism NEC	Integer
Total amount of performed procedures of specialism NEC	Integer
Average duration for surgeries of specialism NEC	Double
Total time spent on procedures of specialism OOG	Integer
Total amount of performed procedures of specialism OOG	Integer
Average duration for surgeries of specialism OOG	Double
Total time spent on procedures of specialism ORT	Integer
Total amount of performed procedures of specialism ORT	Integer
Average duration for surgeries of specialism ORT	Double
Total time spent on procedures of specialism URO	Integer
Total amount of performed procedures of specialism URO	Integer
Average duration for surgeries of specialism URO	Double
Total time spent on procedures of specialism VAT	Integer
Total amount of performed procedures of specialism VAT	Integer
Average duration for surgeries of specialism VAT	Double
Total amount of OR's with more than the allowed amount of overtime	Integer
Total amount of ORdays making overtime	Integer
Total amount of overtime	Integer
Total amount of cancellations	Integer

Value description	Data type
Mean waiting time of type A emergency patients	Double
Mean nr. of. waiting emergency patients of type A	Double
Amount of emergency patients of type A served	Integer
Amount of emergency patients of type A ignored	Integer
Mean waiting time of type B emergency patients	Double
Mean nr. of. waiting emergency patients of type B	Double
Amount of emergency patients of type B served	Integer
Amount of emergency patients of type B ignored	Integer
Mean waiting time of type C emergency patients	Double
Mean nr. of. waiting emergency patients of type C	Double
Amount of emergency patients of type C served	Integer
Amount of emergency patients of type C ignored	Integer
Total time taken into account	Integer
Total time spent on operations	Integer
Utilization rate	Double
Total change time	Double
Amount of emergency patients of type G served	Integer
Total amount of patients served	Integer
Average time spent per served patient	Double
Amount of times the FEOR changes during the day	Integer
Amount of times the FEOR changes because of an emergency surgery	Integer
Total amount of OR's that is still running at the end of the day	Integer
Number of ORdays assigned to specialism CAC	Integer
Number of ORdays assigned to specialism CHI	Integer
Number of ORdays assigned to specialism CHP	Integer
Number of ORdays assigned to specialism GYN	Integer
Number of ORdays assigned to specialism KNO	Integer
Number of ORdays assigned to specialism MND	Integer
Number of ORdays assigned to specialism NEC	Integer
Number of ORdays assigned to specialism OOG	Integer
Number of ORdays assigned to specialism ORT	Integer
Number of ORdays assigned to specialism URO	Integer
Number of ORdays assigned to specialism VAT	Integer
Amount of overtime made by specialism CAC	Double
Amount of overtime made by specialism CHI	Double
Amount of overtime made by specialism CHP	Double
Amount of overtime made by specialism GYN	Double
Amount of overtime made by specialism KNO	Double
Amount of overtime made by specialism MND	Double
Amount of overtime made by specialism NEC	Double
Amount of overtime made by specialism OOG	Double
Amount of overtime made by specialism ORT	Double
Amount of overtime made by specialism URO	Double
Amount of overtime made by specialism VAT	Double
Average amount of overtime per ORday for specialism CAC	Double
Average amount of overtime per ORday for specialism CHI	Double

Value description	Data type
Average amount of overtime per ORday for specialism CHP	Double
Average amount of overtime per ORday for specialism GYN	Double
Average amount of overtime per ORday for specialism KNO	Double
Average amount of overtime per ORday for specialism MND	Double
Average amount of overtime per ORday for specialism NEC	Double
Average amount of overtime per ORday for specialism OOG	Double
Average amount of overtime per ORday for specialism ORT	Double
Average amount of overtime per ORday for specialism URO	Double
Average amount of overtime per ORday for specialism VAT	Double
Amount of cancellations of specialism CAC	Integer
Amount of cancellations of specialism CHI	Integer
Amount of cancellations of specialism CHP	Integer
Amount of cancellations of specialism GYN	Integer
Amount of cancellations of specialism KNO	Integer
Amount of cancellations of specialism MND	Integer
Amount of cancellations of specialism NEC	Integer
Amount of cancellations of specialism OOG	Integer
Amount of cancellations of specialism ORT	Integer
Amount of cancellations of specialism URO	Integer
Amount of cancellations of specialism VAT	Integer
% of elective patients that gets cancelled of specialism CAC	Double
% of elective patients that gets cancelled of specialism CHI	Double
% of elective patients that gets cancelled of specialism CHP	Double
% of elective patients that gets cancelled of specialism GYN	Double
% of elective patients that gets cancelled of specialism KNO	Double
% of elective patients that gets cancelled of specialism MND	Double
% of elective patients that gets cancelled of specialism NEC	Double
% of elective patients that gets cancelled of specialism OOG	Double
% of elective patients that gets cancelled of specialism ORT	Double
% of elective patients that gets cancelled of specialism URO	Double
% of elective patients that gets cancelled of specialism VAT	Double
#emergency patients type A with specialism CAC	Integer
#emergency patients type A with specialism CHI	Integer
#emergency patients type A with specialism CHP	Integer
#emergency patients type A with specialism GYN	Integer
#emergency patients type A with specialism KNO	Integer
#emergency patients type A with specialism MND	Integer
#emergency patients type A with specialism NEC	Integer
#emergency patients type A with specialism OOG	Integer
#emergency patients type A with specialism ORT	Integer
#emergency patients type A with specialism URO	Integer
#emergency patients type A with specialism VAT	Integer
#emergency patients type B with specialism CAC	Integer
#emergency patients type B with specialism CHI	Integer
#emergency patients type B with specialism CHP	Integer
#emergency patients type B with specialism GYN	Integer

Value description	Data type
#emergency patients type B with specialism KNO	Integer
#emergency patients type B with specialism MND	Integer
#emergency patients type B with specialism NEC	Integer
#emergency patients type B with specialism OOG	Integer
#emergency patients type B with specialism ORT	Integer
#emergency patients type B with specialism URO	Integer
#emergency patients type B with specialism VAT	Integer
#emergency patients type C with specialism CAC	Integer
#emergency patients type C with specialism CHI	Integer
#emergency patients type C with specialism CHP	Integer
#emergency patients type C with specialism GYN	Integer
#emergency patients type C with specialism KNO	Integer
#emergency patients type C with specialism MND	Integer
#emergency patients type C with specialism NEC	Integer
#emergency patients type C with specialism OOG	Integer
#emergency patients type C with specialism ORT	Integer
#emergency patients type C with specialism URO	Integer
#emergency patients type C with specialism VAT	Integer
#emergency patients type A treated at corresponding OR of specialism CAC	Integer
#emergency patients type A treated at corresponding OR of specialism CHI	Integer
#emergency patients type A treated at corresponding OR of specialism CHP	Integer
#emergency patients type A treated at corresponding OR of specialism GYN	Integer
#emergency patients type A treated at corresponding OR of specialism KNO	Integer
#emergency patients type A treated at corresponding OR of specialism MND	Integer
#emergency patients type A treated at corresponding OR of specialism NEC	Integer
#emergency patients type A treated at corresponding OR of specialism OOG	Integer
#emergency patients type A treated at corresponding OR of specialism ORT	Integer
#emergency patients type A treated at corresponding OR of specialism URO	Integer
#emergency patients type A treated at corresponding OR of specialism VAT	Integer
#emergency patients type B treated at corresponding OR of specialism CAC	Integer
#emergency patients type B treated at corresponding OR of specialism CHI	Integer
#emergency patients type B treated at corresponding OR of specialism CHP	Integer
#emergency patients type B treated at corresponding OR of specialism GYN	Integer
#emergency patients type B treated at corresponding OR of specialism KNO	Integer
#emergency patients type B treated at corresponding OR of specialism MND	Integer
#emergency patients type B treated at corresponding OR of specialism NEC	Integer
#emergency patients type B treated at corresponding OR of specialism OOG	Integer
#emergency patients type B treated at corresponding OR of specialism ORT	Integer
#emergency patients type B treated at corresponding OR of specialism URO	Integer
#emergency patients type B treated at corresponding OR of specialism VAT	Integer
#emergency patients type C treated at corresponding OR of specialism CAC	Integer

Value description	Data type
#emergency patients type C treated at corresponding OR of specialism CHI	Integer
#emergency patients type C treated at corresponding OR of specialism CHP	Integer
#emergency patients type C treated at corresponding OR of specialism GYN	Integer
#emergency patients type C treated at corresponding OR of specialism KNO	Integer
#emergency patients type C treated at corresponding OR of specialism MND	Integer
#emergency patients type C treated at corresponding OR of specialism NEC	Integer
#emergency patients type C treated at corresponding OR of specialism OOG	Integer
#emergency patients type C treated at corresponding OR of specialism ORT	Integer
#emergency patients type C treated at corresponding OR of specialism URO	Integer
#emergency patients type C treated at corresponding OR of specialism VAT	Integer
Max waiting time of type A emergency patients	Double
Number of type A emergency patients treated outside the norm	Integer
Max waiting time of type B emergency patients	Double
Number of type B emergency patients treated outside the norm	Integer
Max waiting time of type C emergency patients	Double
Number of type C emergency patients treated outside the norm	Integer
Max waiting time of type G emergency patients	Double
Max waiting time of patients with specialism CAC	Integer
Max waiting time of type A emergency patients of specialism CAC	Integer
#type A emergency patients of specialism CAC treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism CAC	Double
#type B emergency patients of specialism CAC treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism CAC	Double
#type C emergency patients of specialism CAC treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism CAC	Double
Mean waiting time of patients with specialism CAC	Double
Mean waiting time of type A emergency patients of specialism CAC	Double
Mean waiting time of type B emergency patients of specialism CAC	Double
Mean waiting time of type C emergency patients of specialism CAC	Double
Mean waiting time of type G emergency patients of specialism CAC	Double
Max waiting time of patients with specialism CHI	Integer
Max waiting time of type A emergency patients of specialism CHI	Integer
#type A emergency patients of specialism CHI treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism CHI	Double
#type B emergency patients of specialism CHI treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism CHI	Double
#type C emergency patients of specialism CHI treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism CHI	Double
Mean waiting time of patients with specialism CHI	Double
Mean waiting time of type A emergency patients of specialism CHI	Double
Mean waiting time of type B emergency patients of specialism CHI	Double
Mean waiting time of type C emergency patients of specialism CHI	Double
Mean waiting time of type G emergency patients of specialism CHI	Double
Max waiting time of patients with specialism CHP	Integer

Value description	Data type
Max waiting time of type A emergency patients of specialism CHP	Integer
#type A emergency patients of specialism CHP treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism CHP	Double
#type B emergency patients of specialism CHP treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism CHP	Double
#type C emergency patients of specialism CHP treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism CHP	Double
Mean waiting time of patients with specialism CHP	Double
Mean waiting time of type A emergency patients of specialism CHP	Double
Mean waiting time of type B emergency patients of specialism CHP	Double
Mean waiting time of type C emergency patients of specialism CHP	Double
Mean waiting time of type G emergency patients of specialism CHP	Double
Max waiting time of patients with specialism GYN	Integer
Max waiting time of type A emergency patients of specialism GYN	Integer
#type A emergency patients of specialism GYN treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism GYN	Double
#type B emergency patients of specialism GYN treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism GYN	Double
#type C emergency patients of specialism GYN treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism GYN	Double
Mean waiting time of patients with specialism GYN	Double
Mean waiting time of type A emergency patients of specialism GYN	Double
Mean waiting time of type B emergency patients of specialism GYN	Double
Mean waiting time of type C emergency patients of specialism GYN	Double
Mean waiting time of type G emergency patients of specialism GYN	Double
Max waiting time of patients with specialism KNO	Integer
Max waiting time of type A emergency patients of specialism KNO	Integer
#type A emergency patients of specialism KNO treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism KNO	Double
#type B emergency patients of specialism KNO treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism KNO	Double
#type C emergency patients of specialism KNO treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism KNO	Double
Mean waiting time of patients with specialism KNO	Double
Mean waiting time of type A emergency patients of specialism KNO	Double
Mean waiting time of type B emergency patients of specialism KNO	Double
Mean waiting time of type C emergency patients of specialism KNO	Double
Mean waiting time of type G emergency patients of specialism KNO	Double
Max waiting time of patients with specialism MND	Integer
Max waiting time of type A emergency patients of specialism MND	Integer
#type A emergency patients of specialism MND treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism MND	Double
#type B emergency patients of specialism MND treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism MND	Double
#type C emergency patients of specialism MND treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism MND	Double

Value description	Data type
Mean waiting time of patients with specialism MND	Double
Mean waiting time of type A emergency patients of specialism MND	Double
Mean waiting time of type B emergency patients of specialism MND	Double
Mean waiting time of type C emergency patients of specialism MND	Double
Mean waiting time of type G emergency patients of specialism MND	Double
Max waiting time of patients with specialism NEC	Integer
Max waiting time of type A emergency patients of specialism NEC	Integer
#type A emergency patients of specialism NEC treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism NEC	Double
#type B emergency patients of specialism NEC treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism NEC	Double
#type C emergency patients of specialism NEC treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism NEC	Double
Mean waiting time of patients with specialism NEC	Double
Mean waiting time of type A emergency patients of specialism NEC	Double
Mean waiting time of type B emergency patients of specialism NEC	Double
Mean waiting time of type C emergency patients of specialism NEC	Double
Mean waiting time of type G emergency patients of specialism NEC	Double
Max waiting time of patients with specialism OOG	Integer
Max waiting time of type A emergency patients of specialism OOG	Integer
#type A emergency patients of specialism OOG treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism OOG	Double
#type B emergency patients of specialism OOG treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism OOG	Double
#type C emergency patients of specialism OOG treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism OOG	Double
Mean waiting time of patients with specialism OOG	Double
Mean waiting time of type A emergency patients of specialism OOG	Double
Mean waiting time of type B emergency patients of specialism OOG	Double
Mean waiting time of type C emergency patients of specialism OOG	Double
Mean waiting time of type G emergency patients of specialism OOG	Double
Max waiting time of patients with specialism ORT	Integer
Max waiting time of type A emergency patients of specialism ORT	Integer
#type A emergency patients of specialism ORT treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism ORT	Double
#type B emergency patients of specialism ORT treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism ORT	Double
#type C emergency patients of specialism ORT treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism ORT	Double
Mean waiting time of patients with specialism ORT	Double
Mean waiting time of type A emergency patients of specialism ORT	Double
Mean waiting time of type B emergency patients of specialism ORT	Double
Mean waiting time of type C emergency patients of specialism ORT	Double
Mean waiting time of type G emergency patients of specialism ORT	Double
Max waiting time of patients with specialism URO	Integer
Max waiting time of type A emergency patients of specialism URO	Integer

Value description	Data type
#type A emergency patients of specialism URO treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism URO	Double
#type B emergency patients of specialism URO treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism URO	Double
#type C emergency patients of specialism URO treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism URO	Double
Mean waiting time of patients with specialism URO	Double
Mean waiting time of type A emergency patients of specialism URO	Double
Mean waiting time of type B emergency patients of specialism URO	Double
Mean waiting time of type C emergency patients of specialism URO	Double
Mean waiting time of type G emergency patients of specialism URO	Double
Max waiting time of patients with specialism VAT	Integer
Max waiting time of type A emergency patients of specialism VAT	Integer
#type A emergency patients of specialism VAT treated outside the norm	Integer
Max waiting time of type B emergency patients of specialism VAT	Double
#type B emergency patients of specialism VAT treated outside the norm	Integer
Max waiting time of type C emergency patients of specialism VAT	Double
#type C emergency patients of specialism VAT treated outside the norm	Integer
Max waiting time of type G emergency patients of specialism VAT	Double
Mean waiting time of patients with specialism VAT	Double
Mean waiting time of type A emergency patients of specialism VAT	Double
Mean waiting time of type B emergency patients of specialism VAT	Double
Mean waiting time of type C emergency patients of specialism VAT	Double
Mean waiting time of type G emergency patients of specialism VAT	Double
Total amount of minutes that elective procedures start later than planned	Integer
Total amount of elective procedures starting later than planned	Integer
Average amount of min. that elective patients start to late	Double
#elective patients treated less than 30 min. to late	Integer
#elective patients that receives treatment 30 - 60 min. to late	Integer
#elective patients that receives treatment 60 - 90 min. to late	Integer
#elective patients that receives treatment 90 - 120 min. to late	Integer
#elective patients that receives treatment 120 - 150 min. to late	Integer
#elective patients that receives treatment 150 - 180 min. to late	Integer
#elective patients that receives treatment 180 - 210 min. to late	Integer
#elective patients that receives treatment 210 - 240 min. to late	Integer
#elective patients that receives treatment 240 - 270 min. to late	Integer
#elective patients that receives treatment 270 - 300 min. to late	Integer
#elective patients that receives treatment 300 - 330 min. to late	Integer
#elective patients that receives treatment 330 - 360 min. to late	Integer
#elective patients that receives treatment 360 - 390 min. to late	Integer
#elective patients that receives treatment 390 - 420 min. to late	Integer
#elective patients that receives treatment 420 - 450 min. to late	Integer
#elective patients that receives treatment more than 450 min. to late	Integer
Total amount of minutes that elective procedures start earlier than planned	Integer
Total amount of elective procedures starting earlier than planned	Integer

Value description	Data type
Average amount of min. that elective patients start to early	Double
#elective patients that receives treatment less than 30 min. to early	Integer
#elective patients that receives treatment 30 - 60 min. to early	Integer
#elective patients that receives treatment 60 - 90 min. to early	Integer
#elective patients that receives treatment 90 - 120 min. to early	Integer
#elective patients that receives treatment 120 - 150 min. to early	Integer
#elective patients that receives treatment 150 - 180 min. to early	Integer
#elective patients that receives treatment 180 - 210 min. to early	Integer
#elective patients that receives treatment 210 - 240 min. to early	Integer
#elective patients that receives treatment 240 - 270 min. to early	Integer
#elective patients that receives treatment 270 - 300 min. to early	Integer
#elective patients that receives treatment 300 - 330 min. to early	Integer
#elective patients that receives treatment 330 - 360 min. to early	Integer
#elective patients that receives treatment 360 - 390 min. to early	Integer
#elective patients that receives treatment 390 - 420 min. to early	Integer
#elective patients that receives treatment 420 - 450 min. to early	Integer
#elective patients that receives treatment more than 450 min. to early	Integer
Average amount of overtime per ORday	Double

Table 30 Output values of the simulation

Appendix B

Interviews

This appendix contains a list of people interviewed regarding this master thesis, topics discussed with the specific interviewees and main “results” of the interview. The interviewees all received the one-pager as shown in Appendix. In the case they reacted interested a meeting was set. Out of the 10 people that received this one-pager, eight reacted positively and were prepared to further discuss the topic.

Name (Function): Berkx, Lizette (Project Manager)
Organization: OR-Benchmarking
Introduction: After being involved in different types of healthcare related projects as a senior-advisor at PricewaterhouseCoopers, Lizette became Officer Health Operations Management & Innovation at Erasmus Medical Center. Through this role her current function was just a small step. Currently she is working towards a PhD by conducting research on the OR database she is managing. Her publications include (van Veen-Berkx, Elkhuizen, Kalkman, Buhre, & Kazemier, 2014), (E. van Veen-Berkx (projectleider Benchmarking OK), 2012) and (van Veen-Berkx, Bitter, et al., 2014) all concerning planning at the OR-department.
Time/date of meeting: 13:00-14:30 30-7-2014
Topics discussed: Slack allocation methods, Current system used within the Erasmus MC, Specialists problems with this system, OK-Benchmarking
Main observations:
- People are using different terminology when it comes to slack allocation methods. This makes it hard to compare literature and discuss the topic.
- Using the terminology of this report, the Erasmus MC is currently using department wide slack as method of allocating slack. The amount of slack allocated differs per OR. Reason for this is that the number of non-elective patients per specialism differs and the amount of slack is adjusted to this difference.
- Although this kind of slack allocation seams fair. Specialists still feel that their specialism is falling short when it comes to the amount of overtime they have to run. More about this can be found in Appendix G.

Further observations:
- People are focused on going home in time while colleagues from other specialism’s have lots of work to do.
- “Guaranteed-OR” is a system within the Erasmus MC that stimulates specialisms to allocate slack on their OR’s.
- Benchmark-OR is a collaboration between UMC’s in the Netherlands. Data of all UMC’s is collected and compared. Results following from analyzing this data are reported back annually to the hospitals.

Name (Function): Bezstarostie – van Eeden, Jeanne (Staff Anesthesiologist and Head of OR-Department)
Organization: Erasmus Medical Center

Introduction:	For over 24 years, Jeanne is involved in the OR-theater of the Erasmus MC. Started as an anesthesiologist for children she is currently Head of the OR-department and concerned with the planning of the OR on operational level. Deciding on the level of urgency of non-elective patients and on which OR they will be served.
Time/date of meeting:	9:30-10:30 7-8-2014
Topics discussed:	FEOR method, Types of emergency patients, Current planning system at the Erasmus MC, Side issues, Specialization of the OR personnel, OK-Benchmarking and its future, Research in OR-planning
Main observations:	**-** After reading the one-pager, Jeanne saw one big problem concerning the FEOR method; current trend was more specialization among specialists. Resulting in most specialist being able to perform just a small set of surgeries. Therefore allocating slack to OR's of these specialists would be impossible. They simply wouldn't be able to perform the needed surgery. This same problem was pointed out by Peer Goudswaard. A solution would be some extra trauma-personal that moves between the OR's together with the FEOR label. However, this brings extra costs. **-** At the Erasmus MC therefore FEOR would not be a solution according to Jeanne. The bottle-neck is mainly personal while they have 3 unused OR's, catching dust all day. - Patients for which the FEOR method would be an absolute outcome for what the people at Erasmus MC call type A patients. Here emergency patients are divided in 4 categories A, B, C and D. Where type B – D match the types A – C used in this research, type A at the Erasmus MC is used when an emergency patient needs surgery immediately and not a single minute can be waited. In this case having an OR ready to go at every time of the day is perfect, but according to Jeanne this happen rarely and when it does it is hardly a problem. Suddenly personal and material can be freed up everywhere to attend the type A patient.
Further observations:	**-** The Erasmus MC officially uses department wide slack with a variable amount of slack allocated to each OR. This system is in use since 2010, following the research of (Wullink et al., 2007) after they closed their dedicated emergency OR. According to Jeanne there currently is a change going on. The amounts of slack being allocated are reduced to closely nothing making it more of a no slack system. Overtime is anticipated and so is not a real problem for specialists. - According to Jeanne, there are two main reasons why the planning in an OR theater is so hard. The first one being the unpredictability of the surgery durations. The second one being all additional resources used such as IC and MC beds. - According to Jeanne the planned duration of surgeries is where most of the effectiveness can be gained. Currently they are estimating the duration of a surgery by taking the average of the last ten surgeries of this type performed by the same surgeon. A problem here is that when one of these 10 was extraordinary long, the next 10 planned durations will be longer then probably needed. Therefore something smarter should be done than just taking the average such as taking the median.

- Overall Jeanne believes that research on the field of OR planning rarely gets implemented. Often the complex reality is so beaten down that the results of the research are not applicable. Besides, the impact of inventions is often so slight that it is not worth to implement. If there is an area where Jeanne sees the possibility for progress it is in the estimation of operating times.

Name (Function): Bos, Gwendy (Project Manager)
Organization: KPMG Plexus
Introduction: As a Project Manager at KPMG Plexus, Gwendy is involved in all kinds of healthcare related projects. For example, she was involved in the case study (section 1.1) that stood at the origin of this research.
Time/date of meeting: 9:30-10:30 7-8-2014
Topics discussed: FEOR method (greedy approach), obstacles that will be faced when implementing the method
Main observations: - The FEOR method is a known mathematical concept (greedy algorithm), used in a new area of application. This makes it innovative.
- There seem to be practical applications for the method, although the implementation will not go smoothly. Foremost it will cause a culture shock. Not only are specialists not used to think in the direction of shared interests, doing nothing while patients are waiting feels pretty counter intuitive when trying to increase the customer satisfaction.

Name (Function): Brandsema, Gerben (Healthcare Operations Advisor), Goudswaard, Peer (Chief Officer Health Operations Management & Innovation), Hoogstins, Tjibbe (Healthcare Operations Advisor)
Organization: University Medical Center Groningen
Introduction: Three employees of S.T.A.R. labsG concerned with OR-planning where attending the meeting concerning this research. Showing the amount of interest for it as well as their involvement. Contact was made through Peer who was the supervisor of the graduation project that resulted in (Pricker, 2011). The overlap between this research and that of (Pricker, 2011) is obvious, making Peer a very interesting person to discuss the results of this research with. Peer was immediately interested and was of great help.
Time/date of meeting: 13:00-15:00 5-8-2014
Topics discussed: USA-patients, Importance of waiting time, Strength of the dedicated emergency-OR, super specialization, reasons for research, master data management, uniqueness of healthcare operations, working in shifts
Main observations: - Within UMC Groningen, emergency patients are divided in U (urgent), S (spoed) and A (acuut) patients. The definition of these groups is in accordance with the in this research used A, B and C types.
- Typical type A emergency patients are patients that are about to lose or have lost organ functionality.
- Having an OR ready for emergency patients at all times is, according to Goudswaard, only useful in very rare cases. Only when the situation is life-threatening and arrives very unexpected this is the case. These

patients mostly do not arrive in batches and when this is the case there is always a contingency plan in place.
- Since it is often known far (15-30 minutes) in advance that emergency patients are coming (since they are picked up by and ambulance for example), waiting times below 15 minutes are not really a problem. The 15-30 minutes give the OR-planner the possibility to even wait for an OR with a low amount of work to perform in comparison to the rest of the OR's (very similar to what the FEOR method does).
- Peer is a big supporter of the dedicated emergency-OR since it has a lot of benefits that are not immediately measurable but do matter. Biggest benefit is that a dedicated trauma team can conduct all the procedures while the average specialist cannot. Same goes for the different OR's that are not all equipped with the right materials to operate on any type of emergency patient. This problem within the FEOR can be solved with an extra trauma team but personnel turns out to be the most costly resource of an OK-department making this an expensive fix. Therefore the FEOR idea would fit better within a more peripheral hospital, with more exchangeable procedures.

Further observations: - To estimate the duration of operations better, an improvement in data quality would be a good first step.
- People with affinity for business often wonder why hospitals work so inefficient. They compare patients to a package and would love to see a "PostNL track and trace" type of system for every patient. Patients however are not packages but human beings that all behave different.
- Within this research, efficiency is improved during the 8 hours of work time a day. Which makes people wonder why the OR's are not or hardly used during the remaining 16 hours of the day. Peer explains that this has multiple reasons.
- OK planning is not so much about space utilization but about utilization of the personnel. Therefore night shifts are definitely not a quick win.

Name (Function): Delleart, Nico (Professor Quantitative Modeling)
Organization: University of Technology Eindhoven
Introduction: Nico Delleart is heavily involved in research within hospitals. Not only is he performing research within this field himself, he is also guiding around four graduate students a year. Of these students 90% is conducting their master research in or around hospitals. One of these researches resulted in (de Keijzer, 2014).
Time/date of meeting: 11:00-11:45 13-8-2014
Topics discussed: FEOR method, Weight functions, modeling the complex reality of an OR-department, research in healthcare
Main observations: **-** The FEOR method makes a solid impression on Nico. Whether or not the method is an improvement depends on the weights attached to the different KPI's. Usually there is a balance between effectiveness and patient satisfaction. Increasing the one results in a decrease of the other. It is important to find a point on this curve where all parties are satisfied (if possible).

Further observations: **-** In Nico's experience, research results in implementation only when specialists where involved in the research from the beginning, Another requirement is that the solution is simple. Medical personal has little affinity with mathematical models and complicated software solutions.

- Even though healthcare is a really unpredictable and difficult area to do research in, for Nico this is also the major challenge and the reasons why it is so interesting. Contradicting the vision of Jeanne mentioned earlier, Healthcare is an area where simple research projects can establish major improvements due to the fact that healthcare is such a undeveloped area.

Name (Function): Glerum, Arvid (Junior Advisor Lean and Healthcare Logistics), van Houten, Renee (Business Analyst)

Organization: St. Antonius Hospital Nieuwegein

Time/date of meeting: 13:00-14:00 18-8-2014

Topics discussed: Practical applications of the FEOR method, types of emergency patients, current status of the OR-planning at St. Antonius hospital, planned surgery durations

Main observations: **-** Arvid and Renee are enthusiastic about the whole research project, but less optimistic about the FEOR method itself. Concerning the research, they agree that it is very interesting and more research like this should be performed. The idea of trying out proven logistic methods in the hospital environment is something that they expect more of in the future.

- The FEOR method is at its current state not usable within the OR-department at st. Antonius hospital for two main reasons: (1) Not every specialist is capable of performing every type of surgery. Using the FEOR method department wide is therefore impossible. An extra trauma team is here not a solution since in accordance with the Erasmus MC, st. Antonius uses only 22 of the 25 available OR's. Bottleneck is thus personnel and not the amount of OR's. Using the FEOR method within a subset of the OR's (for example the ones used by heart specialists) is something they will look at in the future. (2) The type of emergency patients at which the FEOR method aims, the ones that need surgery right away, is rare at the st. Antonius OR-department.

- However, the greedy algorithm behind the method is something Arvid and Renee could implement in the current planning system at st. Antonius. Together they are responsible for remodeling this planning system. Within the new planning system they try to reduce the amount of cancellations (at the moment averaging 1 per day) while performing the same amount of surgeries. Also the quality of planned surgery durations is something they are looking at.

Currently st. Antonius uses a dedicated emergency-OR at which a trauma team is stationed throughout the day. Such a trauma team consists of everything needed to perform an emergency surgery except for the specialist. Depending on the required specialism of an emergency patient the right specialist is grabbed from another active OR or called in from other duties.

Further observations:	**-** Research topics that Arvid and Renee encourage concern the planned surgery durations and planning rules to place type A, B and C emergency patients. Especially what kind of rules to use is something hardly covered in any literature.

Name (Function):	Matthijssen, Ilse (Senior Manager)
Organization:	KPMG Plexus
Time/date of meeting:	10:00-11:00 31-7-2014
Topics discussed:	Influence of the FEOR method on the customer satisfaction of elective patients.
Main observations:	**-** Since the FEOR-label jumps from OR to OR, many elective patients could experience disadvantages of the method. The difference between planned and realized start time for elective surgery is therefore an interesting KPI to watch. This KPI is therefore added to the scope of this thesis as can be found in section 0.

Name (Function):	Wullink, Gerhard (Strategist)
Organization:	Gupta Strategists
Time/date of meeting:	12:00-12:30 14-8-2014
Topics discussed:	Greedy approach, weight function/weight factor for the different KPI's
Main observations:	**-** The greedy approach seems to be an inventive way of deciding which OR could be best used to allocate slack to. However, there are scenarios in which this would lead to non-wanted side-effects. The cases in which this is a smart idea could be further researched. **-** Weight factors are primarily a management decision. Depending on the priorities of the hospital in case, the weight factor for cancellations could be really high for example while other hospitals do not mind using cancellations as a way of preventing overtime. - An elegant way of calculating weight factors is based on the relevant costs. Dividing the total OR costs by the amount of procedures performed gives a rough estimate of the cost per procedure. Overtime brings costs of personnel. Waiting time brings pre-care costs and a certain discomfort for the patient which is hard to evaluate. Cancellations bring extra work later and again discomfort. What the cost of discomfort is, really depends on the management.

Appendix C

One-Pager: Flexible Emergency-Operating Room (FEOR)

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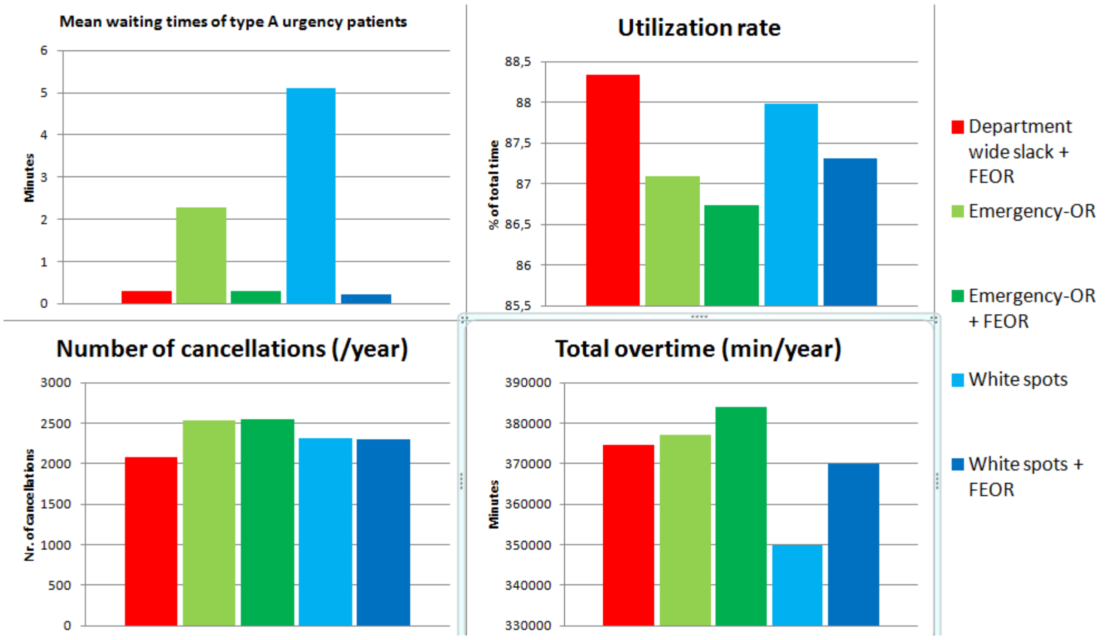
Why – The planner of an OR-department in a hospital faces the constant struggle between effectively using his very expensive resources (operating rooms, medical personal etc.) and offering high-level, patient-friendly service (low waiting times, small number of cancellations). On top of this struggle comes the presence of the unpredictable arrivals of urgent surgeries, on which the planner has to anticipate. To do so, two methods are widely used. The first method, consisting of using a dedicated emergency-OR, facilitates low waiting times for urgent surgery while scoring low on utilization rate. The second method including allocating slack more flexibly to white spots, makes more effective use of OR-time but results in higher tough acceptable waiting times. FEOR combines “the best” of both ideas and can be used both alongside earlier mentioned methods or as a standalone.

What – FEOR is a new method of anticipating urgent surgery in the OR-department. By setting aside the OR with the lowest sum of planned surgery times for the day at all times, it assures short waiting times for urgent surgery while burdening the least busy OR’s with the extra surgery time. It is the perfect example of a greedy algorithm at work. The role of FEOR switches from one OR to the other if the sum of planned surgery times of an OR is lower than that of the FEOR. This check is conducted each time an OR finishes surgery.

Results – Using a discrete event simulation of the OR-department of a large Dutch academic hospital, a variety of planning methods is evaluated based on four key-performance-indicators.



As can be seen in the figures above, using the FEOR method alongside the currently wide used methods results in an enormous decrease in the mean waiting time while only having a slightly negative impact on the utilization rate and the total overtime. The usage of the FEOR method as a stand-alone however while allocating a total of eight hours of slack evenly over all OR’s has a positive impact on closely every aspect in comparison to the currently used methods. This raises the question whether or not this method is implementable and if so, what the impact will be on today’s OR-planning.

Appendix D

Decision trees

This appendix contains the decision trees for the different planning systems built up by combining the base planning strategy with a slack allocation method with and/or without implementation of the FEOR method.

Slack allocation method	FEOR (No = 0, Yes = 1)	Associated decision tree
No slack	0	Figure 17
No slack	1	Figure 18
Emergency OR	0	Figure 19Figure 17
Emergency OR	1	Figure 20
White spots	0	Figure 21
White spots	1	Figure 22
Department wide slack	0	Figure 17
Department wide slack	1	Figure 18

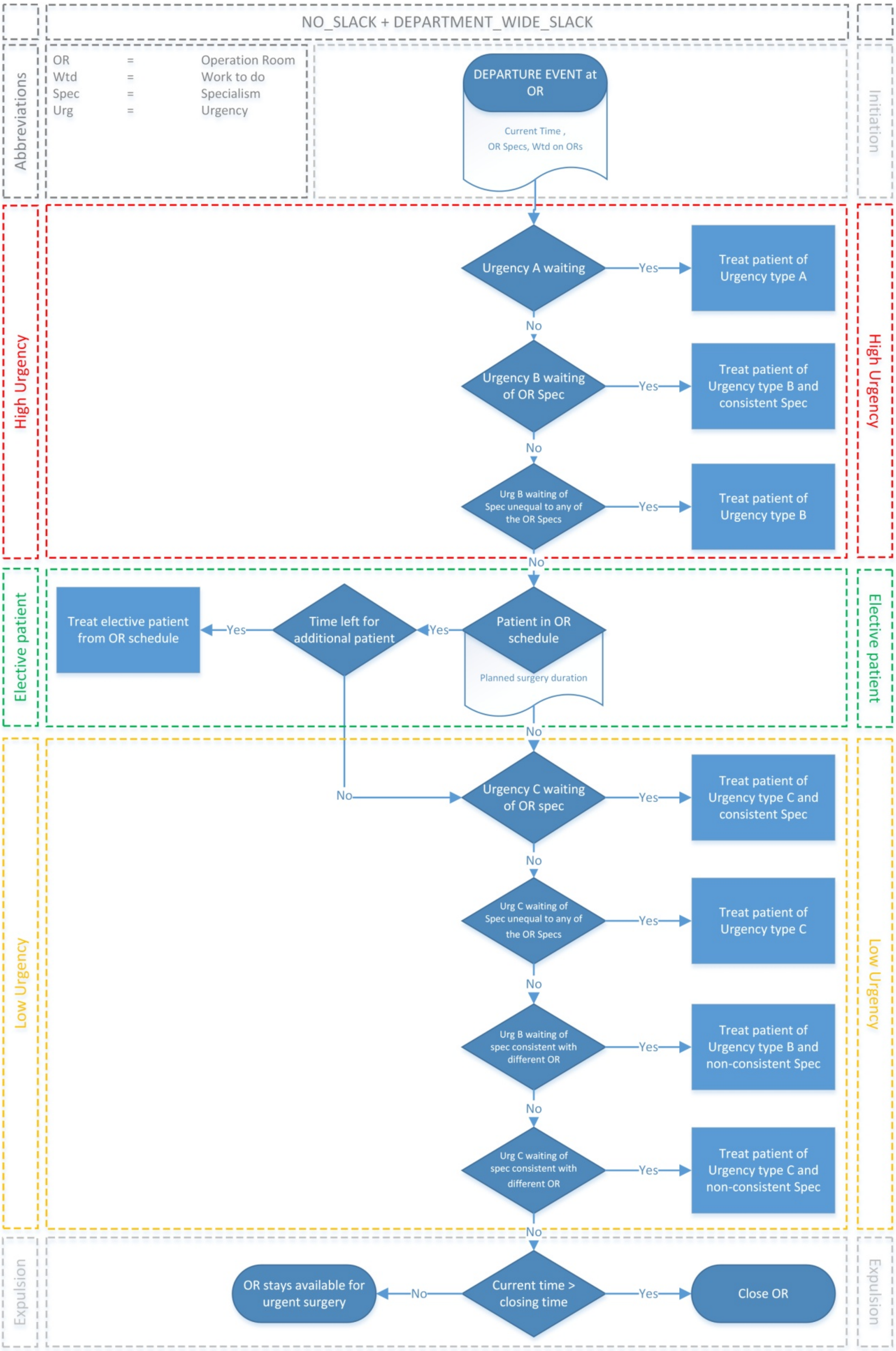


Figure 17 Decision tree No slack and Department wide slack without FEOR

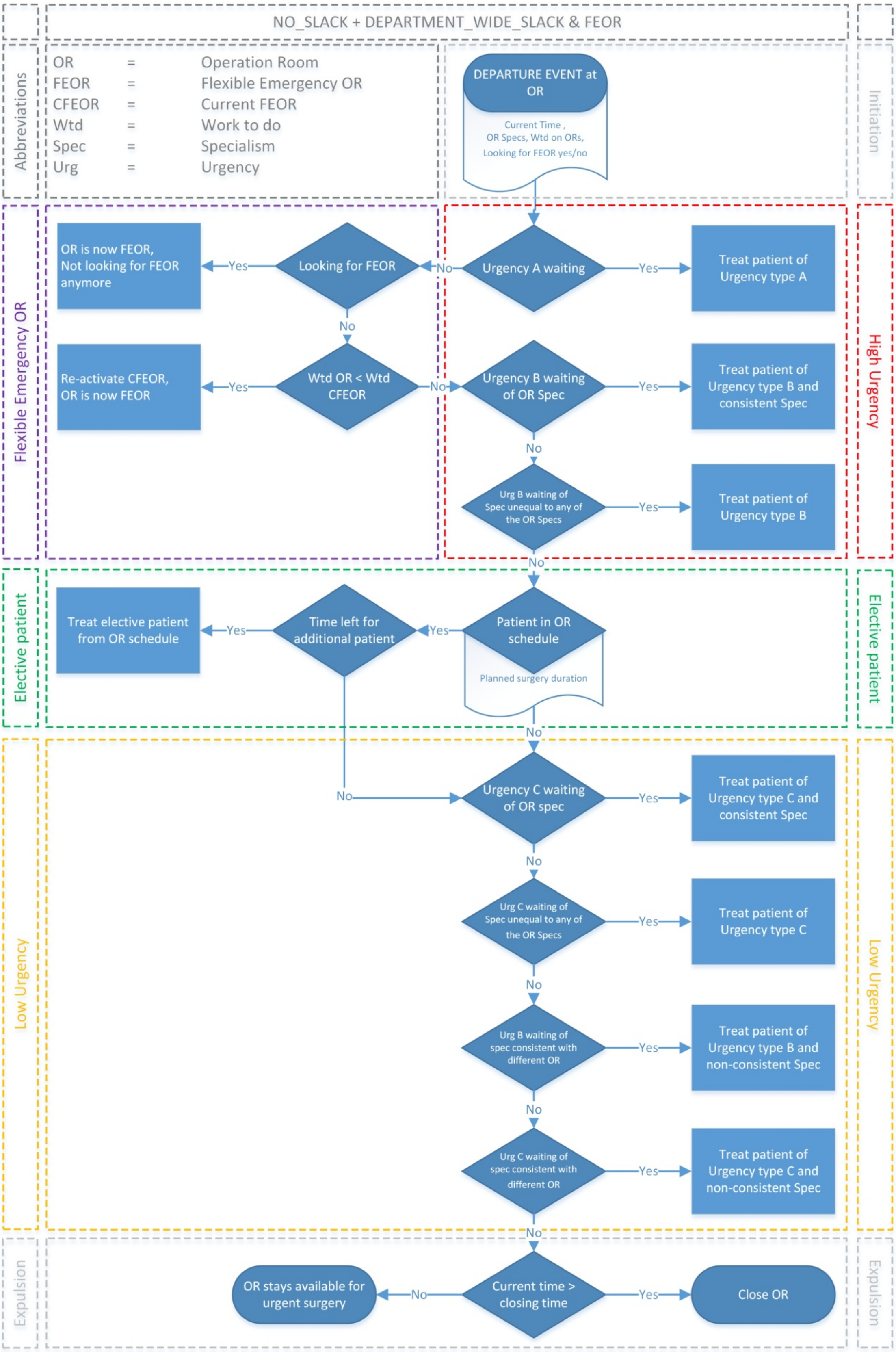


Figure 18 Decision tree No slack and Department wide slack with FEOR

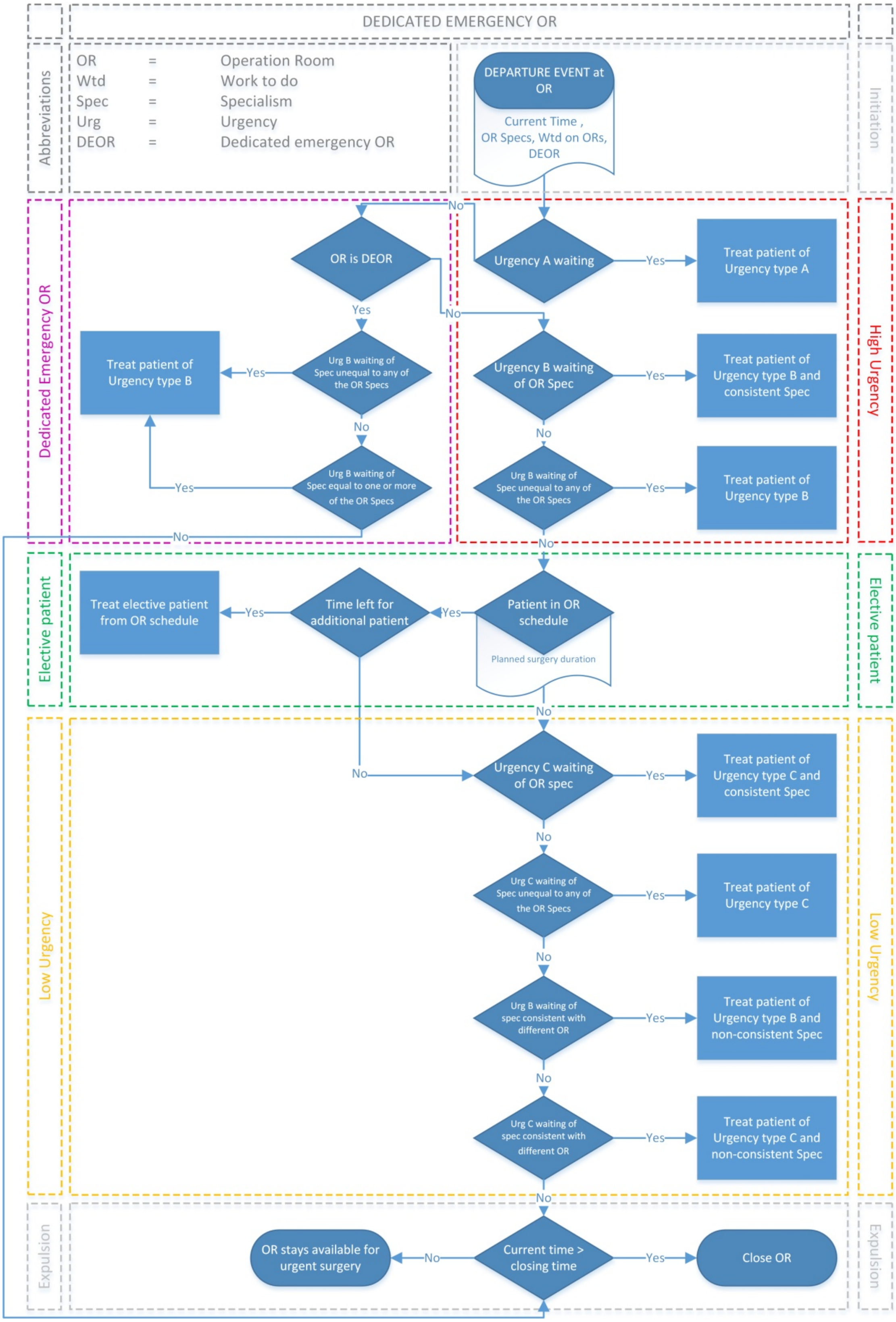


Figure 19 Decision tree Emergency OR without FEOR

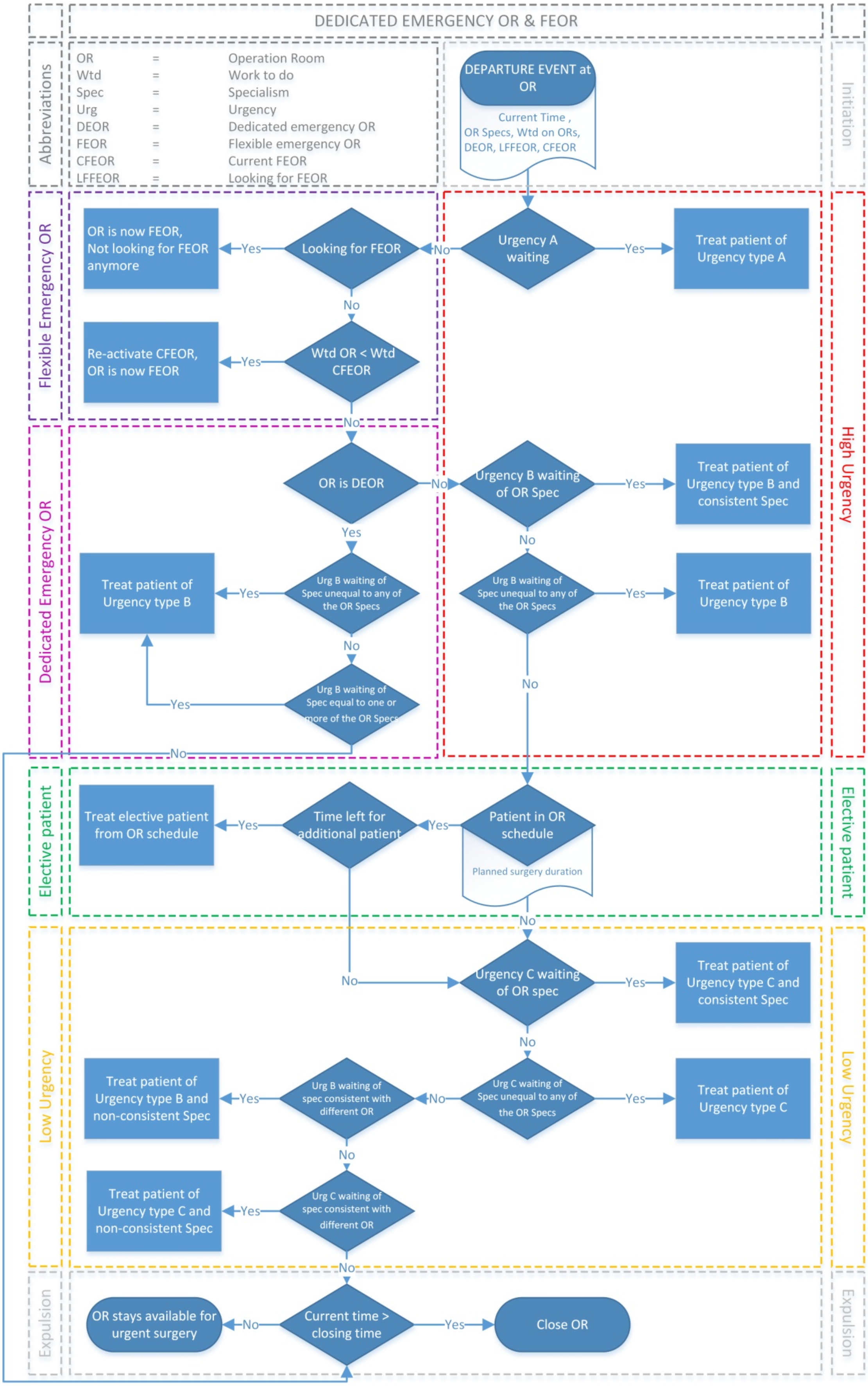


Figure 20 Decision tree Emergency OR with FEOR

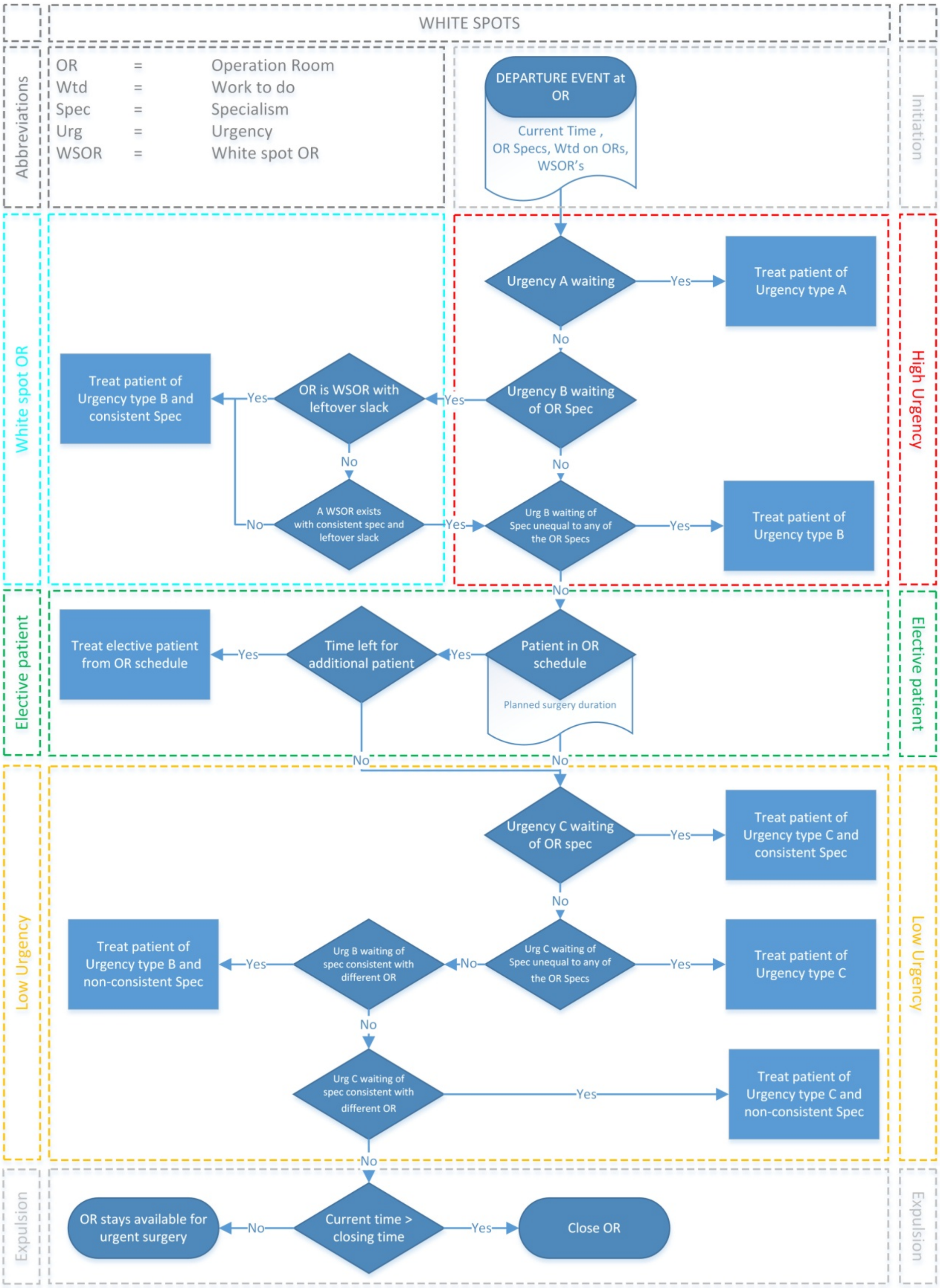


Figure 21 Decision tree White spots without FEOR

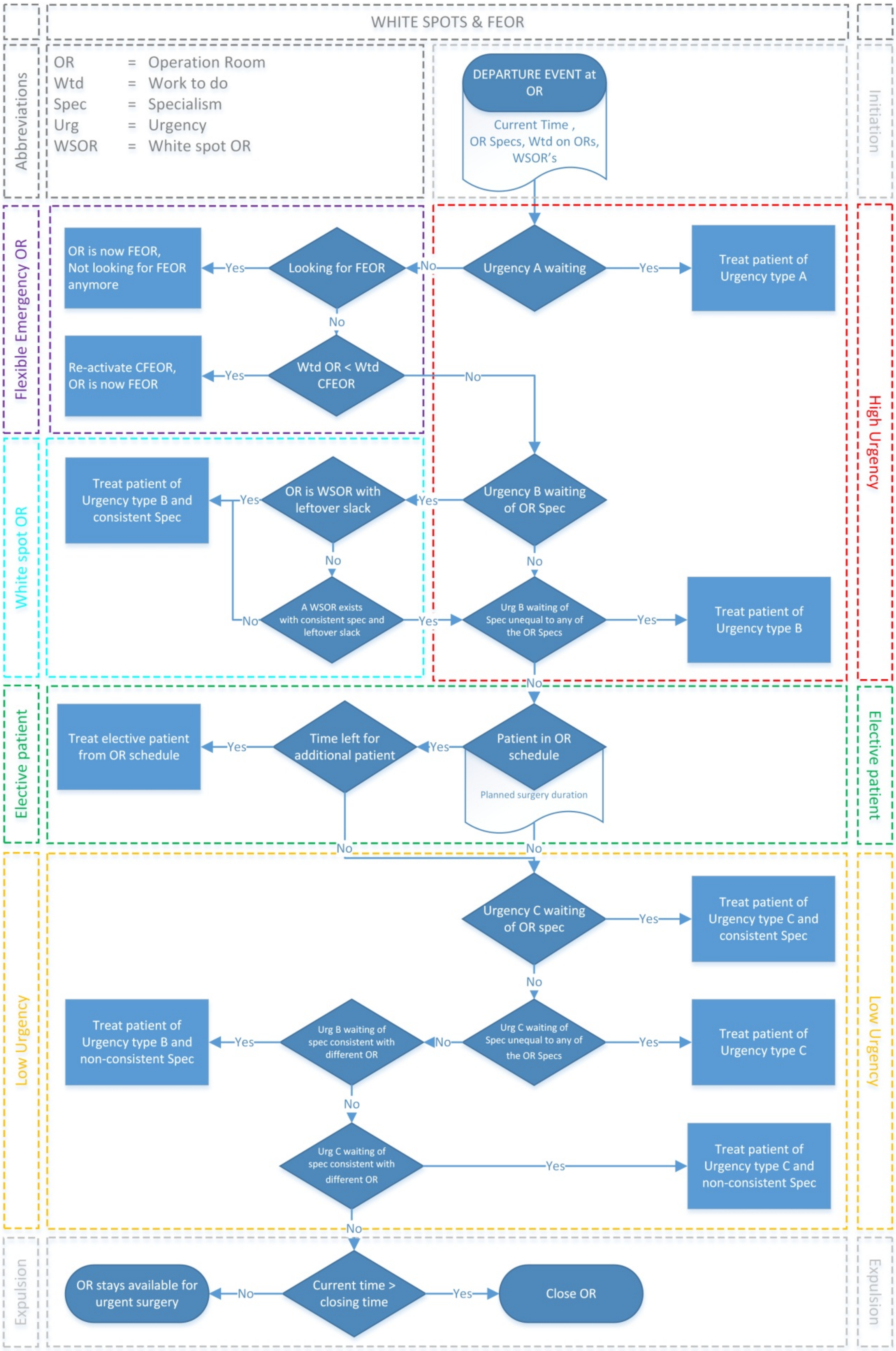


Figure 22 Decision tree White spots with FEOR

Appendix E

S.T.A.R. labs production data 2012

Throughout this research, many decisions and assumptions are based on the daily practice at S.T.A.R. labs. In addition, the values of for example emergency patient arrival rates, the amount of specialisms and the number of OR's are chosen such that the model would mirror this real life OR-department as best as possible. An important factor in this was mirroring the patient group treated at S.T.A.R. labs. This is done using production data from 2012 provided by S.T.A.R. labs. This dataset contains a lot of information concerning the procedures performed for a full year. Two example entries of the dataset, showing which information is stored for each of the performed surgeries at S.T.A.R. labs, is given in Table 31.
Not all the data contained in the original dataset is used during this research. The following steps are taken in order to reduce the dataset to the form in which it would only contain the most relevant data:

- The original dataset contained more than just type A, B and C emergency patients. Patients that need surgery within for example two weeks also are considered of a certain type of emergency within S.T.A.R. labs. For research purposes every none emergency type A, B or C patient, is set to be a general (G) patient and will count as an elective patient within this research.
- The dataset contains procedures that are not real surgeries. These procedures are of specialism ANE and/or sub-specialism BRA, NCL, CT or ANG, of specialism PYN and/or sub-specialism PYN1, PYN2 or PYN3, of specialism RAT and/or sub-specialism RTH, of specialism CMH or of specialism HCK.
- Another time of procedures that are not real surgeries, are procedures performed on the following OR's: 0, 13, 91, 92, 93, F4 and SPK. These procedures are also removed from the dataset.
- Since this research assumes that procedures of every specialism can be performed on any of the OR's and in reality this only holds for class 1 OR's, all procedures not performed within such an OR are removed from the dataset. Non class 1 OR's are represented by the numbers: 24, 26, 27, 28 and 29.
- In this research, only non-weekend days are considered, so Monday-Friday. Therefore all the data concerning procedures performed in weekends is removed from the dataset.
- Some specialisms (DIA, DON, GER and INT) operate a yearly number of patients that is just too small to reserve any time for these specialisms at S.T.A.R. labs. In this research, procedures of these specialisms will therefore be ignored and the associated entries are removed from the dataset.
- Within the dataset, some procedures would be listed under a sub-specialism where a specialism was expected. Since the level of sub-specialisms is out of scope for this research, all specialism related information is translated to the level of specialism. Here is a list of the 11 specialisms included in this research and the [sub-specialisms] that are covered by these specialisms: CAC [CAC, CTC], CHI [CGO, CHI, CTR], CHP [CHP, PLA], GYN [GON, GYF, GYN], MND [KAA, MND], NEC [NCH, NEC], KNO [KNO], OOG [OOG], ORT [ORT], URO [URO] , VAT [VAT]
- Extreme entries such as negative surgery durations or surgery durations equal to 0 are likely to be human errors. Entries like these are altered or entirely removed when the actual mend value or code is not obvious.

- The dataset contained a lot of information for each procedure that was not of any use for this research. Two example entries of the dataset after only the relevant data is preserved, are given in Table 32.

Some more characteristics of both the original and the trimmed dataset can be found in Table 33.

Data value	Procedure 1	Procedure 2
Planned specialism	CHI	ORT
Planned specialist	#####	#####
Planned specialist code	#####	#####
Planned surgery duration	30	210
Actual surgery duration	33	312
Urgency code	A	P
Urgency code description	Emergency type A (<3hours)	Elective
Time of registration	2012-01-20 06:33:00.000	2009-12-02 00:00:00.000
Treatment code	0	0
Treatment description	NULL	NULL
Head of operation code	333631D	338447J
Head of operation description	Artery ligation / incl. Reoperation due to bleeding	(Re) posterior thoracic spinal fusion no fracture 4 more segments
Anesthetic technique code	NULL	NULL
Anesthetic technique description	NULL	NULL
Changing time after surgery	NULL	51
Spent time at holding	NULL	25
Spent time at recovery	0	1221
Department after surgery	U440	P741
Department category after surgery	IC	PACU
Procedure code	2000044363	1400001454
Procedure date	2012-01-20	2012-06-12
Operation room	4	3
Hospital location code	K	K
Entry time operation room	09:58:00.000	08:22:00.000
Departure time operation room	10:31:00.000	13:34:00.000
Actual specialism	CHI	ORT
Time between registration and surgery	205	1329622
Within norm_ABCD	1	
Within 0_2 hours	0	0
Within 2_6 hours	0	0
Within 6_24 hours	0	0
Within 24_72 hours	0	0
Hours between registration and surgery	2	22160

Data value	Procedure 1	Procedure 2
Days between registration and surgery	0	923
Day of the week, registration	Friday	Wednesday
Day of the week, surgery	Friday	Tuesday
Calltime	NULL	NULL
Arrival pre-surgery	NULL	2012-06-12 07:57:00.000
Start monitoring	NULL	NULL
Plan number	1000080440	COP1081944
Postatbest	0	PU
Postatbest description	NULL	PACU
Department description	IC-Centre	OR F4 Recovery
Time of departing OR	2012-01-20 10:31:00.000	2012-06-12 13:34:00.000
Time of aftercare start	2012-01-20 10:31:00.000	2012-06-12 13:53:00.000
Time of arrival at department after surgery	2012-01-20 10:31:00.000	2012-06-13 09:55:00.000
Hospitalization entry start	2012-01-20 00:00:00.000	2012-06-13 00:00:00.000
Hospitalization entry end	2012-01-21 00:00:00.000	2012-06-13 10:21:00.000
Year	2012	2012
Month	1	6
Department after surgery_alt	U440	P741
Department after surgery_alt category	IC	PACU
Department description_alt	IC-Centre	OR F4 Recovery

Table 31 Two example entries of the original production 2012 dataset from S.T.A.R. labs. #### marks information that due to privacy regulations cannot be made visible.

Data value	Procedure 1	Procedure 2
Specialism	OOG	GYN
Urgency code	G	B
Planned surgery duration	60	61
Actual surgery duration	100	62
Change time after surgery	12	14

Table 32 Two example entries of the production 2012 dataset from S.T.A.R. labs after trimming

Characteristics	Original dataset	Trimmed dataset
Nr. of procedures registered	21127	11828
Nr. of different (sub)specialisms used	35	11
Nr of so called elective patients	18640	10795
Emergency patients type A	358	106
Emergency patients type B	1108	408
Emergency patients type C	931	519
Nr. of OR's in scope	33	20

Table 33 Some characteristics of the original and trimmed 202 production dataset from S.T.A.R. labs

Appendix F

Distribution of planned and actual surgery durations, late start and changing times

Planned and actual surgery durations used in this research and more specific in the simulation program, are based on the trimmed 2012 production data of S.T.A.R. labs described in Appendix E. For every patient in the simulation system, this set of properties in the form of values is determined based on how these values are distributed within the given dataset.

To be more precise, each patient in the simulation system receives two values when created. The first one is the planned duration of the surgery it needs. This value is “drawn” from all planned durations of the entries in the trimmed 2012 production dataset in such a way that the probability with which a certain planned time is drawn, represents the amount of times this planned time can actually be found in the dataset compared to the total amount of entries. The second value represents a ratio. Namely the value with which the planned surgery duration of a patient needs to be multiplied to find the associated actual surgery duration of that patient. This ratio is calculated for each procedure in the dataset, creating a set of ratios. In the same way as described for the planned surgery duration, for each patient a ratio is “drawn” from this set.

As can be derived from Figure and Figure there is a significant difference between the specialisms when it comes to the distributions of planned surgery durations and the mentioned ratio’s. This is not strange since different specialisms perform different procedures of varying complexity. For this reason the sets of planned surgery durations and the ratio’s are divided over the associated specialisms. This results in 11 different distributions for both the planned surgery duration and the ratio’s. These specialism specific distributions are visualized in Figure - Figure . An overview of which table represents what distribution is given in Table 34. The different graphs can be seen as mirrored representation of the cumulative density functions. They are represented this way to make it more clear how the above mentioned “drawing” is done.

Specialism	Planned surgery duration	Actual surgery duration	Ratio
CAC	Figure 23	Figure 24	Figure 25
CHI	Figure 26	Figure 27	Figure 28
CHP	Figure 29	Figure 30	Figure 31
GYN	Figure 32	Figure 33	Figure 34
KNO	Figure 35	Figure 36	Figure 37
MND	Figure 38	Figure 39	Figure 40
NEC	Figure 41	Figure 42	Figure 43
OOG	Figure 44	Figure 45	Figure 46
ORT	Figure 47	Figure 48	Figure 49
URO	Figure 50	Figure 51	Figure 52
VAT	Figure 53	Figure 54	Figure 55
Overview	Figure 56	Figure 57	Figure 58

Table 34 Overview of the contents of the different figures contained in this appendix

The “drawing” in the simulation is done as follows:

- First a random number between 0 and 1 is generated.

- This number is multiplied by the size of the dataset belonging to the specialism of the patient.
- The number after multiplication represents which data entry from the dataset is attached to the patient.

From every specialism specific set of the planned surgery durations and ratio's, the median, mode and average are given. An overview of these values can be found in Table 35.

Specialism	Planned surgery duration			Ratio		
	Median	Mode	Average	Median	Mode	Average
CAC	180	180	159,8682746	1,459722222	1	1,632240916
CHI	90	60	100,14	1,323333333	1	1,426768426
CHP	66	60	84,78863	1,083333333	1,2	1,167525918
GYN	60	45	76,77314	1,333333333	1,133333333	1,409541918
KNO	80	64	110,9423	1,03875	1	1,09757992
MND	110	110	138,6494	1,244444444	1,3	1,314772008
NEC	120	180	148,6145	1,344262295	1	1,454713573
OOG	60	60	60,23944	1,111111111	0,8	1,221462453
ORT	79,5	60	94,67767	1,180838641	1,133333333	1,266872442
URO	120	180	132,1795	1,233333333	1,6	1,384087659
VAT	120	120	115,4071	1,386111111	1,533333333	1,505569375

Table 35 Overview of the median, mode and average for the specialism specific sets of the planned surgery durations and ratio's

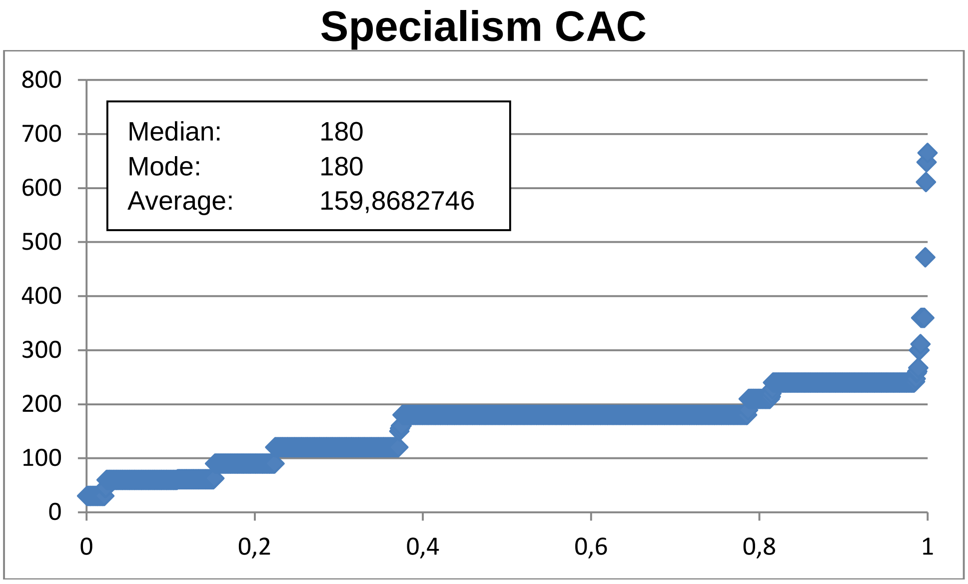


Figure 23 Distribution of the planned surgery duration in minutes for specialism CAC

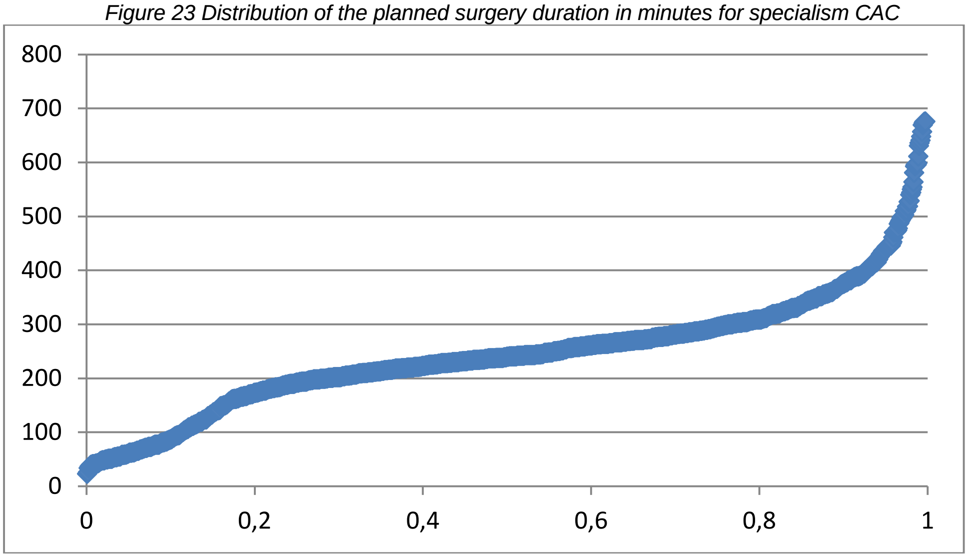


Figure 24 Distribution of the actual surgery duration in minutes for specialism CAC

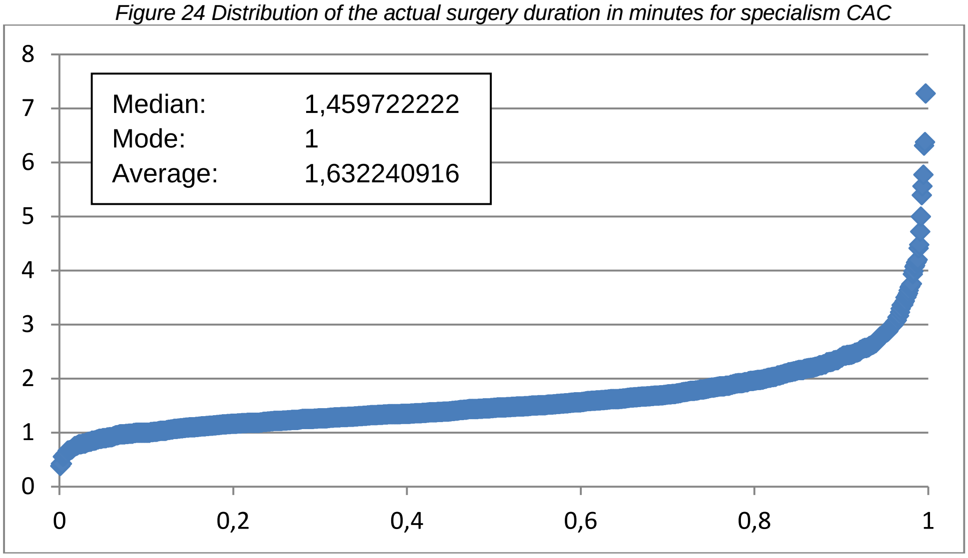


Figure 25 Distribution of the ratio between planned and actual surgery duration for specialism CAC

Specialism CHI

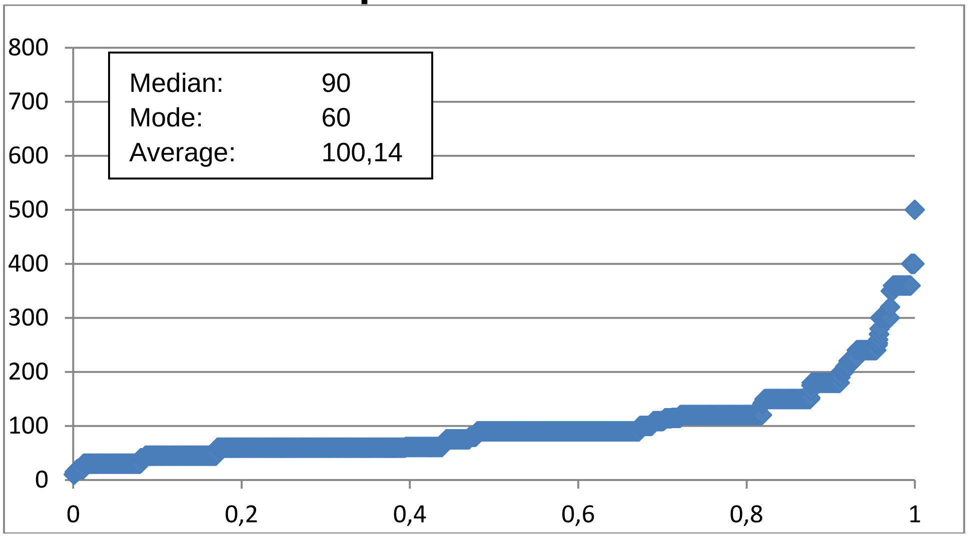


Figure 26 Distribution of the planned surgery duration in minutes for specialism CHI

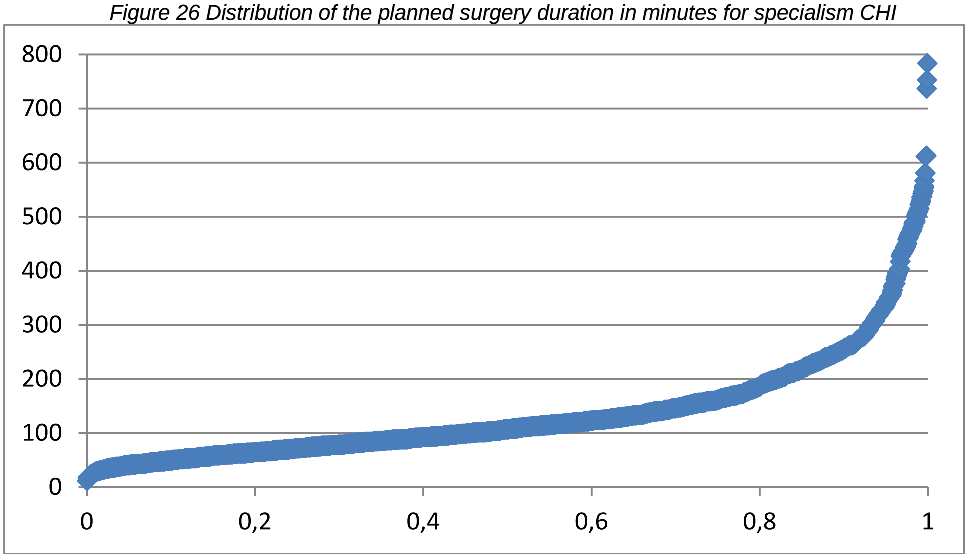


Figure 27 Distribution of the actual surgery duration in minutes for specialism CHI

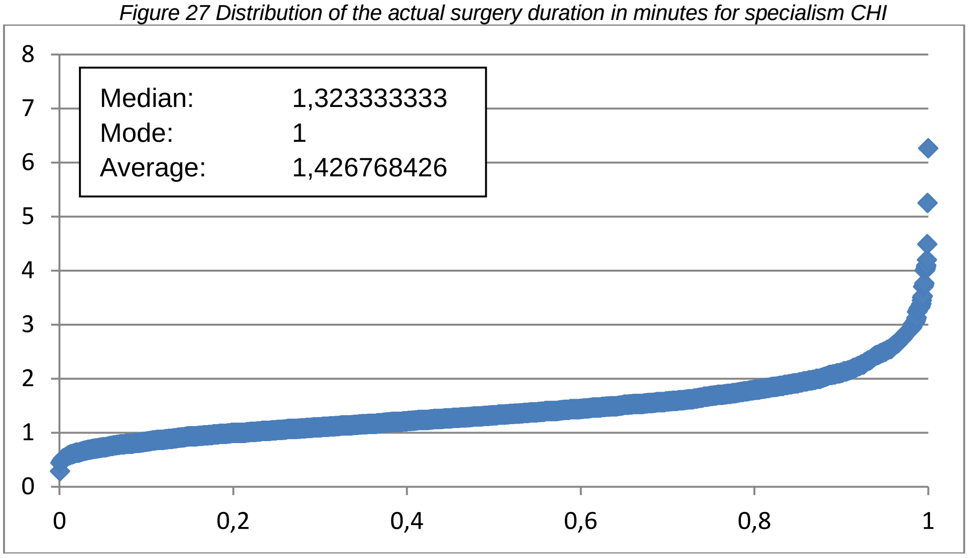


Figure 28 Distribution of the ratio between planned and actual surgery duration for specialism CHI

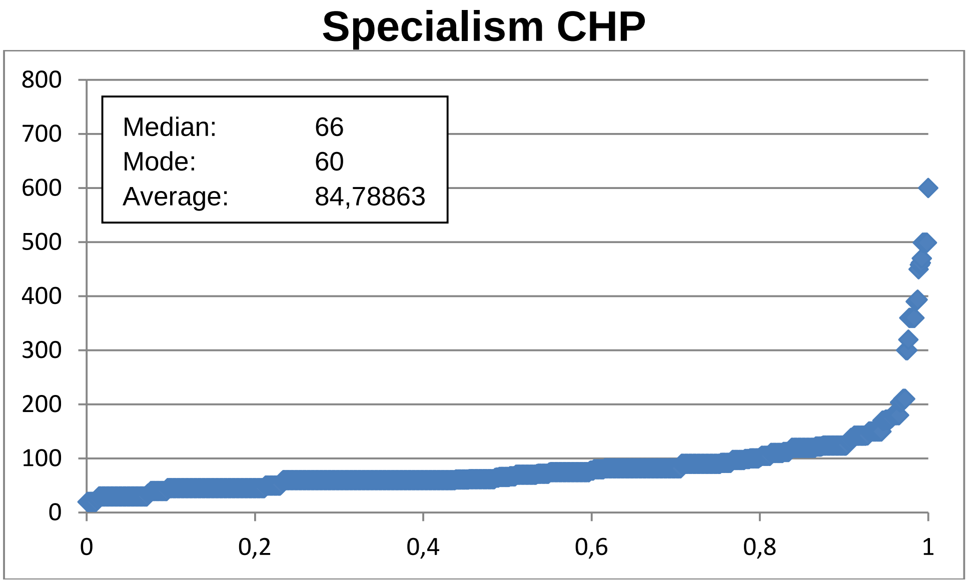


Figure 29 Distribution of the planned surgery duration in minutes for specialism CHP

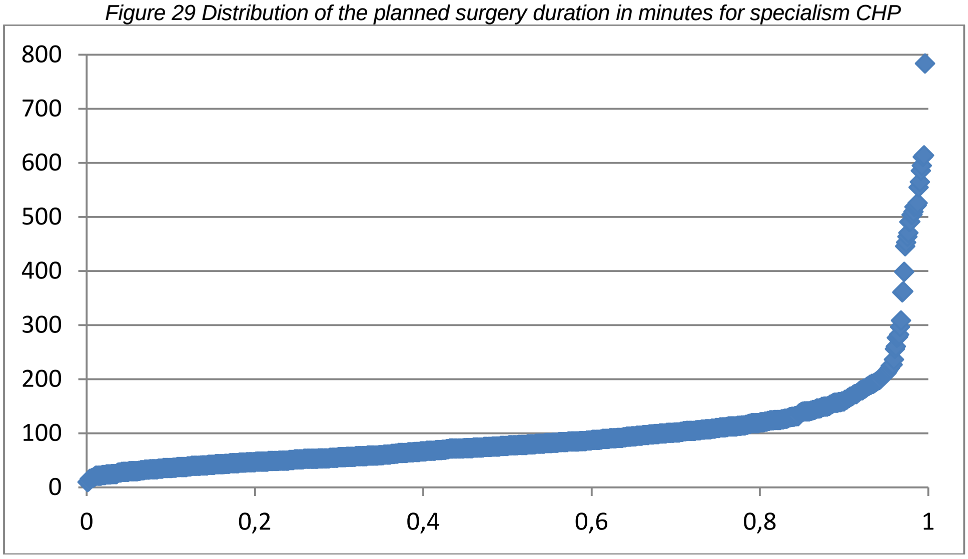


Figure 30 Distribution of the actual surgery duration in minutes for specialism CHP

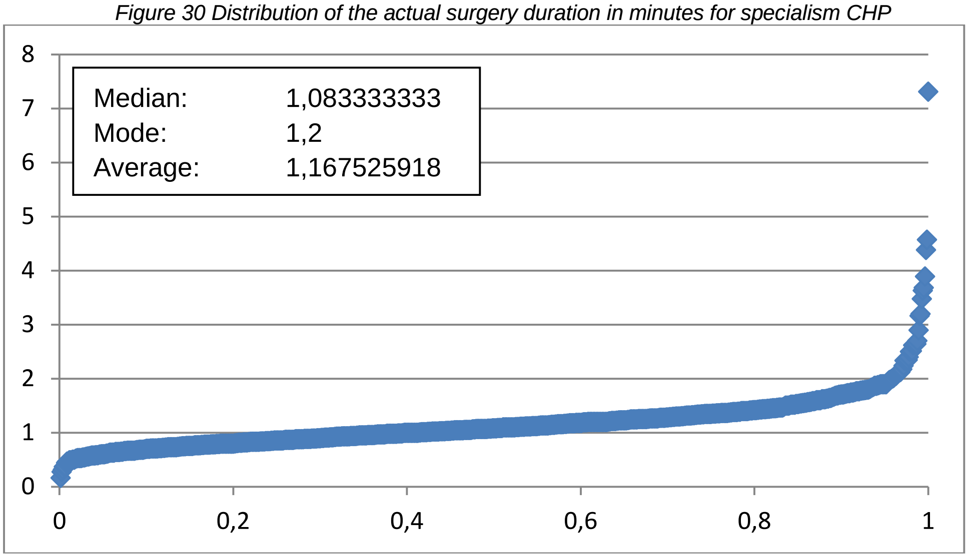


Figure 31 Distribution of the ratio between planned and actual surgery duration for specialism CHP

Specialism GYN

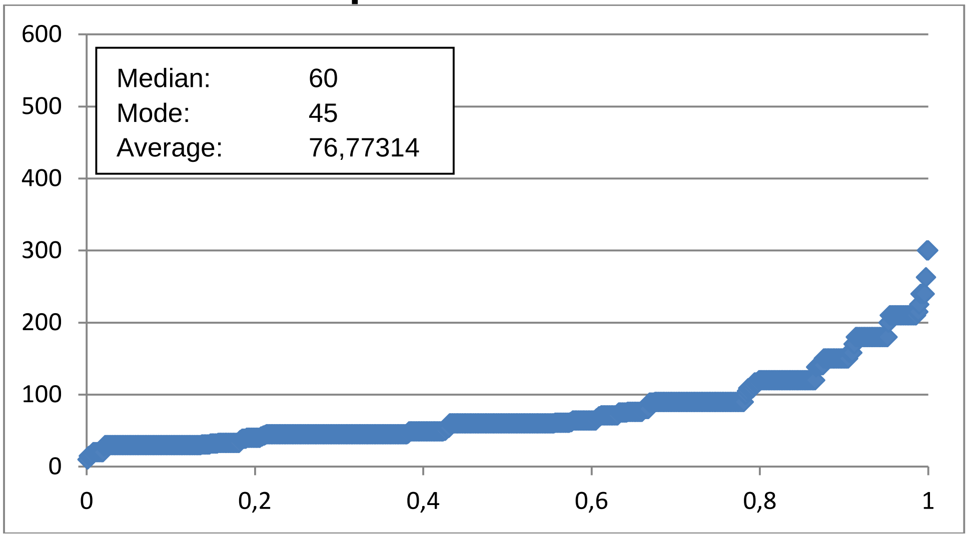


Figure 32 Distribution of the planned surgery duration in minutes for specialism GYN

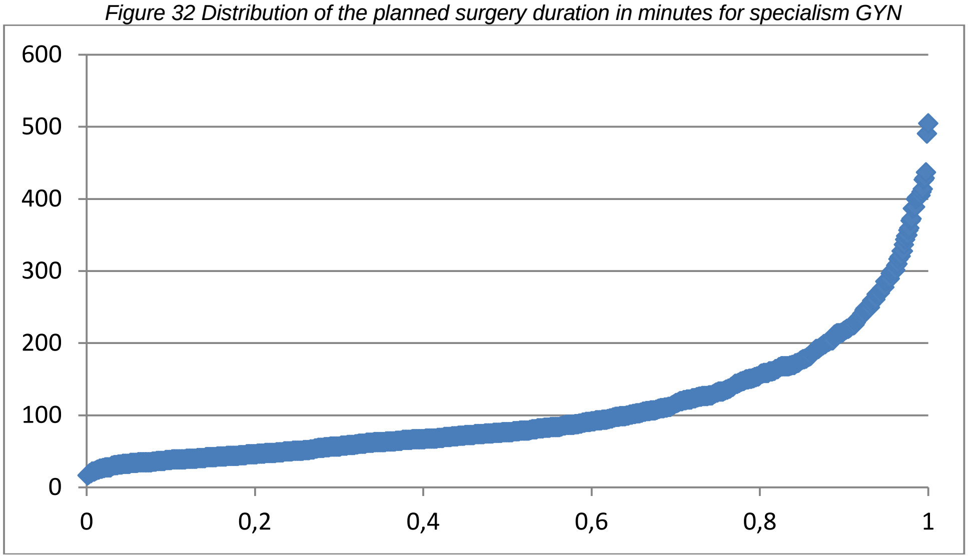


Figure 33 Distribution of the actual surgery duration in minutes for specialism GYN

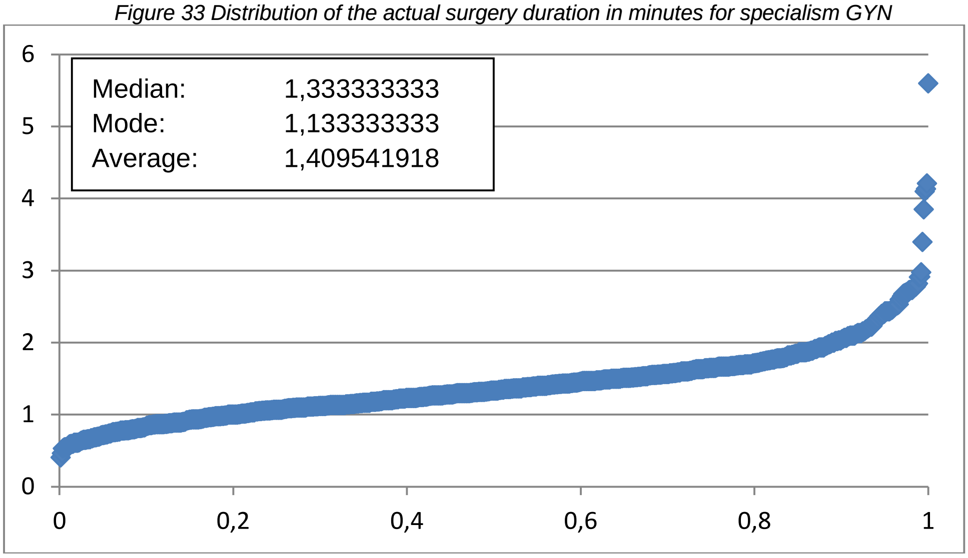


Figure 34 Distribution of the ratio between planned and actual surgery duration for specialism GYN

Specialism KNO

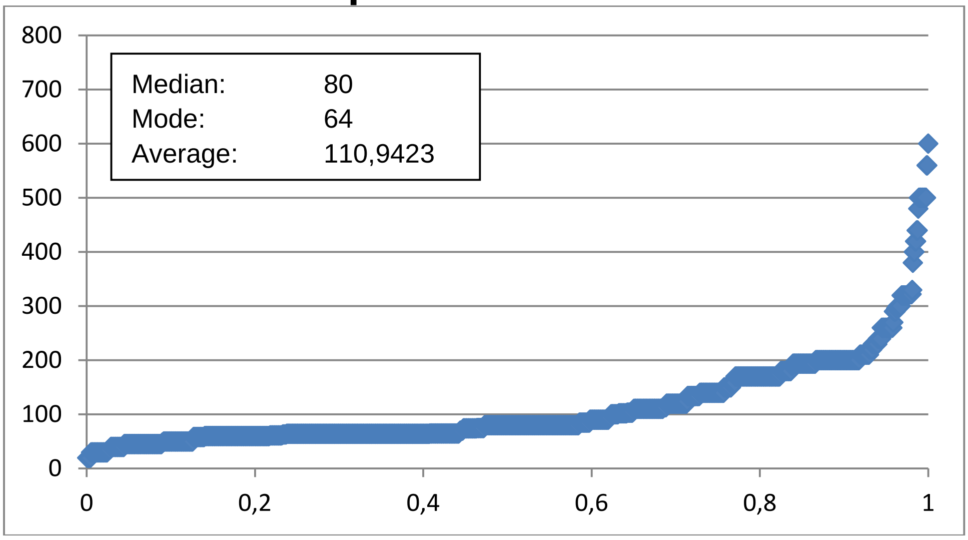


Figure 35 Distribution of the planned surgery duration in minutes for specialism KNO

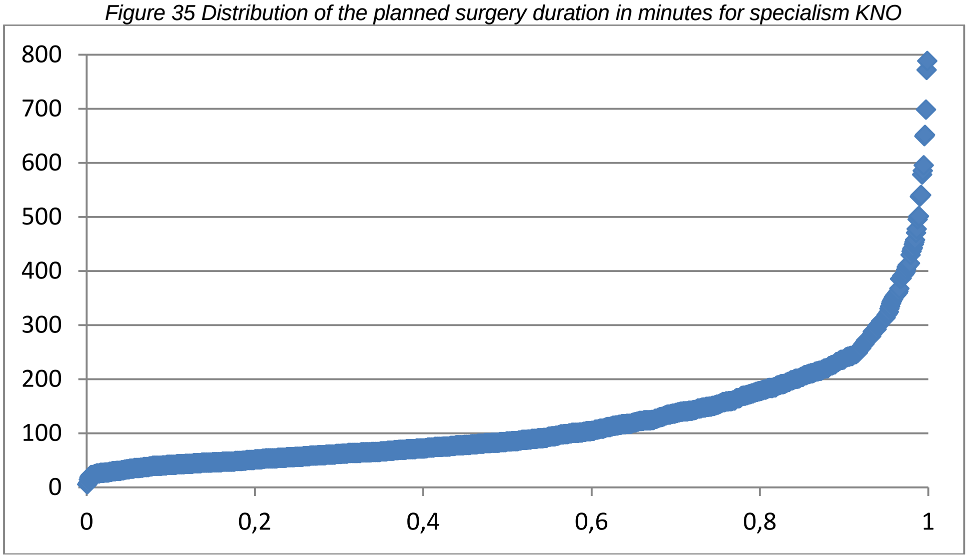


Figure 36 Distribution of the actual surgery duration in minutes for specialism KNO

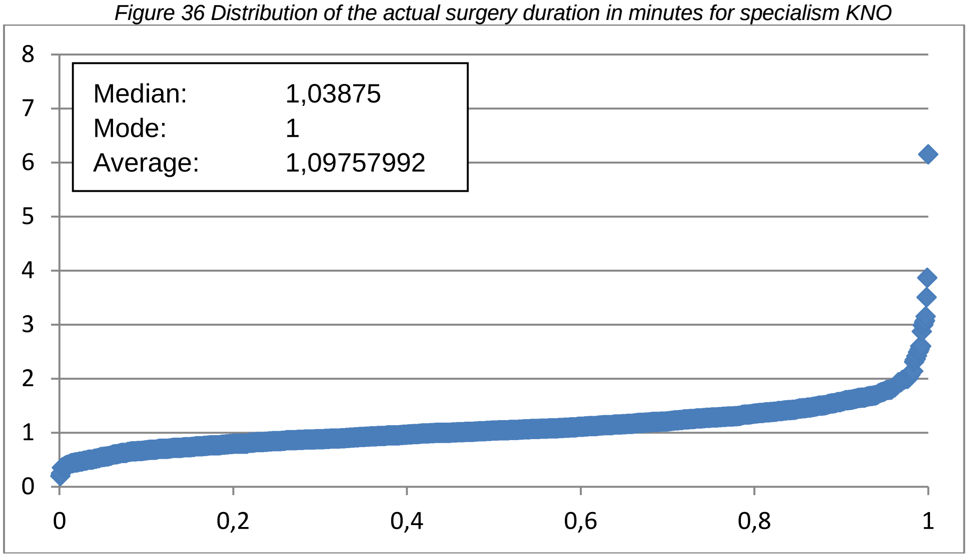


Figure 37 Distribution of the ratio between planned and actual surgery duration for specialism KNO

Specialism MND

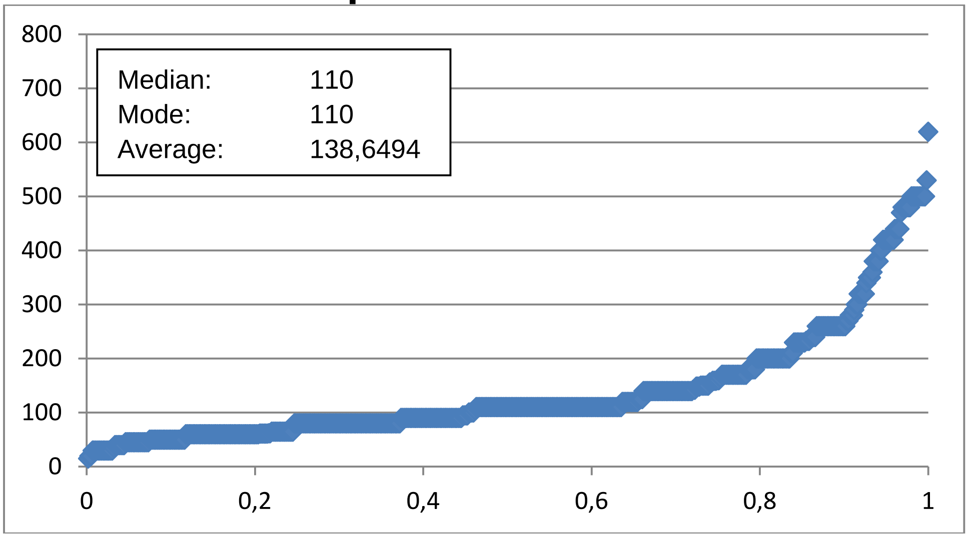


Figure 38 Distribution of the planned surgery duration in minutes for specialism MND

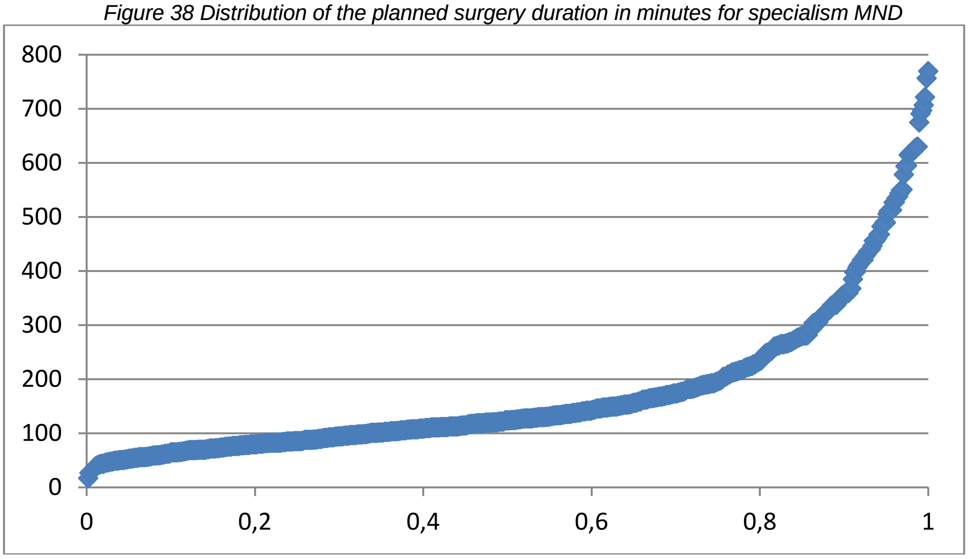


Figure 39 Distribution of the actual surgery duration in minutes for specialism MND

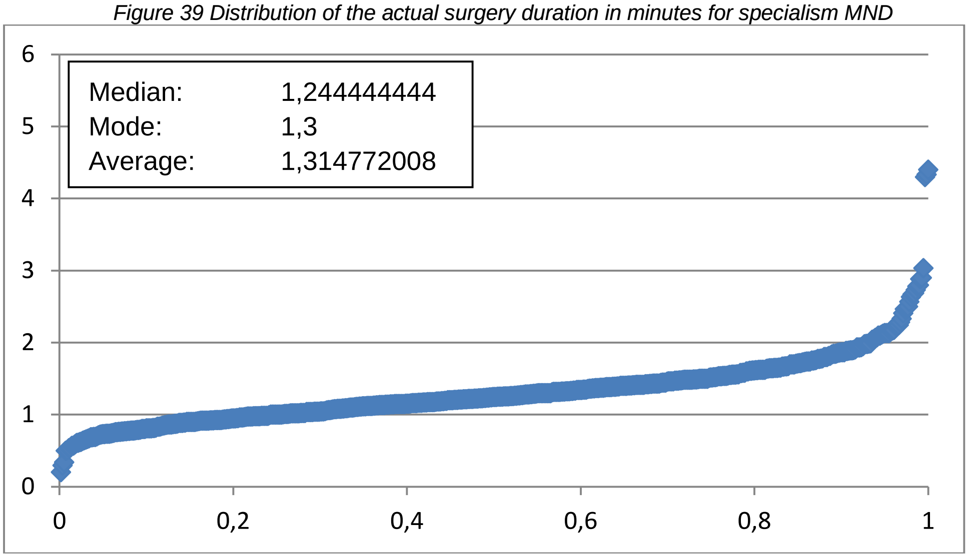


Figure 40 Distribution of the ratio between planned and actual surgery duration for specialism MND

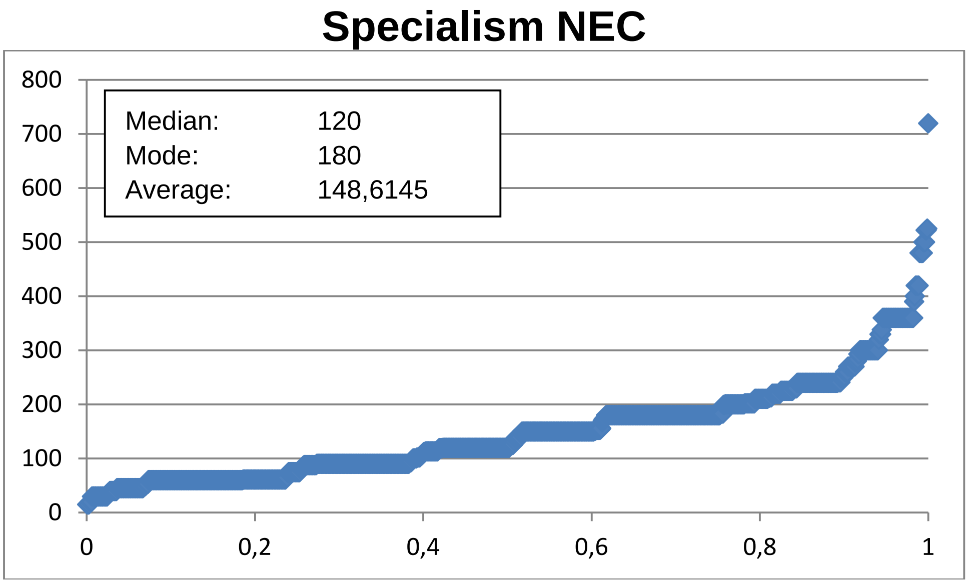


Figure 41 Distribution of the planned surgery duration in minutes for specialism NEC

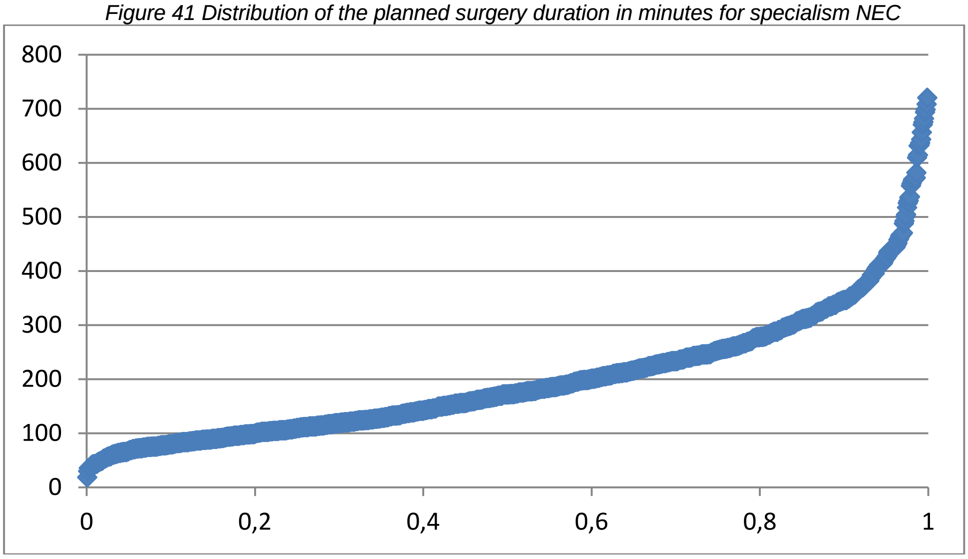


Figure 42 Distribution of the actual surgery duration in minutes for specialism NEC

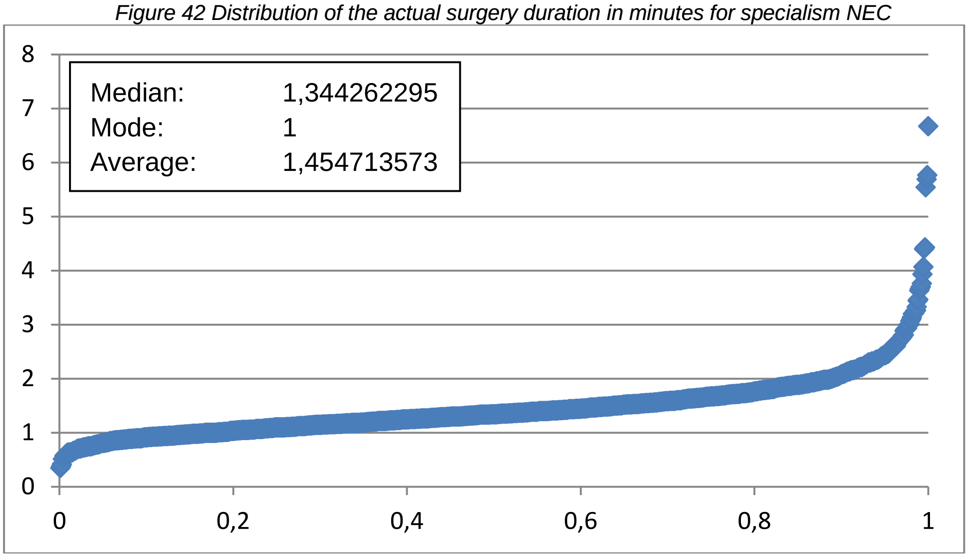


Figure 43 Distribution of the ratio between planned and actual surgery duration for specialism NEC

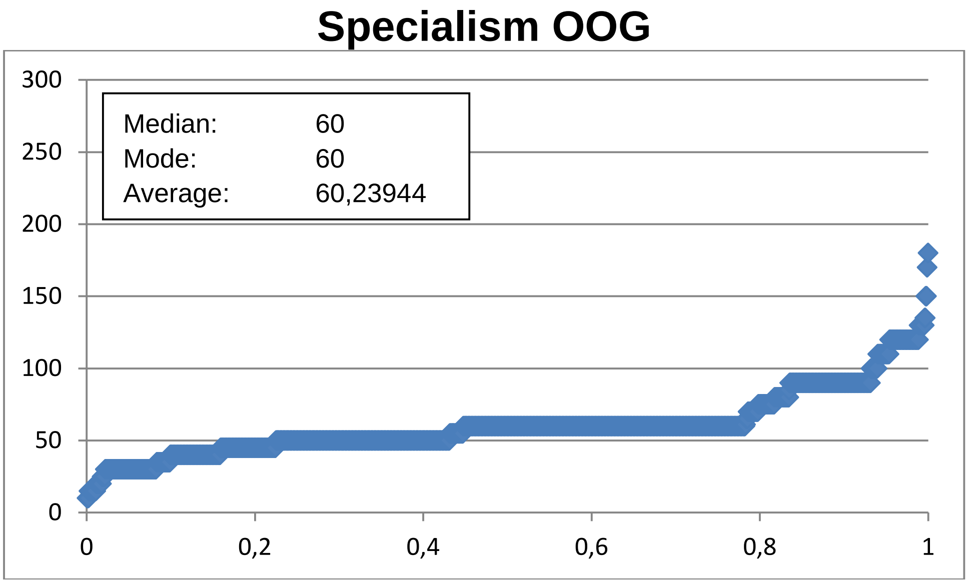


Figure 44 Distribution of the planned surgery duration in minutes for specialism OOG

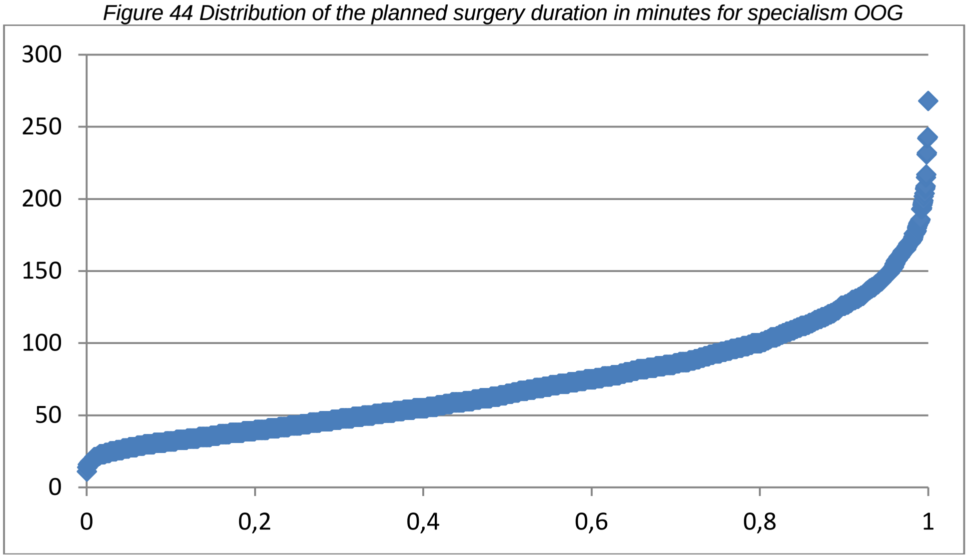


Figure 45 Distribution of the actual surgery duration in minutes for specialism OOG

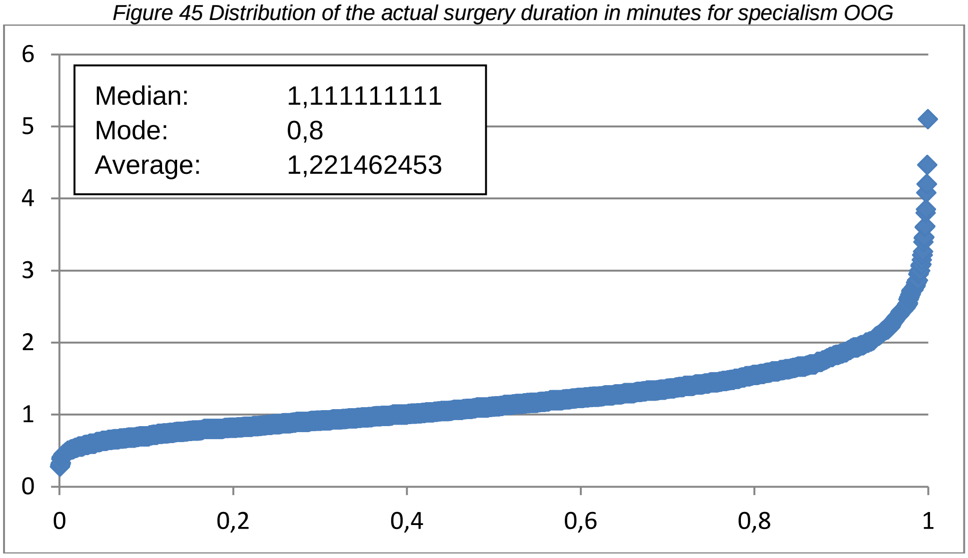


Figure 46 Distribution of the ratio between planned and actual surgery duration for specialism OOG

Specialism ORT

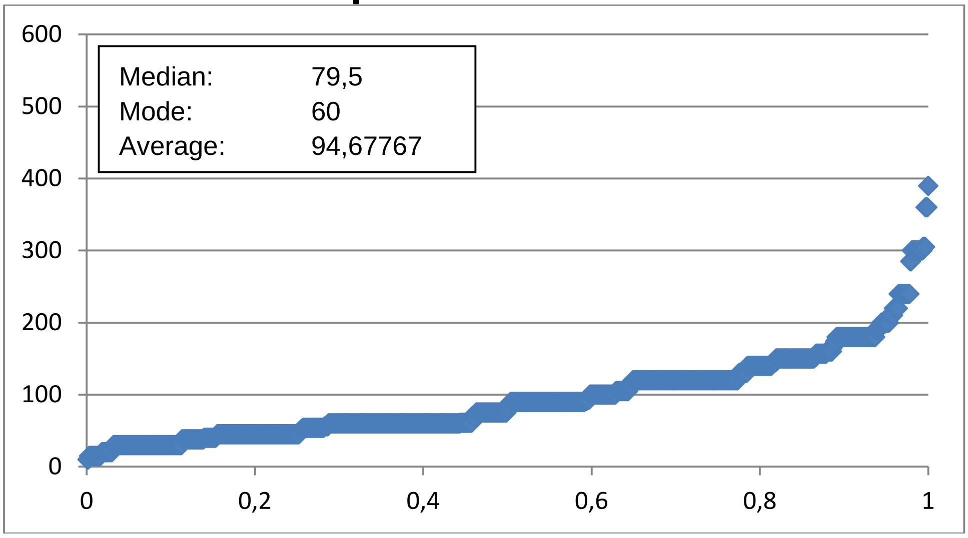


Figure 47 Distribution of the planned surgery duration in minutes for specialism ORT

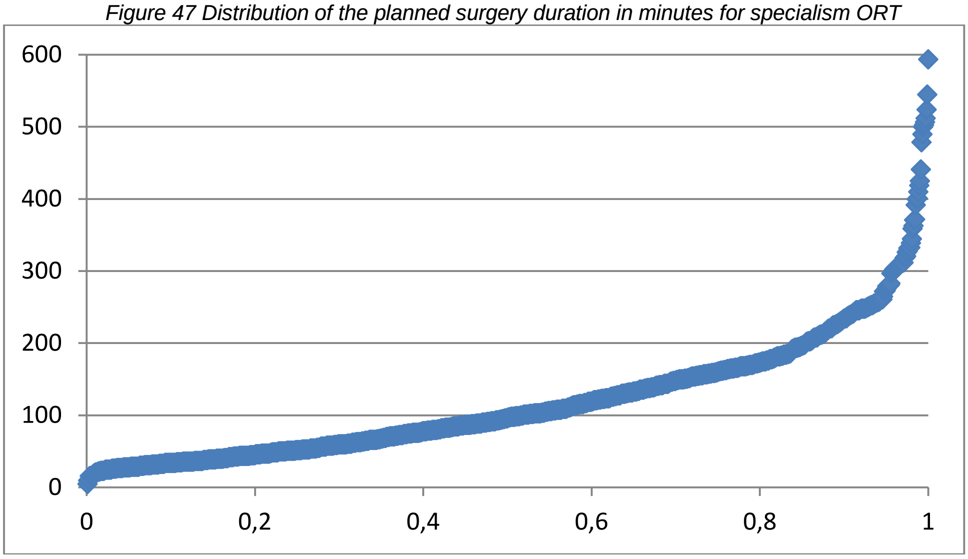


Figure 48 Distribution of the actual surgery duration in minutes for specialism ORT

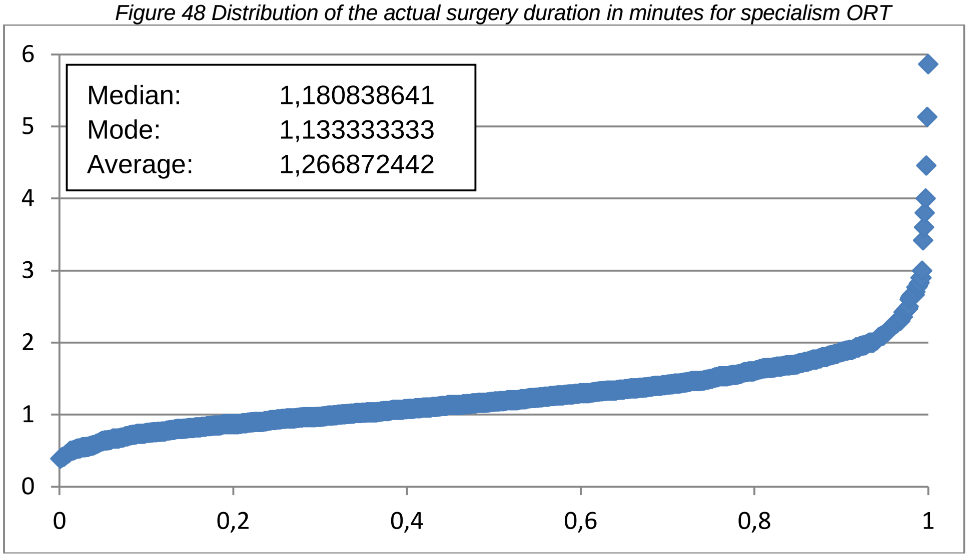


Figure 49 Distribution of the ratio between planned and actual surgery duration for specialism ORT

Specialism URO

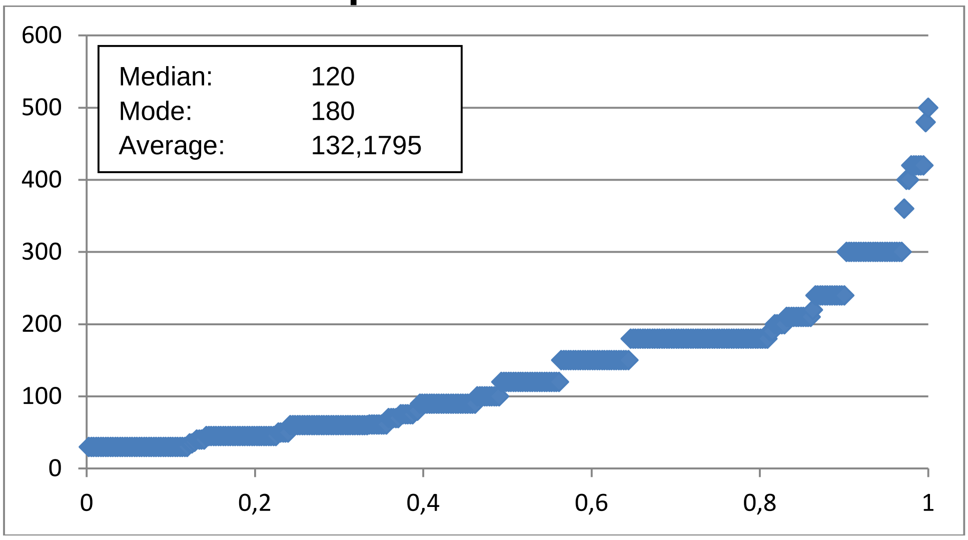


Figure 50 Distribution of the planned surgery duration in minutes for specialism URO

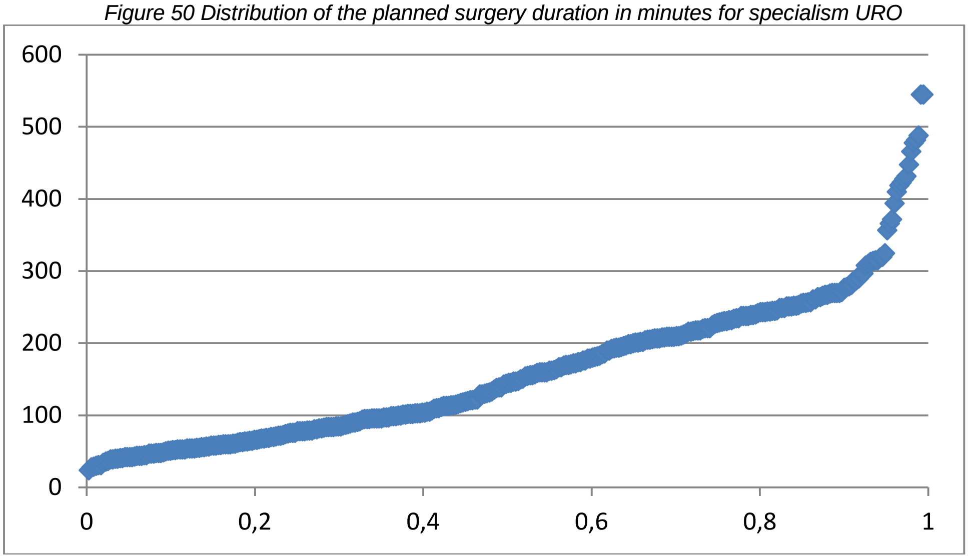


Figure 51 Distribution of the actual surgery duration in minutes for specialism URO

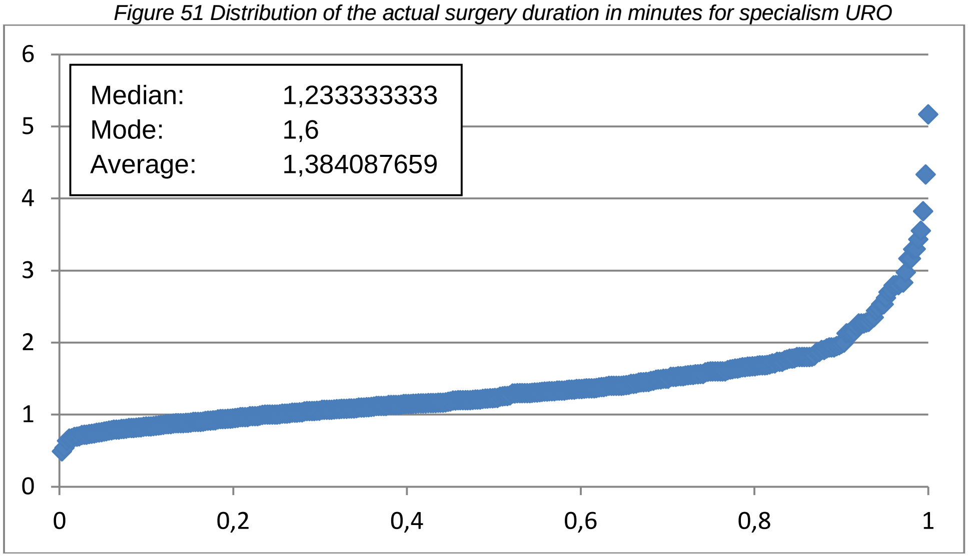


Figure 52 Distribution of the ratio between planned and actual surgery duration for specialism URO

Specialism VAT

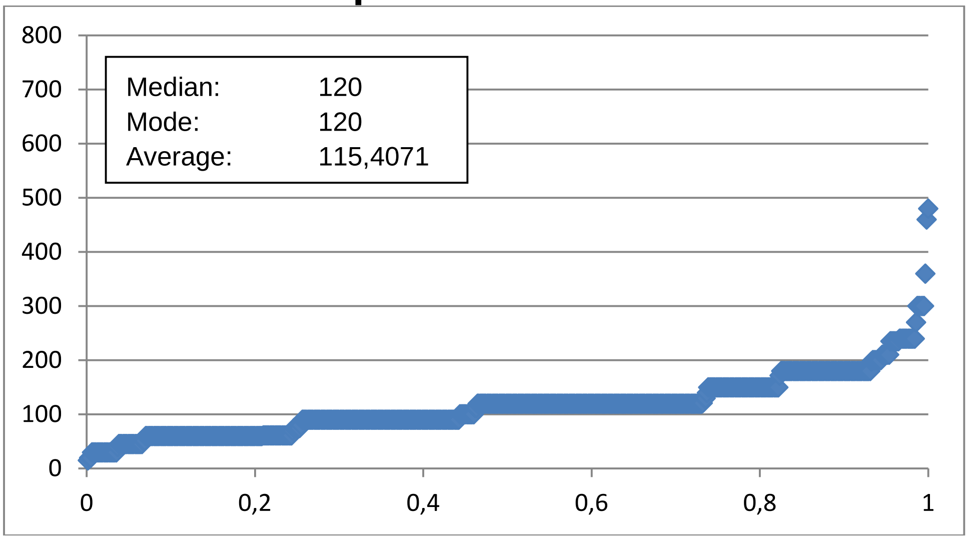


Figure 53 Distribution of the planned surgery duration in minutes for specialism VAT

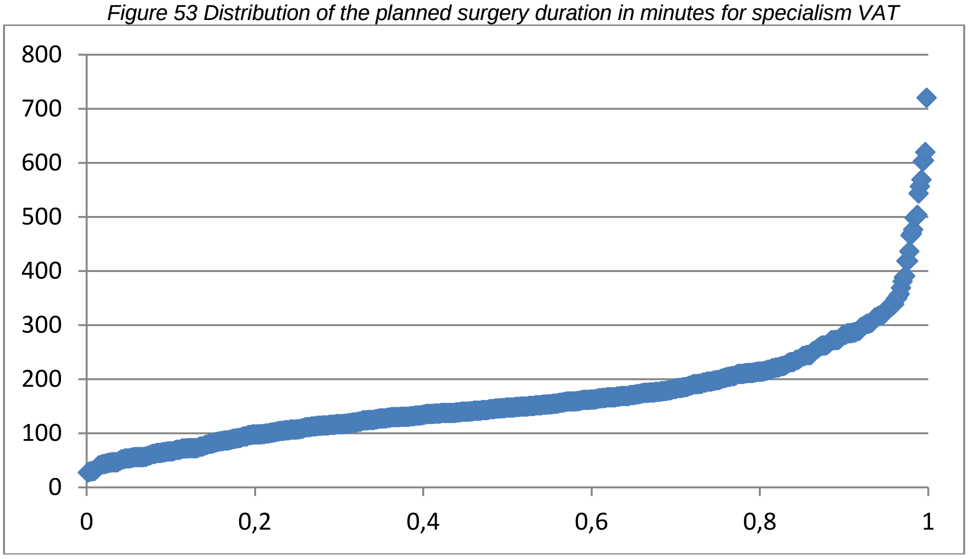


Figure 54 Distribution of the actual surgery duration in minutes for specialism VAT

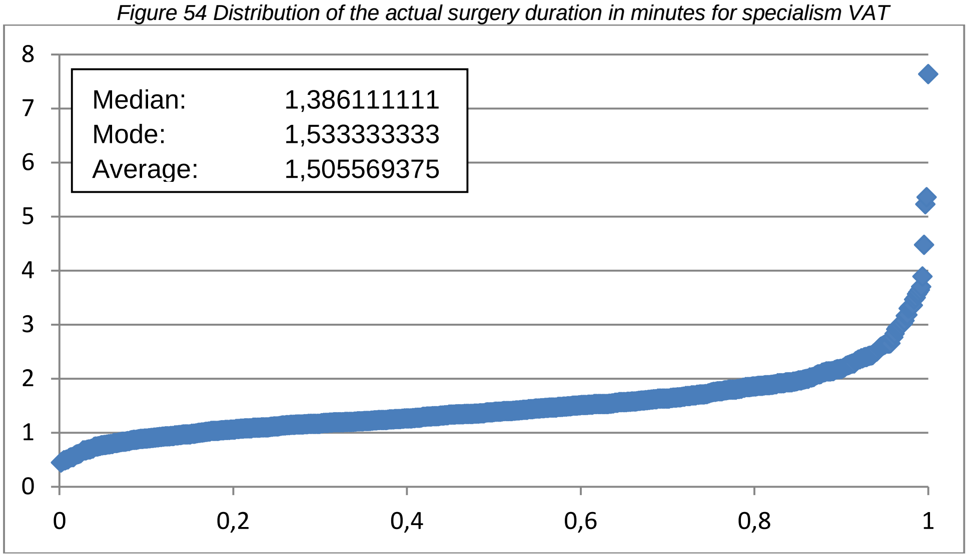


Figure 55 Distribution of the ratio between planned and actual surgery duration for specialism VAT

Overview/comparison of the different specialisms

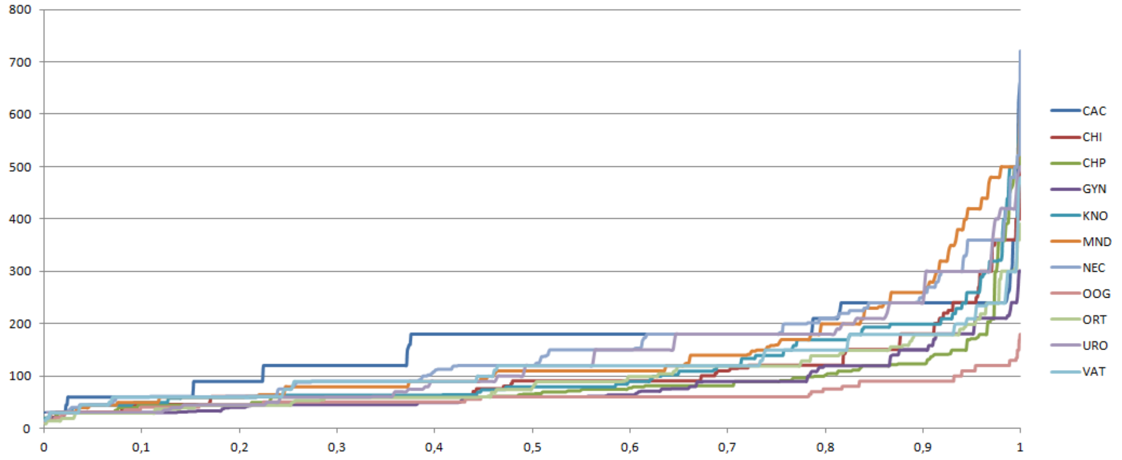


Figure 56 Distribution of the planned surgery duration in minutes for all 11 specialisms

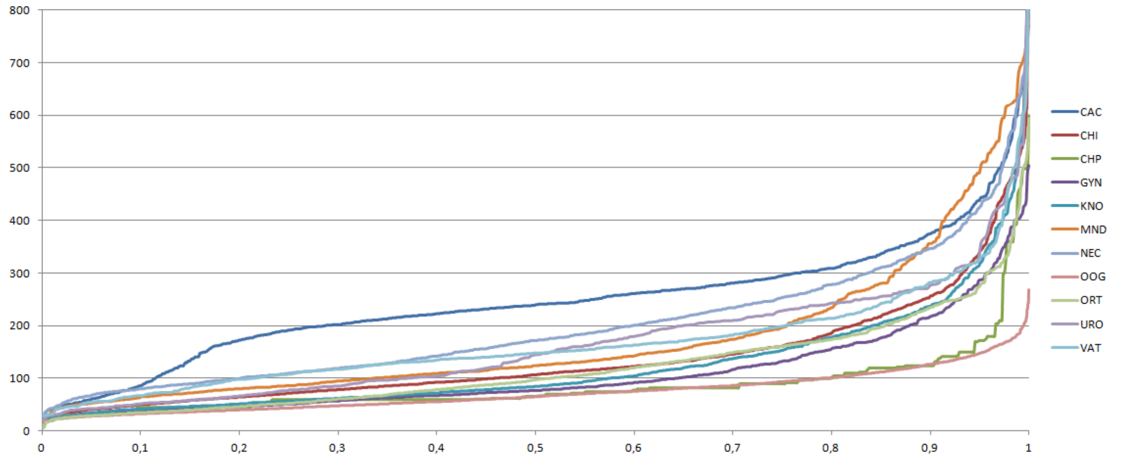


Figure 57 Distribution of the actual surgery duration in minutes for all 11 specialisms

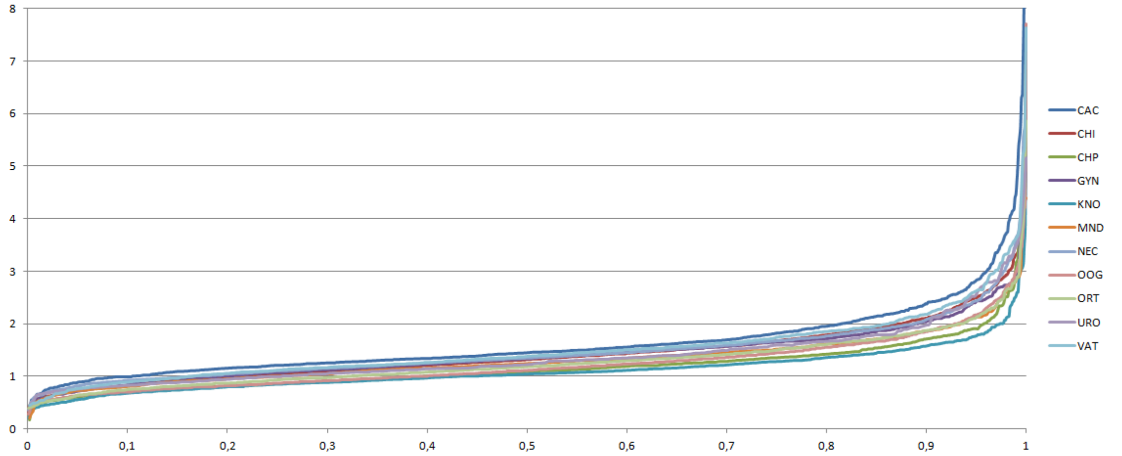


Figure 58 Distribution of the ratio between planned and actual surgery duration for all specialisms

Appendix G

Specialists debate resolved – An example of how the simulation model can be used beyond this research

As can be found in Appendix B , specialist of certain specialism's in the Erasmus MC think that their specialism is falling short when it comes to overtime they got to run and the amount of elective patients they have to cancel as result of non-elective surgery they are performing (of their own and other specialism's), compared to other specialism's. Main reason for this would be shorter surgery times which results in more so called "Break-in-moments" where waiting emergency patients could be inserted. In other words, the specialists work under the following idea:
"Shorter average surgery durations result in more overtime and cancellations. Therefore the current planning system is unfair the specialism's with shorter average surgery duration."
With the simulation written for this thesis, this was something that could be validated. Although the patient group in the Erasmus MC differs partly from the one used for this thesis, the similarities are enough for comparison. Running the simulation using configuration 1.4.0, approaches the OR-department at the Erasmus MC approximately.

Figure 59 shows the related results. The following conclusions can be drawn:

- (Top right) Their seems to be a positive linear relation between the average amount of overtime and the average surgery duration per specialism. This means that shorter average surgery durations do not cause significant amounts of extra overtime compared to longer average surgery durations.
- (Top left) The percentage of elective patients that gets cancelled seems to have a more complex relation than the one mentioned above for overtime. Although the distribution follows the one of the average surgery duration, there are some significant differences that can be observed. For GYN - CHI this difference is most significant.

For CHI this could be the result of the enormous amount of emergency patients of this specialism that arrive at the hospital. Why GYN stands out, cannot be concluded from the information gained here and could be further researched.

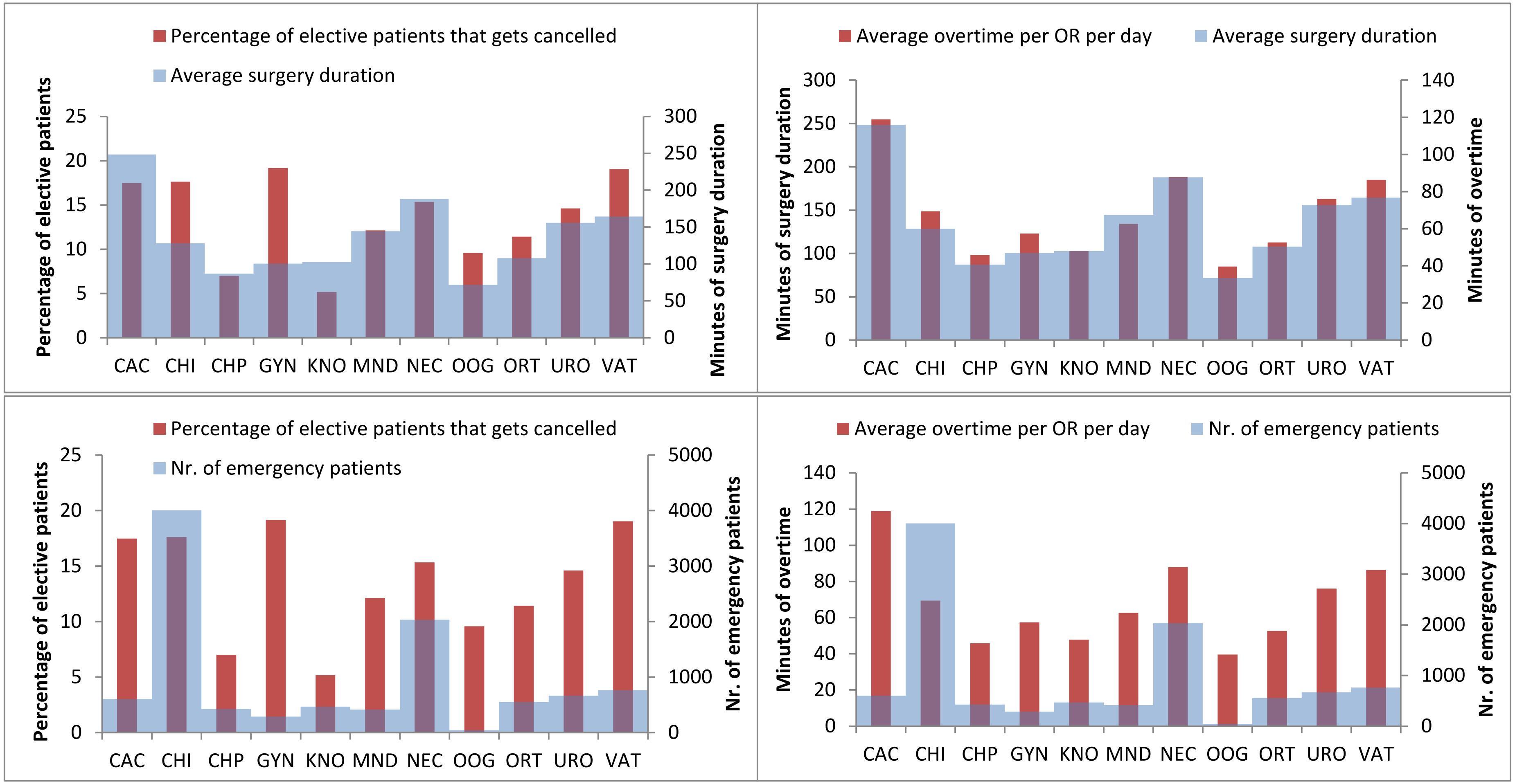


Figure 59 A linear relation between average overtime and average surgery duration seems to exist for the different specialisms. Percentage of cancellations per specialism could be explained by a combination of average surgery duration and the number of emergency patients.