Improving surgery scheduling for urology and vascular surgery in UMC Utrecht

Management summary

Problem description

The operating room (OR) department of UMC Utrecht faces a high demand for surgery time. However, the amount of surgery time it can offer is limited, because both surgical technologists and anesthesia assistants are scarce. The shortage of personnel is caused by a shortage of qualified OR- and anesthesia-assistants in the Netherlands. This leads to cancelled days of surgery because of personnel shortage. Therefore, the production quota is not met.

However, the available surgery time in UMC Utrecht is not utilized completely. In 2008, the gross utilization of the ORs was 89%, so 11% of the available time was not used for surgeries or changeovers. On the other hand, overtime occurred on 36% of the OR-days (an OR-day is one day of surgery in one OR), with an average duration of almost one hour. On top of this, 8.3% of the surgeries were cancelled on the day they were scheduled. Despite that other hospitals encounter the same problems, we strive to improve this situation.

Simulation

The high amount of resources involved when scheduling the OR and the stochastic nature of surgery durations make it hard to use an analytical approach to improve surgery scheduling. Simulation handles stochastic processes well and is able to evaluate several alternative solutions, whilst producing quantitative results. E.W. Hans developed a simulation model for the OR, which we adapt to serve as a basis for a simulation model in this research, and for other research projects in the OR of UMC Utrecht.

Research objectives

To restrict the scope of this research, we focus on the surgeries of urology and vascular surgery. We want to improve the problems we mentioned with the following objectives:

Decrease the percentage of cancelled surgeries and increase utilization while not increasing overtime.

Adapt and implement a simulation model of urology and vascular surgery in the operating department of UMC Utrecht.

Approach

We have studied related literature and designed several interventions that may improve OR performance. These interventions include a change of the number of working hours per day, the scheduling heuristic used, the use of a Master Surgery Schedule (MSS), and a combination of these interventions. An MSS contains slots for surgery types that recur regularly and is cyclically executed [Van Oostrum et al. 2009]. We adapted and implemented a simulation tool for two specialties (urology and vascular surgery) of the OR department of UMC Utrecht based on software developed in cooperation with University of Twente, called OR Manager. We used this tool to evaluate the effects of the interventions.

Conclusions

We performed a simulation study of the aforementioned interventions, from which we have drawn several conclusions:

- Adapting working hours to the MSS (for example, schedule one surgery of 7 hours and 3 surgeries of 3 hours respectively in one day of 7 hours and one day of 9 hours, instead of two days of 8 hours) helps to reduce the number of cancellations by 1 percentage point, with a loss of utilization of 1.4 percentage points.
- Longer working days allow a higher utilization with a lower amount of overtime, while the number of cancellations is not influenced. Utilization increases up to 5 percentage point for vascular surgery and overtime decreases up to 68% for urology, when twelve hours of surgery are scheduled per OR per day.
- Moving delayed surgeries at the end of the day from one OR to the other helps to decrease the number of cancellations by 1.4 percentage points and increase utilization by 0.8 percentage points.
- A combination of the interventions can reduce the number of cancellations by 50%, does not increase overtime and at the same time increase the utilization by 0.9 to 1.5 percentage points.

Recommendations

In de current situation, there are limited incentives for specialties to make good use of the resources on the OR. For example, scheduling too many surgeries on an OR-day can be a way to perform more surgeries, but has a negative effect on the expected overtime. We advise to implement a judgment of the OR performance of each specialty based on overtime, cancellations and utilization. This creates an incentive for OR performance improvement. A pilot implementation based on simulation outcomes of urology and vascular surgery will then be followed with great interest by other specialties and may result in a broad acceptance of the simulation tool. This could ultimately lead to a simulation of the entire OR department, including main resources and emergency surgeries.

Preface

A couple of years ago, in the second year of the bachelor Industrial Engineering and Management, all students had to choose whether they wanted to be in the health care track. For me, this was one of rare occasions that a choice was easy: “I’m not doing the health care track!”

In the past year, I found out that health care is actually an interesting field of research in the track I did choose, production and logistic management. UMC Utrecht has several interesting and complex challenges in production management. Even more interesting was, of course, the opportunity I got to watch live surgeries.

My assignment was to adapt and implement a computer simulation model of the OR department of UMC Utrecht. This simulation model forms the basis for my research and for further research, which my colleague Sabrina Ramwadhdoebe will perform during 2010.

I thank Arjan van Hoorn and Sabrina Ramwadhdoebe for their unremitting support during my internship in UMC Utrecht. I thank Mariken and Mitch for their pleasant company and Marco Schutten for his critical look and comments on this report. Finally, I thank Erwin Hans from University of Twente, for his support in both the research and the simulation tool, and the enthusiasm he showed during the discussions we had about the simulation tool.

Menno Hoeksema
Utrecht, March 2010

Table of contents

Chapter 1 Introduction

University Medical Centre Utrecht (UMC Utrecht) has an operating room (OR) department, which handles 23,000 surgeries per year. There are waiting lists for surgeries, which can be long for surgeries that are not urgent. This is not caused by a shortage of ORs, but due to a shortage of OR staff. We aim to maximize the number of surgeries performed with the limited number of OR staff. This may however not harm the job satisfaction of personnel and should go hand in hand with a reduction of the number of cancelled surgeries. In this research, we use a simulation study to search for interventions that help to reach these goals, by changing the scheduling of elective surgeries.

Early 2009, UMC Utrecht granted funding for a research project, as part of the second round of the 'Slimmer Beter' (smarter better) program, which focuses on organizing hospital processes in a smarter way to improve productivity of personnel and create better patient care. This research project uses the large amount of available data in UMC Utrecht, in combination with a simulation tool that is being developed by University of Twente, to investigate interventions that may improve OR performance.

This chapter starts with a short introduction of UMC Utrecht in Section 1.1. Section 1.2 describes the main problems that currently exist in UMC Utrecht. In Section 1.3, we list the project goals and research questions.

1.1 History and facts about UMC Utrecht

UMC Utrecht is one of the eight University Medical Centers in the Netherlands. It was founded as Stads- en Academisch Ziekenhuis Utrecht (AZU) in 1817 and has moved to a new location at De Uithof in 1989. In 1999 it merged with pediatric Wilhelmina Kinderziekenhuis (WKZ) and the medical faculty of University of Utrecht. WKZ and AZU are located next to each other at De Uithof.

UMC Utrecht has currently over 1,000 beds and employs around 10,000 people. The operating room department has one of the central positions in the organization. In 2008, 23,000 surgeries were performed, of which 9,600 were in the clinical OR department of AZU. Around 7,000 of these surgeries were elective and 2,500 were urgent or semi-urgent (source: ZIS).

1.2 Problem description

The OR department of UMC Utrecht has a high demand for surgery time. The amount of surgery time it can offer is however limited, because both surgical technologists and anesthesia assistants are scarce. This results in a conflict, which has two aspects:

- The limited number of personnel is a problem in the operating department. Some planned OR-days (an OR-day is one day of surgery in one OR) are cancelled because of personnel shortage. Therefore, the production quota is not met. The shortage of personnel is caused by a shortage of qualified OR- and anesthesia-assistants in the Netherlands. Some vacancies are filled by hiring temporary personnel. This is very costly.
- The second aspect of the conflict is the amount of surgeries that the personnel can do in a certain amount of time. During working hours in 2008, the gross utilization of the ORs in regular time was 89%, so 11% of the available time was not used for surgeries or changeovers. On the other hand, overtime occurred on 36% of the days, averaging 55 minutes per day with overtime. On top of this, 8.3% of the surgeries were cancelled within 24 hours before the planned start, which affects quality of care.

1.3 Goals and research questions

The problems described in Section 1.2 call for measures to improve OR performance. This is the first goal of this research:

Decrease the percentage of cancelled surgeries and increase utilization while not increasing overtime.

In Chapter 2 we explain which indicators we will use to measure performance. In this research, we will investigate several interventions that may improve the OR performance, for which we use a simulation model. This simulation model will also be used in further research to OR performance in UMC Utrecht, by other researchers. To enable this research, we formulate a second goal:

Adapt and implement a simulation model of urology and vascular surgery in the operating department of UMC Utrecht.

To reach both goals, we pose several research questions. Between brackets, we denote the chapter or section that answers a question.

The first step in this research is to analyze the processes, the control, and the logistical performance of the OR department.

1. How is the OR department currently organized? (Ch.2)
    a. How can the operating room process be described? (2.1)
    b. How is the planning process organized? (2.2)
    c. How does the OR department perform? (2.3)
        i. Which performance indicators describe OR performance best? (2.3)
        ii. On which indicators does the OR department under-perform? (2.4)

We observe some surgeries to learn about the working procedures. To investigate the current planning procedures, we interview planners. We obtain further information in informal meetings with surgical technologists and OR management. We also obtain information from the hospital information system.

2. Which interventions may improve the OR department's performance? (Ch. 3)
    a. Which literature is relevant to this research? (3.1)

We search the literature for interventions that may improve OR performance. We apply these interventions to the OR department and try to come up with more interventions. To evaluate the effect of the interventions, we use a simulation tool, which will be developed in cooperation with University of Twente (E.W. Hans). This tool is called OR Manager. We pose the following questions:

3. How can we model the current situation? (Ch.4)
    a. How can we design a simulation model? (4.1)
    b. How can we analyze data in such a way that the input of the simulation model resembles practice? (4.2)
    c. How valid is the model? (4.3)

We describe the OR manager and make some improvements to adapt it to UMC Utrecht's situation as closely as possible. We develop a base scenario of the current situation. For the simulation model, we need input of surgery data. We will derive this input from historical data of surgeries in 2008. We simplify data when this is possible without loss of generality and filter out any erroneous data. Therefore, we group surgeries in cooperation with a surgeon. We make sure that all surgeries are grouped in representative groups. We validate the model by comparing simulation outcomes with the results in the year 2008 and ask the planning surgeons whether the simulation resembles practice.

4. How do the interventions affect OR performance? (Ch. 5)

With the model, we simulate the interventions and interpret the resulting performance.

5. How can we use the obtained results to improve performance in practice? (Ch. 6)

We select the appealing interventions and investigate how to implement these.

1.3.1 Demarcation

This research is subject to several restrictions. Some of the restrictions are a consequence of UMC Utrecht's environment; others are to demarcate the research scope.

1. The focus of this research will be on the tactical and operational planning.
2. We focus on elective surgeries in the inpatient OR-department, which mainly serves large and complex surgeries.
   - This is the largest department, so it has the highest improvement potential. Leaving out the outpatient OR-department, which serves less complex surgeries, and the pediatric hospital reduces research complexity.
3. We focus on two specialties: urology and vascular surgery.
   - This reduces the amount of data analysis, and enables us to develop a method for data analysis, which can also be used for other specialties in the future. Urology and vascular surgery are specialties with a small operating volume, compared to other specialties. This makes them a suitable test case. They have different surgery characteristics, i.e. in the number of emergency surgeries and the duration and variability of surgeries.

4. We will not consider the effects of the surgery schedule on the use of intensive care and ward beds.
    - This reduces research complexity.

Chapter 2 Description of the OR department

This chapter describes the main processes in the clinical operating room department. Section 2.1 describes the current surgery process, followed by Section 2.2 with the control and planning processes. Section 2.3 describes the performance indicators and Section 2.4 describes the performance of the system. Section 2.5 concludes this chapter and states several bottlenecks.

2.1 Description of the surgery process

A patient who needs a surgery must first be screened by an anesthesiologist. For many patients, this can be done in the outpatient department. In this pre-operative screening, the anesthesiologist screens the patient for allergies and fitness for surgery and determines the type of anesthesia.

Before surgery, the patient arrives and receives a bed on the ward. The patient is not allowed to eat after midnight the day before the surgery. On the day of the surgery, the patient is brought to the holding. Table 2.2 shows the process in the OR department.

During the surgery process, the duration of the surgery and the duration of different phases during the surgery are registered. Illustration 2.1 shows the phases of a surgery the hospital registers.

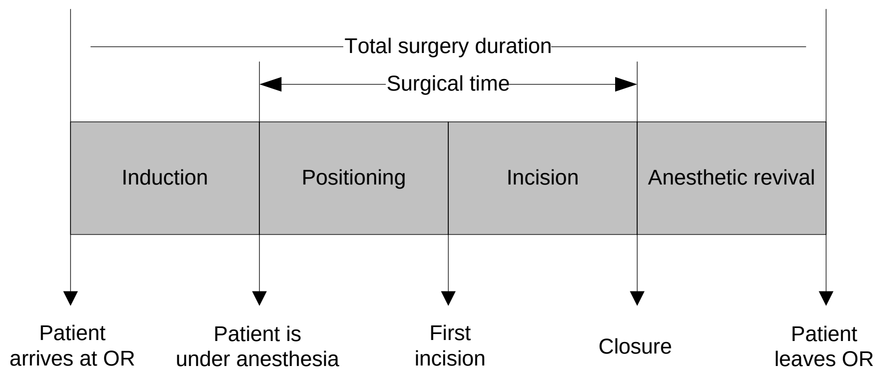


Illustration 2.1: phases of a surgery [Hoorn and Wendt 2008]

Phase	Surgery	Anesthesia
Patient transfer	Surgeons inform personnel of the OR about the patient, the surgery, and the instruments they need.	Anesthesiologist decides which anesthesia techniques will be used and which techniques cannot be used, i.e. because of allergies.
Preparation OR and anesthesia	Surgical technologists prepare instrumentation.	Anesthesiologist and anesthesia assistant bring patient from holding to the OR and attach monitoring equipment to the patient. Then they provide anesthesia, after which the patient is positioned for the surgery.
Incision	Surgeon performs surgery. OR assistants hand the surgeon instruments and assist if necessary.	Anesthesiologist and anesthesia assistant monitor vital functions and keep the patient stable.
Anesthetic revival	Surgeon is finished and OR assistants tidy the OR, the used equipment, and disposables.	Anesthesiologist and/or anesthesia assistants prepare the patient for departure of the OR.
Clean up	OR assistants weigh the instrument trays to check whether the trays are complete. If necessary, the OR is cleaned.	Anesthesia team brings the patient to the recovery.

Table 2.2: the surgery process

During the working day, there is not always a patient in the OR. At the start of the day, the personnel needs time to prepare the equipment and to brief the day. During the day, the changeovers between surgeries take time as well. At the end of the day, the personnel needs time to clean up the OR. If the last surgery finishes before the planned end of the day, an early end is counted. If it finishes after the planned end of the day, overtime is induced. Illustration 2.3 shows the elements of a day the hospital registers.

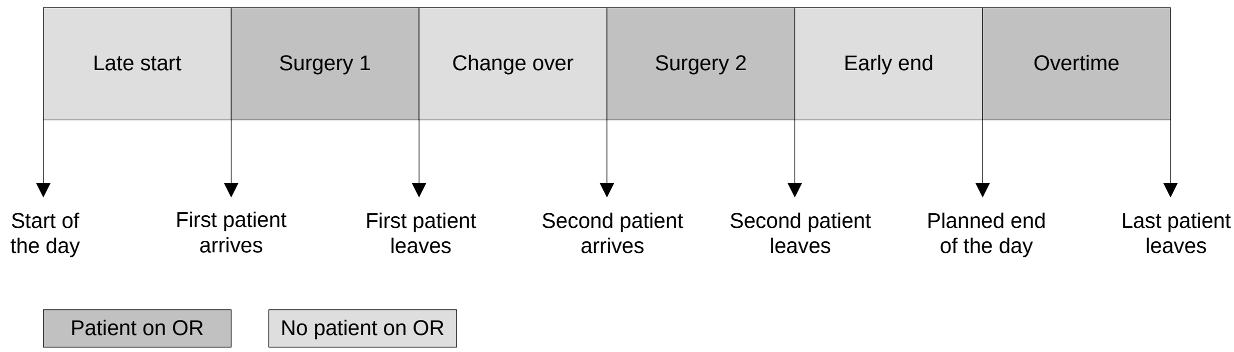


Illustration 2.3: registration of an OR-day [Hoorn and Wendt 2008]

A surgery may consist of several surgical procedures. A surgical procedure is for example the placement of a vascular prosthesis. If the surgeon places several prostheses in different vessels, these will be regarded as different surgical procedures. The main purpose of the surgery, the most important surgical procedure, is called the main surgical procedure. All other surgical procedures are auxiliary surgical procedures.

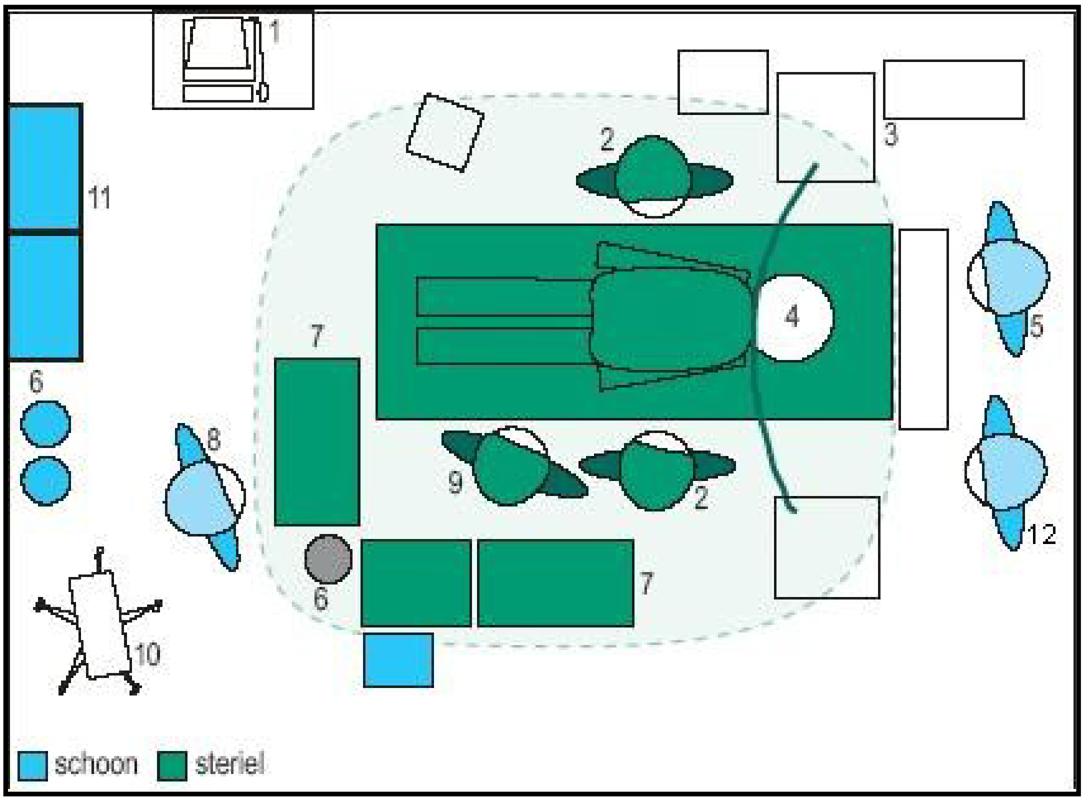
2.1.1 Work force

With a standard surgery in the inpatient department, at least five people are necessary: a surgeon, an anesthesiologist, an anesthesia assistant, and two surgical technologists. The surgeon performs the surgery, often accompanied by a doctor assistant or a co-assistant. Surgeons are grouped in 11 specialties (see Table 2.4).

Specialty	**Abbreviation**
Cardiac surgery	CAC
General surgery	CHI
Plastic surgery	CHP
Gynecology	GYN
Ear Nose and Throat (ENT)	KNO
Mouth and Jaw (Orthognathic surgery)	MND
Neuro surgery	NEC
Ophthalmology	OOG
Orthopedics	ORT
Urology	URO
Vascular surgery	VAT

Table 2.4: main specialties in the OR

The scrub surgical technologist hands the operator the instruments he needs from the sterile table with instruments. The circulation surgical technologist restocks the table with instruments. An extra circulation surgical technologist can bring instruments and supplies from outside the OR. An anesthesiologist is responsible for the vital functions and anesthesia, mostly in two rooms at the same time. In each OR, the anesthesiologist is assisted by an anesthesia assistant, who stays with the patient all the time. All personnel and equipment is shown in Illustration 2.5. For larger surgeries, more personnel may be required. Sometimes several surgeons operate a patient at the same time or in succession. In these cases, sometimes more OR-assistants and anesthesia assistants are needed.



1 computer	5 anesthesiologist	9 scrub surgical technologist
2 surgeon	6 litter bin	10 stock
3 anesthesia equipment	7 instrument tables	11 stock
4 patient	8 circulating surgical technologist	12 anesthesia assistant

Illustration 2.5: interior and personnel in an OR [Los 2004]

In the morning, every OR team starts with a briefing, in which the surgeries of the day are considered. The first patient usually arrives in the OR around 8:15. At 16:00, the last patient should have left the OR.

Some specialties, for example cardiac surgery, have surgeries that take longer than a normal working day and many surgeries that take over half a working day. The involved specialties sometimes have longer working days and are allowed to finish at 17:00, 18:00, or later. Three teams of OR personnel starting at 12:30 cover these hours. Additionally, these teams take over the duties of different OR teams during the day for their lunch break and afternoon tea. Another exception to the usual working hours are the “parent-ORs”. These ORs have working hours from 9:15 to 14:45. Working parents can get these special working hours to be able to pick up their children from school.

During the night, three teams of surgical technologists can be present and will be called, in case they are needed. If there are no emergency surgeries, no surgical technologists are present. In this case, only an anesthesia assistant and an anesthesiologist are present.

The weekend is divided in three shifts per day. During these shifts, one surgical technologist and one anesthesia assistant are present. Additionally, three more surgical technologists and anesthesia assistants are on call. When an emergency surgery is performed, the surgical technologist from the involved specialty is called in. Both working day and weekend shifts are shown in Illustration 2.6.

“Anders Roosteren”

Parallel to this research, hospital management performs another project called “Anders Roosteren” (scheduling differently). This project aims at scheduling the work force in such a way that individual wishes can be met. These wishes can include a different number of working hours per day, or a different moment to start the working day. Some of the findings of this project that may be useful for our research are (source: Anders Roosteren):

1. A nine hour working day may convince personnel who work four days of eight hours to work four days of nine hours, which results in an increase of capacity.
2. 40% of the personnel prefers an eight hour working day, whereas 35% of the personnel prefers a nine hour working day.

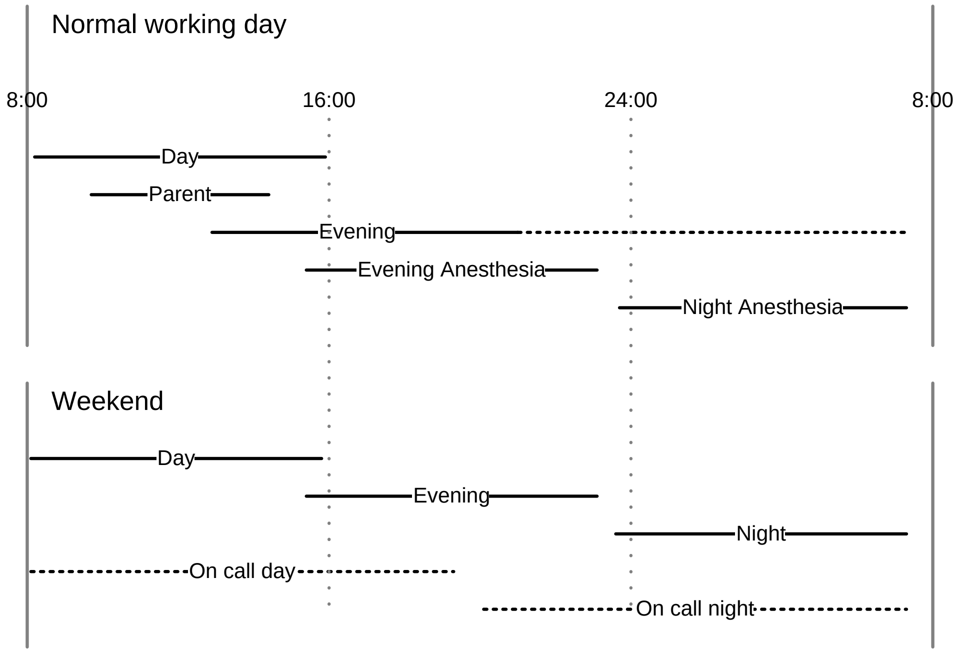


Illustration 2.6: working hours. Dotted lines represent shifts on call

2.1.2 Surgery statistics

In 2008, around 23.000 surgeries were performed in UMC Utrecht. This is about the same number as the years before (see Table 2.7). The surgeries were performed in three locations. In 2008, 9605 of these surgeries were performed in the clinical OR.

	Location			
Year	**Outpatient**	**Inpatient**	**WKZ (children)**	**Total**
2005	7286	10095	5879	**23260**
2006	7039	9740	5838	**22617**
2007	6977	9794	5795	**22566**
2008	7441	9605	5889	**22935**
Total	**28743**	**39234**	**23401**	**91378**

Table 2.7: surgeries in UMC Utrecht (source: ZIS)

Illustration 2.8 shows the division of surgeries between the specialties and between elective and urgent, within the inpatient ORs of the AZU in 2008. Urology and vascular surgery are amongst the specialties with a smaller volume. The total number of elective surgeries was 7098, the total number of urgent surgeries was 1157, and the total number of semi-urgent surgeries was 1339. Urgent surgeries are surgeries that need to start as soon as possible. If no OR is available, the start of other surgeries will be delayed to enable a quick start of the urgent surgery. Semi-urgent surgeries are surgeries that need to start within 24 hours of their arrival. All other surgeries are considered to be elective surgeries. These surgeries are normally scheduled over a week in advance.

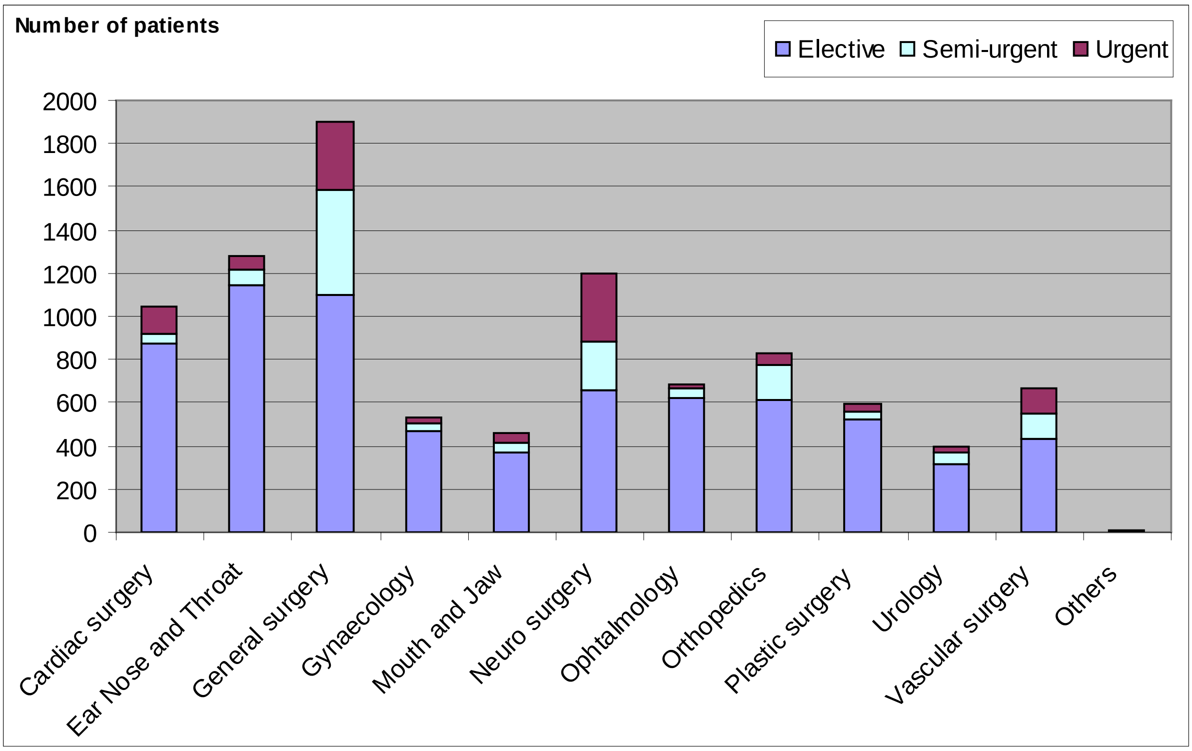


Illustration 2.8: inpatient surgeries in 2008 (source: ZIS)

The specialties have a different case mix and different surgery characteristics. One example is the average surgery duration (see Table 2.9). The average inpatient surgery durations of for example cardiac surgery and neuro surgery, are over three times as large as the duration of an average ophthalmology surgery. Illustration 2.10 shows the difference between two measures of size of a specialty: total surgery duration versus total number of patients. We see large differences between these measures.

Specialty	Av. Surgery duration (min)
Cardiac surgery	242
Ear Nose and Throat	131
General surgery	167
Gynecology	124
Mouth and Jaw	224
Neuro surgery	245
Ophthalmology	75
Orthopedics	149
Plastic surgery	118
Urology	176
Vascular surgery	172
Others	66
Total	**165**

Table 2.9: average inpatient surgery duration per specialty in 2008 (source: ZIS)

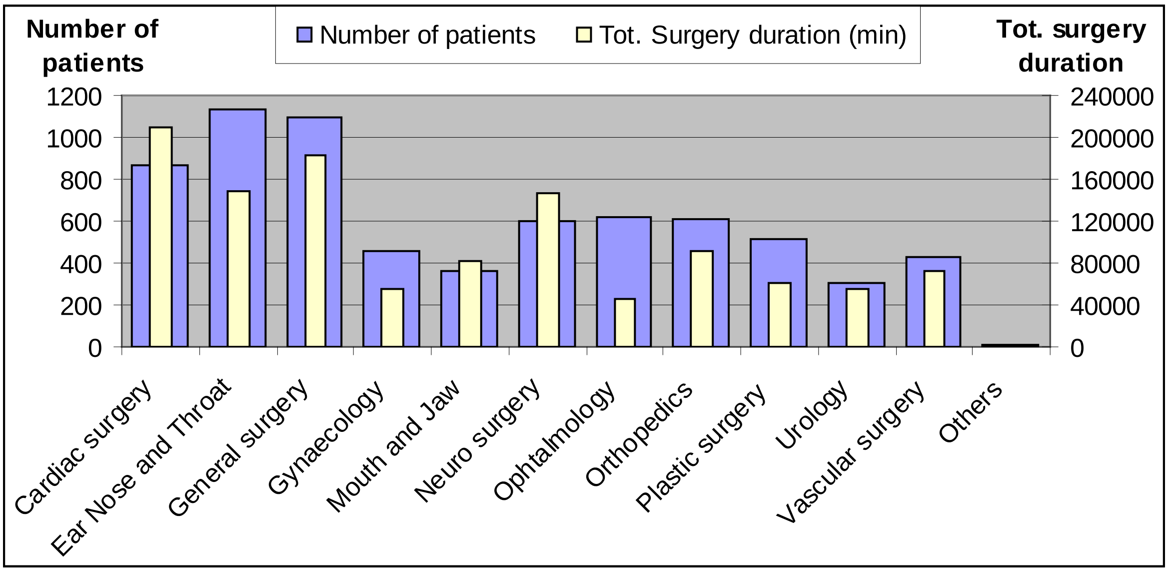


Illustration 2.10: inpatient surgery duration per specialty in 2008 (source: ZIS)

We have summarized the main surgery characteristics of the chosen specialties, urology and vascular surgery, in Table 2.11. The most salient difference is the average standard deviation. This is caused by the wider range of both small and large surgeries urologists perform, compared to vascular surgeons. Note that the number of vascular surgeries is higher than the number of urological surgeries, while the number of different (main) surgical procedures is approximately the same for both specialties. The number of surgical procedures is larger for urology. This is caused by a number of small surgical procedures that urologists often perform as an auxiliary surgical procedure, for example chromocystoscopy (looking in the bladder).

	Urology	**Vascular surgery**
Number of surgeries	340	500
Average duration (min)	169	165
Average standard deviation	132	80
Number of different main surgical procedures	118	112
Number of different surgical procedures	159	148
Number of unique combinations of surgical procedures	210	200
Average number of surgical procedures per surgery	1.9	1.6

Table 2.11: characteristics of inpatient vascular and urology surgeries in 2008 (source: ZIS)

When we look at the emergency surgeries, we see that the number of emergency surgeries is growing in the past few years (see Table 2.12). General surgery and neuro surgery have the most emergency surgeries, contributing around half of the cases.

Specialty	**2005**	**2006**	**2007**	**2008**
Cardiac surgery	150	188	201	165
Ear Nose and Throat	100	101	105	132
General surgery	730	744	761	790
Gynecology	89	86	95	73
Mouth and Jaw	65	73	96	93
Neuro surgery	412	395	396	583
Ophthalmology	54	48	86	74
Orthopedics	188	198	170	210
Plastic surgery	54	77	73	73
Urology	38	60	69	90
Vascular surgery	295	220	201	235
Others	13	14	8	5
Total	**2188**	**2204**	**2261**	**2523**

Table 2.12: number of inpatient emergency surgeries per specialty per year (source: ZIS)

The emergency surgeries are split in urgent surgeries, which have to be handled immediately, and semi-urgent surgeries, which need to be handled within 24 hours. As we can see in Table 2.13, there are a few differences between urgent and semi-urgent average case durations, although urgent surgeries tend to be a quarter of an hour longer, on average, than semi-urgent surgeries. Between specialties however, large differences exist. Cardiac urgent surgeries for example, average around 4 hours, almost twice as long as several other specialties.

	Urgent		Semi-urgent	
Specialty	**Av. duration (min)**	**Stdev. (min)**	**Av. duration (min)**	**Stdev. (min)**
Cardiac surgery	233	181	177	110
Ear Nose and Throat	100	63	94	67
General surgery	123	73	112	88
Gynecology	95	65	85	43
Mouth and Jaw	124	80	148	107
Neuro surgery	132	80	144	89
Ophthalmology	76	57	70	27
Orthopedics	143	87	149	84
Plastic surgery	122	64	100	72
Urology	108	48	100	50
Vascular surgery	152	95	130	76
Others	52	6	72	28
Total	**138**	**101**	**123**	**86**

Table 2.13: average duration and standard deviation of (semi-) urgent inpatient surgeries in 2008 (source: ZIS)

2.2 Description of the planning process

We divide the planning process roughly into four main steps. Strategic planning (Section 2.2.1), tactical planning (Section 2.2.2), operational off-line planning (Section 2.2.3), and operational on-line planning (Section 2.2.4)[Hans and Wullink 2006].

2.2.1 Strategic planning: management contract / production agreement

Once a year, the hospital management and the specialties decide how many hours of OR time will be assigned to each specialty. This is mainly based on historical production and gets adjusted only incrementally. These production agreements are written down in a management contract.

2.2.2 Tactical planning: assigning OR-days to specialties

Yearly, a planner assigns each available OR-day to a specialty, based on the production agreement. Every day, one OR is used for emergencies. This assignment is mostly based on history. Many ORs have specialized equipment for the specialty they are assigned to.

This rough-cut division of capacity is refined by making a yearly provisional schedule in which individual OR-days are assigned, in such a way that the production agreements are met. In the resulting schedule, some OR-days are parent-ORs-days, some have longer working hours (see Section 2.1.1), and some are not used.

The planner makes the final schedule on a monthly basis. In this schedule, availability of personnel and some wishes of specialties are taken into account. Due to the shortage of personnel, this usually leads to the cancellation of some OR-days.

2.2.3 Operational planning off-line: assigning surgeries to OR-days

The planning of individual surgeries is done by planners from each specialty. Their way of working differs between the specialties. The aim of these planners is to fit as many surgeries as possible into the assigned OR time, and to create a workable schedule for the surgeons.

The planner of vascular surgery uses a master surgery schedule (MSS). An MSS contains slots for surgery types that recur regularly and is cyclically executed [Van Oostrum et al. 2009]. This schedule is presented in Table 2.14. Note that the number of abdominal aneurysms planned on Tuesdays depends on the expected complexity of the surgeries and is decided by the planner.

Day	**Surgeries**
Monday	Open Aneurysm + Small surgeries
Tuesday	2 or 3 * Abdominal Aneurysm
Wednesday	Nefrectomy + Kidney transplant
Thursday	3 * Carotid
Friday	Other surgeries (if Friday is assigned)

Table 2.14: Vascular surgery MSS

The planner tries to schedule the surgeries in the MSS first. One of the Carotid surgeries is left open for a semi-urgent surgery and is filled in two days up front. If no more surgeries with a place in the MSS are available, the planner schedules other surgeries in and around the MSS slots. Long surgeries and surgeries that have been on the waiting list for a long time have priority. The availability of (specialized) surgeons and other resources fix the MSS in its current form. A change of schedule would cause changes in several other departments.

The planner of Urology does not use an MSS. She schedules the surgeries based on the availability of specific surgeons. A surgery is selected based on its urgency and the amount of time is has been on the waiting list.

Every Thursday, next week's operating schedules of all specialties are brought together and evaluated in a central meeting. If there are any resource conflicts, these should appear in this meeting, so the schedule can be adjusted.

2.2.4 Operational planning on-line: dealing with emergencies

If there are any changes in schedule during the day of surgery, or in case of emergency surgeries, this is coordinated by an OR-coordinator. Upon an emergency surgery arrival, the OR-coordinator discusses with surgeons and anesthesiologists to find a suitable place, time, and surgeon. Disturbances during the day can also cause a need for on-line rescheduling. This happens for example when a surgery takes much longer than expected or when the IC (intensive care) bed needed is suddenly occupied.

2.3 Performance indicators

To evaluate the performance of the OR, we use several performance indicators. The performance indicators we choose need to take the interests of the main stakeholders into account. We have listed several stakeholders and their interests.

- Patients and their families want a short waiting time and a small risk of errors. They want to be sure about the moment the surgery takes place.
- The surgeon also wants to be sure about the operating schedule and prefers to get extra operating time when there are emergency surgeries.
- Surgical technologists and anesthesia assistants prefer not to work in overtime too often.
- The hospital management adds the goal of cost reduction.

We have selected three performance indicators that represent the main interests of the above mentioned stakeholders.

- The *OR utilization* has a direct influence on the cost per surgery and the number of patients the hospital can serve and is therefore important for hospital management.
- The *average overtime per week* is an important indicator for the surgical technologists and anesthesia assistants. A high amount of overtime may lead to a low job satisfaction and may at the same time lead to high costs for the hospital.
- The *percentage of cancelled surgeries* is an important quality measure for patients. For a patient, this indicator appears as the chance to be cancelled. This indicator is also important for the doctor, who wants to give the best care to his patients. However, we will not consider all cancelled surgeries in this research. Surgeries that are cancelled because of medical reasons, i.e. a change of indication, and surgeries which are cancelled because of patient reasons, i.e. a patient did not show up, cannot be explained by the model, so we will treat these cancellations as external parameters. Only cancellations caused by a delay of surgeries will be included.

The three indicators have a strong relationship with each other. For example, when management decides to increase OR utilization by scheduling a larger daily workload, the percentage of cancelled surgeries and the average overtime are likely to increase. The definition of the performance indicators is stated below.

The *Gross Utilization* is the sum of the surgery durations and changeover times, within working hours, divided by the amount of working hours (see Illustration 2.2 and Illustration 2.3) [Hoorn and Wendt 2008]. The amount of working hours per day is currently 8 hours in a regular OR.

Overtime occurs when the last surgery of the day finishes after the end of scheduled working hours. The duration of the *overtime* equals the difference between the moment the last patient leaves the OR and 16:00, the end of the day [Hoorn and Wendt 2008]. We multiply this number with the overtime frequency and the number of days per week, to get the average overtime per week.

2.4 Measured performance

Table 2.15 shows the main figures per specialty in 2008. We can see that for cardiac surgery for example, on six out of ten days, 1 hour and 50 minutes of OR time is unused. Over all, early end occurs on over half of the OR-days (56%), averaging over 1 hour of lost time on these days. The amount of overtime is smaller, but still over one third of the OR-days finishes late, causing on average 55 minutes of overtime on these days. A subtraction of these figures shows that the average daily workload is on average 17 minutes smaller than the daily OR capacity (see Table 2.15).

Specialty	**Number of OR-days**	**Gross Utilization (%)**	**Early end frequency per day (%)**	**Average early end (min)**	**Overtime frequency per day (%)**	**Average Overtime per day with overtime (min)**	**Changeover time (min)**	**Average late start (min)**
Cardiac surgery	512	85	60	110	25	79	23	27
Ear Nose and Throat	344	89	64	59	29	47	12	18
General surgery	461	89	56	59	38	54	16	13
Gynecology	126	93	61	47	34	42	10	10
Mouth and Jaw	152	93	51	54	44	44	13	12
Neuro surgery	368	91	47	72	42	79	22	11
Ophthalmology	141	89	67	55	30	27	10	17
Orthopedics	216	92	48	43	46	39	16	17
Plastic surgery	146	92	60	42	36	34	14	20
Urology	124	93	55	47	44	41	15	19
Vascular surgery	188	92	49	48	41	54	16	14
Other	401	85	54	64	35	61	27	-
Total	**3179**	**89**	**56**	**66**	**36**	**55**	**16**	17

Table 2.15: performance of inpatient surgery department F4 in 2008 (source: ZIS)

Table 2.16 shows the cancellation rates for all specialties in 2008. The percentage of cancelled surgeries amounts up to 10% of the elective surgeries, or even 16% for cardiac surgery. The reasons for these cancellations vary. Most cancelled surgeries are caused by the delay of previous surgeries, but medical reasons, resource capacity and the priority of other surgeries also cause over 1% of cancellations each. In this research, we focus on cancellations caused by the delay of surgeries, which is the highest for urology and vascular surgery, averaging 4.8% and 4.4% of the surgeries respectively.

	Reason for cancellation						
Specialty	**Resource capacity**	**Medical**	**Patient**	**Delay of surgeries**	**Priority of other surgery**	**Other**	**Total**
Cardiac surgery	6.5%	2.3%	0.1%	1.6%	4.0%	2.0%	**16.5%**
Ear Nose and Throat	0.6%	1.7%	0.3%	1.8%	0.3%	0.6%	**5.4%**
General surgery	0.9%	2.4%	0.4%	2.7%	0.4%	1.4%	**8.1%**
Gynecology	0.0%	0.6%	0.2%	4.1%	0.9%	0.0%	**5.8%**
Mouth and Jaw	0.0%	0.8%	0.8%	1.9%	0.8%	0.5%	**4.9%**
Neuro surgery	1.5%	2.1%	0.2%	4.1%	2.0%	1.1%	**10.9%**
Ophthalmology	0.0%	2.1%	0.0%	0.8%	0.5%	0.3%	**3.7%**
Orthopedics	0.5%	2.3%	0.5%	2.1%	0.7%	0.3%	**6.3%**
Plastic surgery	1.3%	1.2%	0.4%	2.5%	0.2%	0.4%	**6.0%**
Urology	1.9%	1.3%	0.3%	4.8%	0.6%	0.6%	**9.6%**
Vascular surgery	0.5%	2.1%	0.7%	4.4%	1.9%	0.7%	**10.3%**
Total	**1.5%**	**1.9%**	**0.3%**	**2.6%**	**1.2%**	**0.8%**	**8.3%**

Table 2.16: percentage of cancelled elective surgeries in the inpatient department in 2008 (source: ZIS)

2.5 Conclusion, bottleneck analysis

In the figures presented in Section 2.4, we find several bottlenecks for both urology and vascular surgery. We will discuss several bottlenecks we notice in this section.

Utilization below 100%

Urology and Vascular surgery have a gross utilization of respectively 93% and 92% (see Table 2.15). This means that we loose 7 to 8 percent of the surgery time at the end of the day, which is over half an hour of surgery time per day. This lost time costs money and cannot be used to shorten the waiting lists.

Overtime

On average, overtime occurs on 44% of the days, averaging 41 minutes per day of occurrence for Urology. If we assume that urology operates three days a week, the resulting overtime per week is 54 minutes (0.44*41*3=54). The overtime per week for vascular surgery is 110 minutes (see Table 2.15). Overtime causes an uncertain end of the day for the personnel and is costlier than regular surgery time. The average overtime per day is smaller than the average idle time per day, which may indicate an improvement potential.

Surgery Cancellations

Surgeries are cancelled on a regular basis. The percentage of cancelled surgeries was 9.6 for urology and 10.3 for vascular surgery in 2008. This means that a patient has a 10% chance that his or her surgery does not take place, causing uncertainty, needless sobriety and possibly a decline of patient condition. Around 4.4% (vascular surgery) or 4.8% (urology) of the surgeries are cancelled because the preceding surgeries in the same OR are delayed. These surgeries may benefit from a better surgery planning.

When we zoom in to the cancellations caused by delayed surgeries, we see that for vascular surgery, most cancellations take place on Tuesdays (see Table 2.17). On these days, aneurysm surgeries are performed (see Table 2.14).

	Percentage of OR-days with a cancelled surgery caused by delay of surgeries	
Day	**Vascular surgery**	**Urology**
Monday	9%	10%
Tuesday	16%	-
Wednesday	2%	12%
Thursday	8%	-
Friday	0%	12%

Table 2.17: percentage of OR-days with a cancelled surgery caused by delay of surgeries in 2008 (source: ZIS)

In the next chapter, we investigate which interventions may improve the utilization, overtime and surgery cancellations.

Chapter 3 Design of interventions

In this chapter, we suggest possible ways to improve the bottlenecks we described in Section 2.5. Section 3.1 describes literature on simulation and surgery scheduling. We used this literature as inspiration for the interventions we formulate in Section 3.2. These interventions will be evaluated in the simulation study (Chapter 4 and Chapter 5).

3.1 Literature

Simulation

As mentioned in Chapter 1 we will use simulation to answer the proposed research questions. Simulation is a way to imitate and understand the functioning of a system in practice. It and can be used to evaluate the effect of interventions and scenarios in a laboratory setting. Simulation is mostly used when the system under consideration is too complex to evaluate in an analytical way [Law and Kelton 2000].

Simulation of a system can be done by hand, but since the number of calculations is very high for most simulation models, it is usually done by computer. Simulation originates in the field of Operations Research and was used mostly in an industrial environment [Allen and Wigglesworth 2009]. Even early in its development, simulation was used in health care (see for example [England and Roberts 1978]), but it got more widely adopted since the 1990s for management support on logistical issues in health care [Jun et al. 1999].

Despite the complexity of most health care organizations, an analytical approach is quite common in health care operations research (see for example [Cardoen et al. 2009] and [Fei et al. 2009]). However, these studies do not research the effect of the resulting schedule in a stochastic environment, but evaluate the surgery schedule on the properties of the schedule itself.

Simulation enables the researcher to evaluate the performance of a surgery schedule in a stochastic environment, even when this is not possible in practice. Simulation also enables the evaluation of several possible alternatives in a short period of time. From these alternatives, the best solution can be selected to be implemented in practice. Moreover, the simulation produces quantitative results, which can be strong arguments in the discussion about the implementation.

The reliability of the results of the simulation depends highly on the validity of the simulation model and the quality of input data. An invalidated simulation model or unreliable input data may lead to unreliable or even incorrect results [Law and Kelton 2000]. This stresses the need for a solid analysis of input data for the model.

Ashby et al. [2008] for example, used discrete event simulation to support the design of a new facility for a hospital in Los Angeles. They examined the effects of a limited capacity and determined how the patient mix can be allocated to the best possible wards.

Ramwadhdoebe et al. [2009] have researched the use of discrete event simulation (DES) in health care. As an example, they use a simulation model to find out whether a new screening method for developmental dysplasia is feasible and cost effective. They conclude that "DES is most readily applicable when the problem or the system being studied involves competition for resources, where the timing of events a priori is not known, or when examining the interdependence between events or the flow of information or entities (e.g., patients) is important. (…) DES provides very useful outcome measures such as wait time, flow time, and resource utilization; metrics that are increasingly important in healthcare problems."

Simulation of OR planning and scheduling

Several researches using discrete event simulation have been performed to the OR. Persson and Persson [2009] for example, analyze the OR planning at a department of orthopedic surgery in Sweden. They share several goals of their research with our research, such as the improvement of the number of cancellations, the amount of overtime and the utilization of OR time. However, they also focus on the length of the waiting list and the allocation of time for emergency surgeries, which is not within the scope of our research. The main solution approach of Persson and Persson includes the introduction of both stand-by patients, which can be called in if idle time emerges, and stand-by personnel, to cover emergency surgeries. They conclude that this approach improves the performance of the OR department.

Hans et al. [2008] have researched several heuristics to schedule surgeries in such a way that capacity utilization is maximized and the risk of overtime and cancelled patients is minimized. They demonstrate that regret based random sampling may result in an improved OR performance, compared to regular scheduling techniques. However, current and nearfuture scheduling practice in UMC Utrecht is performed by hand and is therefore not suitable for complex scheduling methods such as regret based random sampling.

Beliën and Demeulemeester [2007] present a decision support system for cyclic Master Surgery Scheduling (MSS). They aim at leveling the resulting bed occupancy, concentrating surgeons of the same group in the same rooms, and keeping the schedules consistent from week to week. Blake and Donald [2002] also describe the introduction of an MSS, in a hospital in Toronto. They find many advantages regarding the time spent on organizing the OR. The number of conflicts is reduced and discussion is only necessary on a high level, when the MSS is discussed. Note that the definition of an MSS used by Beliën, Demeulemeester, Blake and Donald is different than the definition of an MSS used by Van Oostrum [2009], we used earlier in this report. Van Oostrum assigns specific a surgery type to an MSS slot, whereas the other authors we mentioned assign a combination of resources to an MSS slot. These resources can be used for various surgery types.

Based on the literature we discussed, we will formulate several interventions in Section 3.2.

3.2 Design of interventions

In this section, we formulate several interventions that may improve surgery scheduling in UMC Utrecht. We will compare the interventions with the current situation, which we will denote as Current-VAT and Current-URO.

3.2.1 Guaranteed surgery schedule

A guaranteed surgery schedule is one way to reduce the percentage of cancelled surgeries. The hospital management is interested in halving the number of cancellations. The idea is simple, expected overtime is not a reason to cancel a surgery. We want to know which effect a guaranteed surgery schedule has on utilization and overtime. Furthermore, we want to know more about the trade-off between the three performance indicators (see Section 2.3). Therefore, we want to know how we can adapt the amount of surgeries per day and the rules for cancelling a surgery in such a way that the percentage of cancelled surgeries will be reduced and the utilization is increased, while not increasing the amount of overtime. These interventions are applicable to both urology and vascular surgery and will be denoted as Guaranteed-VAT and Guaranteed-URO.

3.2.2 No MSS

In the current situation, vascular surgery uses an MSS, and Urology does not use an MSS (see Section 3.1). We want to find out which effect the MSS has on the performance and whether the use of an MSS results in a better OR performance, compared to the situation without an MSS. Since the construction of an MSS is a study on itself and not one of the main purposes of this study, we do not construct an MSS, but we investigate the effects of the existing MSS on the performance of the OR. This means we will only be able to research this intervention with vascular surgery and denote it as NoMSS-VAT.

3.2.3 Different day length

The literature suggests that a longer duration of the OR-days (different day length) may improve OR utilization [Collins 2006], if the workload per day of surgery is increased with the same rate. The number of OR-days will decrease as a result of this, since the total workload does not increase. We will test whether a longer duration of the OR-days improves OR utilization for urology and vascular surgery in UMC Utrecht. We want to know which effect a different day length has on the performance of the OR. The interventions with a different day length will be denoted with DayLength-VAT and DayLength-URO.

3.2.4 Adapt working hours to MSS

In Section 2.5 we noticed that most cancellations of vascular surgery are on Tuesdays. This calls for extra attention for Tuesdays. The high number of cancellations may indicate a work load that is too large. A possible way to improve performance on Tuesdays may be the adaptation of working hours to the duration of the surgeries. This may enable the last surgeries to take place as planned. The hospital management is interested in halving the number of cancellations. Therefore, we want to know which working day duration on Tuesdays reduces the number of cancellations.

To check whether we do not pay back the better performance on cancellations on Tuesdays with a lower utilization and higher overtime, we want to know what the effect of the proposed intervention is on the utilization and overtime. This intervention is only possible with vascular surgery and is denoted as AdaptHours-VAT.

3.2.5 Two ORs per day, move surgeries at end of day

On some OR-days, idle time arises, because surgeries take less time than expected. On other OR-days, overtime arises, because surgeries take more time than expected. If we could find a way to use the idle time of one OR-day to cover the overtime of another OR-day, this may improve performance. An OR can take over surgery time from another OR by taking over a surgery, so OR 1 is finished early with its scheduled surgeries and takes over a surgery from OR 2, which is likely to finish in overtime. We would need the last surgery of the day to be eligible for moving, i.e. the surgeon of the other OR is able to perform the surgery and all resources are available to both ORs. We create this by scheduling two ORs of the same specialty on the same day. We want to know which effect moving a delayed surgery to another OR has on OR performance.

We will research this intervention only with urology, because many vascular surgeries need specialized surgeons and resources and can therefore not be moved to another OR. We denote this intervention as MoveSurg-URO.

3.2.6 Scheduling heuristic

Hans et al. [2008] suggest that surgery scheduling based on regret based random sampling can result in an improvement of OR performance. This heuristic is designed for use with a computer. The current ICT environment in UMC Utrecht is not ready for automated scheduling techniques. Therefore, we choose to compare scheduling techniques that can be executed by hand. We want to know which of the following scheduling heuristics results in the best OR performance: Earliest due date first, longest surgery duration first, or largest standard deviation first. We denote these interventions as Heuristic-VAT and Heuristic-URO.

3.2.7 Combination of interventions

With the above interventions we expect that we will find several possible improvements in surgery scheduling. We will try to combine some of these interventions into one intervention with an even better performance than the interventions above. For this intervention, we select interventions that improve the OR performance. We will also take some practical issues into account in this solution, in order to present an implementable set of interventions. We denote these interventions as Combi-VAT and Combi-URO.

3.2.8 Summary

The interventions are listed in Table 3.1. We will analyze the effects of these interventions in Chapter 5, after we have designed a simulation model of the current situation in Chapter 4.

	Intervention	**Abbreviation**
1	Guaranteed surgery schedule	Guaranteed
2	No MSS	NoMSS
3	Different day length	DayLength
4	Adapt working hours to MSS	AdaptHours
5	2 ORs per day, move surgeries at end of day	MoveSurg
6	Scheduling heuristic	Heuristic
7	Combination of interventions	Combi

Table 3.1: summary of the proposed interventions

Chapter 4 Simulation of the current situation

To evaluate the interventions we proposed in Chapter 3, we will compare the performance in the current situation with the performance after an intervention. In this chapter, we develop a simulation model of the current situation in the OR department, VAT-0 and URO-0. In Chapter 5, we will evaluate the effect of the interventions on the simulation of the current situation.

Our goal in this chapter is to make a model that resembles practice best. We use the simulation tool developed by various researchers and students at University of Twente, under supervision of associate professor E.W. Hans. This tool is called OR manager. The model is developed in collaboration with Dutch hospitals and has been used in several research studies. It is a good starting point for our simulation study, because of many built-in options and the possibility to fit it to UMC Utrecht's situation, without the need to build an entirely new simulation model.

We start describing the conceptual design of the simulation model in Section 4.1. Next, we design a method to analyze the input data to the simulation model (Section 4.2). We describe how we clean the data and how we group surgeries. We determine the probability distribution and estimate the parameters. Finally, we validate the simulation model and settings by comparing the results of the model to the results in practice (Section 4.3).

4.1 Design of the simulation model

In this section, we describe the design of OR manager and its configuration. A more detailed description of the settings can be found in Appendix B.

We divide the simulation model into three basic steps. **Step A** defines the OR department at hand and specifies the required process data. In this part, the number of ORs, the working hours, the existing specialties, and surgery characteristics are defined. These form the basis for the next steps. We choose to simulate a period of one year. This period is easy to compare with registrations in practice. We divide the year in 52 *periods* of one week. For simplicity, we set the *number of OR-days per week* to 5 for vascular surgery and 3 for urology.

In **step B**, surgeries are generated based on historical data and a schedule is constructed, based on the expected durations of the surgeries. An example of this schedule is presented in Illustration 4.1. Every column represents an OR-day. The blocks are surgeries.

To generate a new set of surgeries, the tool generates a waiting list, which is used as input for the schedule. The initial waiting list contains a workload of two weeks and is filled to the same amount of surgeries after each scheduled week. Surgeries are not allowed to be on the waiting list longer than four weeks. Schedules are constructed per week, as is the case in practice. First, surgeries with a critical due date are scheduled. Next, surgeries are assigned to the reserved MSS slots. Finally, the remaining surgeries are scheduled, using largest surgery duration first. When a surgery does not fit into the schedule, it is postponed to the next week. The surgeries are scheduled in the OR where the remaining surgery time after scheduling is the least. This is called a ‘best fit’ heuristic. After scheduling one week, new surgeries from a random surgery type are generated, to restore the initial number of surgeries on the waiting list.

Please note that the waiting list we use in the simulation model is not the same as the waiting list in practice. The simulation waiting list contains the surgeries that are on top of the waiting list and therefore eligible for scheduling. Surgeries that are not long enough on the waiting list are not eligible for scheduling and do not appear in the model.

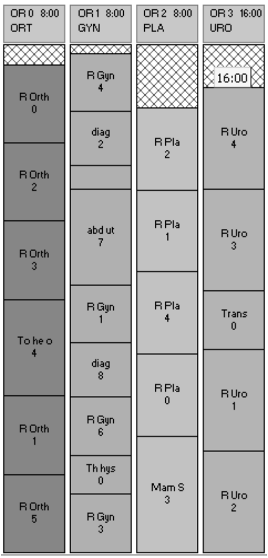


Illustration 4.1: example of a surgery schedule (result step B)

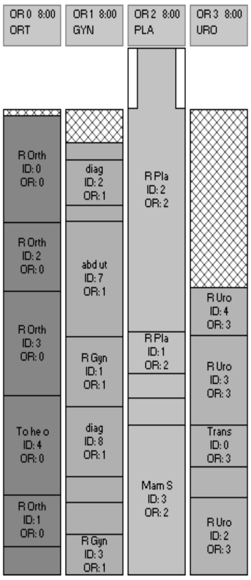


Illustration 4.2: example of a realization of the surgery schedule (result step C)

Step C is the actual simulation. The surgery schedule is evaluated using discrete event simulation. *Discrete event simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time [Law and Kelton 2000]*. This means that the basis of the simulation is a list of events. An event handler handles the first event of the list. When this event is handled, the event handler picks the next event. Events are normally triggered by other events. For example: the start of the simulation generates the first event, *start of day*; *start of day* triggers *start of OR* in every OR, which in turn triggers *start of surgery*; *start of surgery* triggers *end of surgery*, which triggers the start of the next surgery. When an event is handled, for example *end of surgery,* the tool updates the associated statistics, in this case amongst others the number of surgeries performed and the time used for the surgeries.

In practice, some surgeries are cancelled because of factors that are not explained by the simulation model. These factors include patient reasons (i.e. a patient does not show up), medical reasons (i.e. the patient is ill) and cancellations because of a capacity shortage (i.e. x-ray or surgeon shortage). In the model these factors are represented by a figure which is the chance a surgeries will be cancelled. This figure is assumed to be equal for all surgeries of the same specialty and is set to the level measured in 2008 (see Table 2.16).

OR manager has several options for decision rules during the simulation. We will use these options to match the simulation with the situation in practice.

- Elective surgeries may start before their planned start time. This is the case in practice, since all patients are inpatient and patients are called to the OR by the OR personnel based on the progress of the previous patient.
- Surgeries that finish late will be cancelled if the expected surgery duration lies more than a certain percentage (the *cancellation parameter*) in overtime. The value of the *cancellation parameter* is not measurable in practice and is therefore determined in the simulation fine tuning (see Section 4.3.3). Appendix C describes how we implemented cancellations in the model in more detail.

The output of the tool consists of both a graphical representation of the realization of the surgery schedule (see Illustration 4.2) and a list of measured statistics. The realized durations of surgeries are randomly generated based on a probability distribution function. This causes some ORs to finish late, in our example OR 2, and others to finish early.

4.2 Data preparation

For the simulation, we reconstruct the patient mix of UMC Utrecht, based on historical data collected in 2008. Using one year of data eliminates possible seasonal influences.

To prepare the historical data for use in the simulation model, we need to perform three steps. The first step is to clean the data by eliminating faulty registrations (Section 4.2.1). The second step to group the data (Section 4.2.2). These groups are necessary for the third step, in which we estimate the distribution and parameters of the duration of the surgeries (Section 4.2.3).

4.2.1 Data cleaning

The historical data of UMC Utrecht are often accurate, but still have some incorrect registrations. Amongst others, the following problems exist.

Missing or incorrect time registration is often easy to detect. Registered negative durations are clearly incorrect. It is harder to spot whether a surgery is incorrectly registered when this results in a positive duration, for example a very long duration. We will handle non-negative outliers after we have made surgery groups in Section 4.2.3, because these outliers can only be qualified as such based on its expected value.

Incorrect registration of main surgical procedures means that the obvious auxiliary surgical procedure is registered as the main surgical procedure. This often happens with chromocystoscopy, which is looking in the bladder, for example. This surgical procedure is usually part of a larger surgery. An incorrect registration of the main surgical procedure can be detected when the same combination of surgical procedures occurs several times with different main surgical procedures. The decision which of the surgical procedures should be the main surgical procedure can be made based on data from similar surgeries or based on the specialists' knowledge. An important guideline for this can be the data field of the variable Indication, a registered description of the surgery.

Our data set contains several cases with incorrect registrations, but only a few of them occur in elective vascular surgeries in the inpatient department in 2008. We did however correct 95 urology surgeries with incorrect or (the majority) indecisive registrations. Incorrect registrations of main surgical procedures are corrected manually and surgeries with incorrect time registrations are included in the calculation of the case mix, but excluded in the calculation of average surgery duration, standard deviation, and distribution.

4.2.2 Surgery grouping

For the grouping of the surgeries, we want to make a separate group for each surgery type with unique properties in the simulation program. These properties can for example be the average duration, standard deviation of the duration, the need for an IC bed, the specialty or the resources needed during the surgery. In this research however, we do not take into account resource usage (see Section 1.3.1), so the most interesting properties are the duration of the surgeries and the specialty.

Currently, surgeries are classified by means of the main surgical procedure and auxiliary surgical procedures. This distinguishes 429 surgery types for urology and 196 types for vascular surgery. Many surgeries are of a unique type and many surgery groups are too small for a good estimation of parameters. Therefore, we need to reduce the number of groups. First we used a numerical approach, in which we tried to deduce which surgical procedures contribute most to the duration of a surgery. The method we used is described in Appendix D, but did not lead to a workable surgery grouping.

We base the grouping of surgeries on medical similarity of the surgeries. We asked a surgeon to construct groups of these similar surgeries, taking the surgery duration in account. We merged groups with too few surgeries with a similar group or added together in the ‘others’ group. Because the ‘others’ group had a standard deviation over twice as high as the average standard deviation of the groups, we decided to split up the ‘others’ group into two groups with small and large surgeries. The sizes of the ‘others’ groups are set in such a way that the standard deviations are similar to, or larger than the standard deviations of other groups of the same size. The resulting surgery types are coded, for example AA1 (Abdominal Aneurysm), C1 (Carotid) and NTX (Kidney transplantation). The surgery groups for urology and vascular surgery are given in Appendix E.

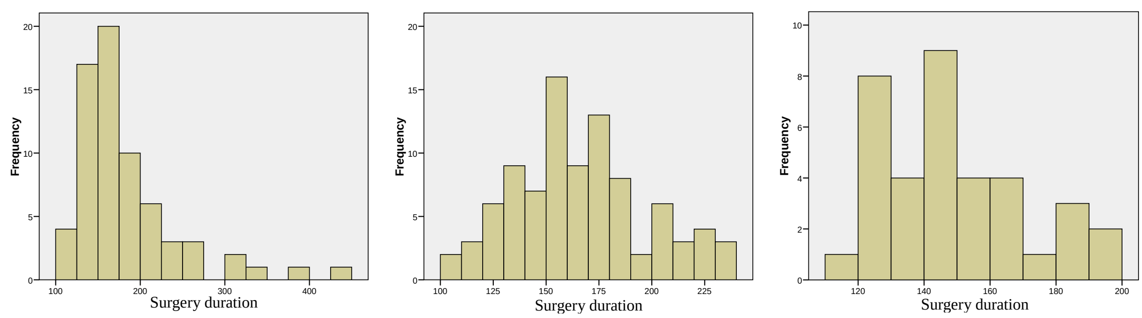
The above mentioned grouping is based on the registration after the surgery is performed. A grouping based on indication would be better, because this is the case when surgeries are scheduled in practice. The indications are however not properly recorded. The only option we have is to use the registration afterwards. This leads to some differences with practice:

- The uncertainty in practice may be more, because in practice a surgeon may need to perform unexpected extra surgical procedures. The simulation data set is constructed as if these surgical procedures were known in advance.
- The uncertainty in practice may be less, because the scheduler knows more about the complexity of surgery and the patient, and thus about deviations of the average surgery duration, than we do in the simulation.

For simplicity, we assume that both effects cancel each other, which enables us to use the registration of surgical procedures afterwards to base the grouping on.

4.2.3 Estimation of distribution and parameters

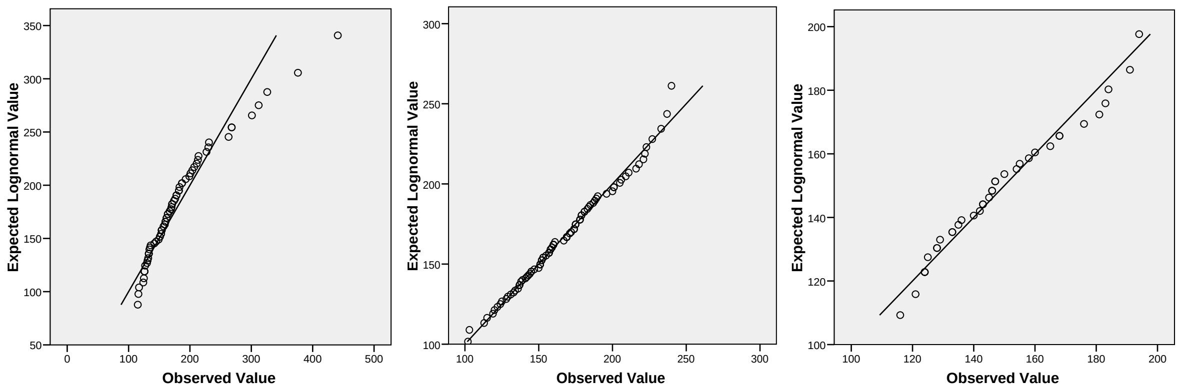
For every group, we want to determine the probability distribution of the surgery duration. Our aim is to use the same probability distribution for every group, since this simplifies the data handling. We will use the largest three groups of vascular surgeries as an example, because a large group will give a reliable result. The histograms of these surgery groups show that the groups have a different behavior of surgery duration (see Illustration 4.1). Surgery group AA1 is much skewed and has a long right hand tail, whereas C1 is less skewed.



AA1: Abd. Aneurysm *C1: Carotid* *NTX: Kidney transplantation*

Illustration 4.1: Three histograms of surgery duration.

Strum et al. [2003] suggest that surgery groups can best be described with a lognormal distribution. QQ plots of the three surgery groups are given in Illustration 4.2. The QQ plots indicate a good fit for C1 and a reasonable fit for NTX, but AA1 is clearly curved. This indicates that the surgery duration of AA1 is not lognormal distributed. The results of the Shapiro-Wilk [Shapiro and Wilk 1965] test for normality on the natural logarithms of the surgery durations prove that the surgery durations of AA1 are not lognormal distributed (alpha 0.05, see Table 4.3).



AA1: Abd. Aneurysm *C1: Carotid* *NTX: Kidney transplantation*

Illustration 4.2: Three lognormal QQ plots of surgery duration.

	Shapiro-Wilk		
	Statistic	**df**	**W0.05**
AA1	0.922	68	0.95
C1	0.990	91	0.95
NTX	0.959	36	0.94

Table 4.3: Shapiro-Wilk test statistics

Looking back at the histogram of AA1 (Illustration 4.1), we wonder why the lognormal distribution does not fit, although the histogram is so typically lognormal shaped on first sight (see Illustration 4.4). When we compare the histogram of AA1 with a lognormal histogram with the same shape, we discover that the difference lies in a shift along the horizontal axis. The shift along the horizontal axis can be considered a minimum duration of the surgery. We subtract 100 minutes from every surgery duration and generate a new QQ plot and Shapiro-Wilk test (see Illustration 4.5). The QQ plot and Shapiro-Wilk test show that this distribution fits.

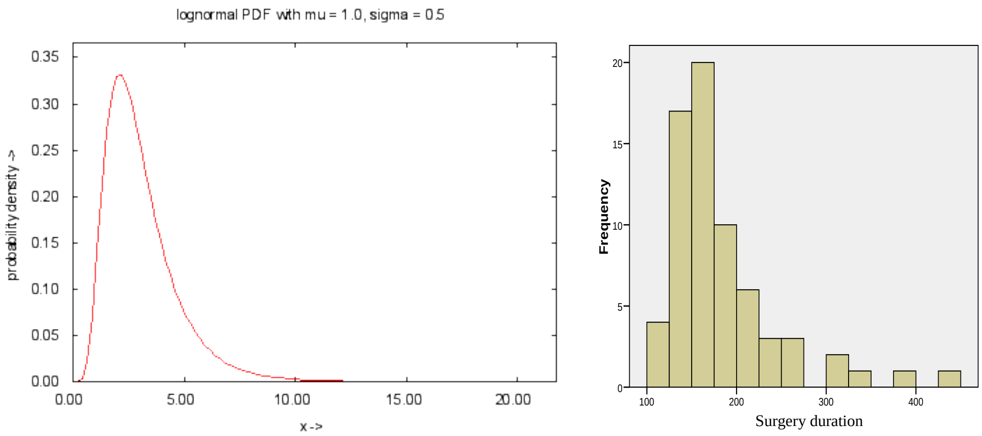
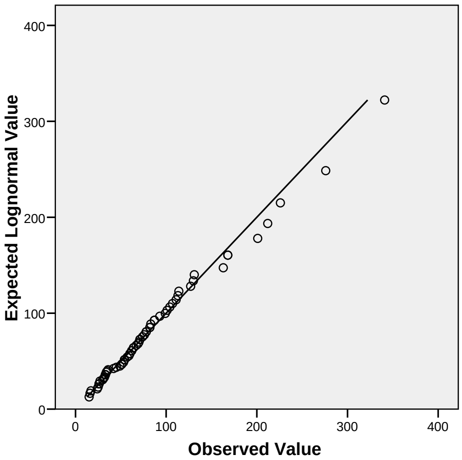


Illustration 4.4: a typical lognormal probability distribution and the histogram of Ab. Aneurysm



	Shapiro-Wilk		
	Statistic	**df**	**Sig.**
AA1 - 100	0.9883	68	0.7767

Illustration 4.5: QQ plot and Shapiro-Wilk test statistics for the lognormal distribution of the surgery duration of AA1 - 100

Further literature research reveals the existence of the 3-parameter lognormal distribution [Iwase and Kanefuji 1994]. This distribution differs in one aspect from the normal 2-parameter lognormal distribution. The third parameter shifts the distribution along the horizontal axis, which is exactly what we did with the distribution of the AA1 surgery durations. Stepaniak et al. [2009] have researched the use of the 3-parameter lognormal distribution on surgery durations and concluded that it yields a better fit than the 2-parameter lognormal distribution. We will use the 3-parameter lognormal distribution to generate random surgery durations in this simulation study.

To estimate the 3 parameters of the 3-parameter lognormal distribution in an easy way, we enumerated all possible shifts along the horizontal axis, with an accuracy of one minute. The lower bound for this shift is 0, because a negative shift could cause negative surgery times when generating random durations based on the distribution. The upper bound of the shift is the smallest surgery duration minus one, because a larger shift leads to zero or negative input surgery times in the estimation of the other two parameters of the lognormal distribution, which is infeasible. We select the parameter with the highest Shapiro-Wilk test statistic. The resulting parameters are presented in Appendix E. Since the resulting test statistic is larger than the critical level for all surgery groups, we can conclude that for all groups, there is no reason to reject the hypothesis that the surgery groups are 3-parameter lognormal distributed. We added the 3-parameter lognormal distribution to the set of input distributions of the OR-manager tool.

Changeover time

During a session, a surgery does not start immediately after the previous surgery has finished. Anesthesia team needs time to bring the previous patient to the recovery or IC and to bring the next patient to the OR. Surgical technologists need time to clean up the OR after the surgery and prepare for the next surgery. However, the simulation tool plans surgeries immediately after each other. The tool only considers surgery time and idle time. Therefore, we add the changeover times to the surgery duration. We define the changeover time as the time between the registered departure of a patient and the registered entry of the next patient in the same session, during working hours. If the time between surgeries is longer than 30 minutes, it is not considered to be a changeover time. These longer times between surgeries may for example be caused by a cancelled surgery, or a resource shortage.

When we try to determine the changeover time per surgery, we find that it is not clear which part of the changeover time is caused by the first surgery, and which part is caused by the second surgery. Additionally, set up times at the beginning of the day are not only a preparation to the first surgery and clean up time at the end of the day are not recorded. Combined with the low number of surgeries per day, thus a low number of changeovers, this results in an unclear view of changeover times per surgery group. Many surgery groups have too few registered changeover times to estimate a reliable average duration. The average changeover times of groups which do have enough changeover times, seem to be similar. For Vascular surgery, average durations vary between 13 and 16 minutes and the standard deviation lies between 3 and 5 minutes. Therefore, we assume that the changeover time per surgery is equal for every surgery per specialty.

We consider two options to add the changeover time to the probability distribution. For both options we add the average duration of the changeover to the average surgery duration. Option one is to add the standard deviations as well (take the square root of the sum of the squared standard deviations). For option two, we assume that the changeover time is deterministic. In this way, we can add the average changeover time per specialty τ, to the third parameter of the 3-parameter lognormal distribution θ. We performed a numerical experiment, in which we added random chosen lognormal distributed changeover times to the historical surgery durations. We estimated the parameters of the new 3-parameter lognormal distribution. The experiment showed that $\theta_{new} \approx \theta_{old} + E(\tau)$ and the variance did not increase. Therefore, we will add the average changeover time per specialty to the average duration and to the third parameter of the 3-parameter lognormal distribution.

Outliers

In some surgery groups, surgeries with an extremely short or long duration exist. Sometimes these extreme values indicate that the surgery in fact belongs to another surgery group. We have corrected these cases based on surgical procedures and the description of the surgery. Some other extreme values arise from medical complications. These cases do not happen very often, so it is due to coincidence if a surgery group contains such an outlier. Groups that do contain an outlier will have a higher estimated variability than we would expect if the outlier had not occurred. Groups without an outlier may have a lower variability than we would expect if an outlier had occurred. We expect that the best estimate lies in between these cases, probably closer to the estimated variability without outliers. Therefore, removing the outlier will increase accuracy of estimated parameters per surgery group in the groups with outliers. This will however decrease the average variability of the surgery duration, because the variability of all groups would be underestimated. In the situation without the removal of outliers, the variability of some surgeries, with outliers, is overestimated and the variability of some other surgeries, without outliers, is underestimated. In this situation, the variability in the system as a whole is therefore closer to the variability in practice than in the situation with removal of outliers. We conclude that our simulated case mix resembles practice best when we do not remove outliers.

4.3 Validation of the simulation model

The goal of the simulation model is to reproduce the current practice and its results. Because the current situation is subject to many ad-hoc changes, we are not able to exactly reproduce the input and decision rules that are used in practice. When an elective surgery is cancelled for example, it may be possible to perform another (non-) elective surgery on the day itself. This is not possible in the simulation tool. In Sections 4.1 and 4.2 we have modeled current practice. In this section, Section 4.3, we validate the simulation model we made. In Section 4.3.1 we discuss the warm-up time we have to deal with in the simulation model. In Section 4.3.2 we determine the number of replications we need to perform, to achieve reliable simulation results. The simulation results may however not be the same as in practice. Therefore, in Section 4.3.3, we will fine tune the simulation, by adjusting the workload and the decision rule on surgery cancellations, to make sure that the number of cancellations, the average overtime and the average gross utilization match the registered figures. Finally, we discuss the validity of the obtained model (Section 4.3.4).

4.3.1 Warm-up time

A single day of surgery has a natural beginning and end. The resulting startup and ending effects are covered by the simulation model. The surgery scheduling however, is a non-terminating process. At the start of the simulation the simulation model generates a waiting list with two weeks of surgery load. Half of the due dates of these surgeries are set to the end of week three; the other half of the due dates is set to the end of week 4. This is an approximation of the situation after the warm-up period and may result in a small deviation of the surgery schedule during the first three weeks, compared to the other weeks. This effect is however small, so we will assume that there is no warm-up time.

4.3.2 Number of replications

We have already set the run length to one year (see Section 4.1). Now we need to decide on the number of years we simulate. There are two ways to generate multiple outcomes of a simulation run, with the same input parameters: the use of a different set of randomly generated surgeries (replication) and a different realization of the schedule (run). Because the use of a large number of runs does not take much time, 1000 runs of the one year vascular surgery schedule take about three seconds, we can easily use this large amount of runs in this research. We determined the number of replications with the sequential method described by Law and Kelton [p513-514, 2000], with a confidence level of 95% (α=0.05). We set the relative error to 0.2% of the total patient volume, or 0.2% of the total available OR time. This means that our estimates for the utilization and the percentage of surgeries cancelled are at most 0.2 percentage points off target, with a 95% chance. Our estimate for the overtime per day is at most approximately 1 minute off target, with a 95% chance. The resulting γ for each criterion is given in Table 4.6.

Criterion	**γ**
Utilization	0.00227
Overtime per week	0.0439
% cancelled surgeries	0.0457

Table 4.6: relative error γ per criterion

We computed the confidence-interval half-length after 2 replications and divided it by the mean values. If this value was larger than the adjusted γ' ($\gamma' = \gamma/(1+\gamma)$), we added one replication and computed the confidence-interval half-length again. If the confidence-interval half-length divided by the mean values is smaller than γ' for all performance criteria, we stop the procedure and conclude that the current number of replications is the least number of replications for which the estimated means are at most 0.2 percentage point off target, with a confidence level of 95%.

After 13 replications, all performance criteria satisfy the stopping criterion for vascular surgery. The same is true for urology after 20 replications. See Appendix F for the results. This difference is due to the smaller number of OR-days urology has per week, 3, compared to vascular surgery, 5. Based on this difference, we would expect the minimal number of replications for urology to equal 5/3 times the minimal number of replications for vascular surgery, which is approximately the case.

To simulate these replications easily, we multiply the number of weeks and the number of surgeries per year by the number of replications. In this way, all replications can be performed jointly.

4.3.3 Simulation fine tuning

The simulation model should produce figures that are similar to the figures measured in practice. We can accomplish these figures by adjusting the scheduled surgery volume per day (the *capacity target*) and the *cancellation parameter* (see Section 4.1). The *capacity target* is not known in practice, because schedulers do not use historical durations and total surgery duration in the scheduling. In Section 2.3, we described three important indicators. We have fine tuned the simulation model in such a way that the values given in Table 4.7 are reached.

Performance indicator	Vascular surgery	Urology
Gross occupation	92	93
Cancelled surgeries	4.4%	4.8%
Average overtime per day (min)	22	18

Table 4.7: OR performance in 2008

In Table 4.8 and Table 4.9, we show the settings that produce figures that are the most similar to practice. We used the required amount of replications in this study, which are determined in Section 4.3.2. Note that the utilization in the simulation is lower than the utilization in practice. In practice, a higher utilization rate can be achieved, because long periods of idle time, caused by no-show or early end for example, can be filled with extra (emergency) surgeries. This is currently not possible in the simulation model.

		Utilization (%)			**Cancellations (%)**			**Overtime per week (min)**		
		Cancellation parameter								
		62	**63**	**64**	**62**	**63**	**64**	**62**	**63**	**64**
***Capacity target* (%)**	**103**	87.1	87.1	87.2	4.2	4.1	4.0	101	102	104
	104	87.7	87.7	87.7	4.4	4.3	4.2	107	108	109
	105	88.2	88.2	88.3	4.7	4.6	4.5	113	114	116
Practice		**92**			**4.4**			**110**		

Table 4.8: fine tuning vascular surgery

		Utilization (%)			**Cancellations (%)**			**Overtime per week (min)**		
		Cancellation parameter								
		58	**59**	**60**	**58**	**59**	**60**	**58**	**59**	**60**
***Capacity target* (%)**	**103**	87.5	87.5	87.5	4.5	4.5	4.4	52	53	53
	104	88.0	88.0	88.0	4.9	4.8	4.7	57	58	58
	105	88.4	88.4	88.4	5.5	5.4	5.3	59	60	60
Practice		**93**			**4.8**			**54**		

Table 4.9: fine tuning urology

We have chosen parameters that produce the most similar results. For vascular surgery, a *capacity target* of 104% and a *cancellation parameter* of 62 or 63 produce the most similar results. One minute off target for overtime represents 0.041% of the total surgery time and is therefore equivalent to 0.041% of cancellations. We choose to use a cancellation parameter of 62, because the sum of the deviations of the target, multiplied by 0.041 in case of the overtime, is the smallest with this setting. For urology, we use the same line of reasoning and choose a *capacity target* of 104%, with a *cancellation parameter* of 59. Table 4.10 shows the parameters that will be use throughout the simulation study.

Parameter	**Vascular surgery**	**Urology**
Capacity target (%)	106	103
Cancel if overtime is more than (%)	62	60

Table 4.10: simulation parameters

4.3.4 Validation of the model

In this chapter, we have designed a simulation model of the current situation in the inpatient OR department. We asked the planning surgeons of both urology and vascular surgery to compare the simulation model to practice. They indicated that the scheduling method and the obtained schedules are similar to practice. There is however one difference at urology. The simulation model does not take the use of resources and the presence of surgeons on particular days of the week into account. This relaxes the scheduling; all surgeries may be scheduled on every day of the week. Therefore, the resulting schedule is assumed to be slightly better than in practice, i.e. there may be less idle time in the schedule. This problem mainly exists at urology, because vascular surgery has incorporated surgery presence in the MSS.

Table 4.11 and Table 4.12 summarize five performance indicators of vascular surgery and urology. We have fine tuned the cancellations and overtime per week (see Section 4.3.3), so it is no surprise that these figures are approximately the same in the simulation and in practice. The utilization is higher in practice. This results from the extra (emergency) surgeries that are added when long idle times emerge in practice.

The overtime frequency for vascular surgery is about 40% in both practice and the simulation. For urology, the overtime frequency is lower in the simulation. We have no explanation for this. The total surgery durations are similar in all situations.

Indicator	Practice	Simulation
Utilization (%)	91	88
Cancellations (%)	4.4	4.4
Overtime per week (min)	110	108
Overtime frequency (%)	41	40
Average surgery duration	187	183

Table 4.11: comparison of indicators in practice and simulation for vascular surgery

Indicator	Practice	Simulation
Utilization (%)	92	88
Cancellations (%)	4.8	4.8
Overtime per week (min)	54	58
Overtime frequency (%)	44	39
Average surgery duration	191	188

Table 4.12: comparison of indicators in practice and simulation for urology

4.4 Conclusions

In this chapter, we have described how we designed the simulation model of the OR department of UMC Utrecht. We use an event based simulation tool, OR Manager, which generates surgeries based on historical surgeries in 2008. Surgeries are scheduled using a waiting list. Surgeries with a critical due date are first to be scheduled, followed by surgeries in the MSS and the other surgeries. We fine tuned the simulation, which resulted in a valid simulation model. This is confirmed by surgeons of the specialty at hand. In Chapter 5, we use this simulation model to calculate the effects of the interventions proposed in Chapter 3.

Chapter 5 Computational results

In this chapter, we start explaining how we translated the interventions we proposed in Chapter 3 to an experiment approach in Section 5.1. Then we describe the results of these experiments in Section 5.2.

5.1 Experiment approach

In Table 3.1 we summarized the interventions we proposed. We simulate each intervention separately. Sections 5.1.1 to 5.1.7 describe the experiment approach of the interventions.

5.1.1 Guaranteed surgery schedule

We will compare the current situation, Current-VAT and Current-URO, with the situation in which we guarantee the surgery schedule. To find out which effect a guaranteed surgery has on utilization and overtime, we switch off the cancellation option in the simulation model. These interventions will be called Guaranteed-VAT-1 and Guaranteed-URO-1.

To find out how we can adapt the amount of surgeries per day and the cancellation parameter in such a way that the percentage of cancelled surgeries will be reduced, while keeping the amount of overtime at least equal, we will perform several experiments with a different *capacity target* (see Section 4.3.3) and *cancellation parameter*. We select the interventions that satisfy the criterion that the percentage of cancelled surgeries is reduced and the overtime is equal. These interventions will be called Guaranteed-VAT-2 and Guaranteed-URO-2. We will compare the results of the interventions with Current-VAT and Current-URO.

5.1.2 No MSS

To find out which effect the MSS has on the OR performance, we compare the performance of the situation with MSS, Current-VAT, to the performance of the situation in which the surgery schedule is constructed without the use of an MSS. This intervention is called NoMSS-VAT.

5.1.3 Different day length

To find out which effect a different day length has on the performance of the OR, we simulate a day length of 6 to 12 hours, for both urology and vascular surgery. For vascular surgery, the MSS complicates the situation. A day schedule with 8 hours of surgeries in the MSS cannot be performed in a 6 hour OR-day. Therefore, we will not use the MSS, but the situation without MSS. Since urology does not have an MSS, we can use Current-URO as basis.

A longer working day leads to a higher number of surgeries per day, which would lead to more surgeries per week, if the number of OR-days per week would stay the same. Therefore, we need to adjust the number of OR-days per week. We do this in such a way that the total number of working hours per week is closest to the current number in the simulation, which is 40 hour in case of vascular surgery and 24 hours in case of urology. For example, if a working day has a duration of 9 hours for vascular surgery, 4 days per week would result in 36 working hours and 5 days per week would result in 45 working hours. Since the difference between 40 and 36 is smaller than the difference between 40 and 45, we choose to use 4 days per week. We adjust the amount of overtime per week to the amount of over work per 40 hours (in case of vascular surgery) or 24 hours (in case of urology) of OR capacity.

The interventions are summarized in Table 5.2. Intervention DayLength-VAT-3, the situation with 8 working hours is in fact equal to NoMSS-VAT and DayLength-URO-3 is equal to Current-URO.

Intervention		**Number of working hours per OR-day**	**Number of days per week Urology**	**Number of days per week Vascular surgery**
DayLength-URO-6	DayLength-VAT-1	6	4	7
DayLength-URO-7	DayLength-VAT-2	7	3	6
DayLength-URO-8	DayLength-VAT-3	8	3	5
DayLength-URO-9	DayLength-VAT-4	9	3	4
DayLength-URO-10	DayLength-VAT-5	10	2	4
DayLength-URO-11	DayLength-VAT-6	11	2	4
DayLength-URO-12	DayLength-VAT-7	12	2	3

Table 5.1: Interventions with a different day length

5.1.4 Adapt working hours to MSS

To find out which working day duration on Tuesdays reduces the number of cancellations, we simulate several interventions, in which we evaluate a different day length on Tuesday. The day length ranges from 8 to 12 hours and the difference between two interventions is half an hour. We simulate only Tuesdays, all with three aneurysms scheduled. We select the first intervention for which the cancellations on Tuesday are below or equal to half the number of cancellations when there are 8 working hours on Tuesday. The interventions are listed in Table 5.3.

Intervention	**Number of working hours on Tuesday**
AdaptHours-VAT-8	8
AdaptHours-VAT-8.5	8.5
AdaptHours-VAT-9	9
AdaptHours-VAT-9.5	9.5
AdaptHours-VAT-10	10
AdaptHours-VAT-10.5	10.5
AdaptHours-VAT-11	11
AdaptHours-VAT-11.5	11.5
AdaptHours-VAT-12	12

Table 5.2: Interventions with a different day length on Tuesday

5.1.5 Scheduling heuristic

To find out which of the following scheduling heuristics results in the best OR performance, we design two interventions for each specialty, in which we schedule surgeries in a different way. In intervention Heuristic-VAT-1 and Heuristic-URO-1, we schedule surgeries based on earliest due date first. In intervention Heuristic-VAT-2 and Heuristic-URO-2, we schedule surgeries based on largest standard deviation first. We compare these results with Current-VAT and Current-URO, which are scheduled with a longest surgery duration first heuristic.

5.1.6 Combination of interventions

For the last intervention, we gather the best interventions per specialty. We combine them in one intervention. Some interventions cannot be combined, for example because one intervention uses an MSS and another intervention does not use an MSS. This may lead to several combinations of interventions. We fine tune the interventions (see Section 4.3.3) in such a way that the overtime is at most equal to the measured overtime in 2008.

A table of the interventions is given in Appendix G.

5.2 Results

In this section, each subsection shows the results of one of the interventions described in Chapter 3 and Section 5.1. When interpreting the results, we need to know which results significantly differ from the current situation. The minimal significant difference is determined in Section 5.2.1. Sections 5.2.2 through 5.2.8 describe the results of the interventions.

5.2.1 Significance of the results

In this section, we determine the minimal difference between two instances of each performance indicator, for which the difference is significant with a confidence level α of 5%.

We use the regular statistical methods to compare two samples with average μ and ν [Altman 1991, Armitage and Berry 1994]. We assume that the standard deviation σ and the number of replications n are equal in both samples. The null hypotheses (H_0) is $\mu = \nu$ and H_1 is $\mu > \nu$. H_0 is not true if T > S, where

$$S = \frac{\mu - \nu}{\sigma\sqrt{\frac{2}{n}}}$$

and T has a student distribution with 2n-2 degrees of freedom and a second parameter of $\alpha/2$. We transform this equation to calculate the minimum difference $\delta = \mu - \nu$ for which we would reject H_0 (T=S).

$$\delta = T_{2n-2} \cdot \sigma \cdot \sqrt{\frac{2}{n}}$$

We apply this equation on the performance indicators of Current-URO and Current-VAT and calculate the critical interval. If the value of a performance indicator of an intervention is lower than or equal to the lower bound of the critical interval, or larger than or equal to the upper bound of the critical interval, the difference is significant (see Table 5.4).

Specialty	Performance indicator	Average	σ	n	T	δ	Lower bound	Upper bound
Urology	Overtime (min)	55	5.2	20	2.06	3.36	51	59
	Utilization (%)	87.9	0.28	20	2.06	0.18	87.7	88.1
	Cancellations (%)	4.8	0.39	20	2.06	0.26	4.5	5.1
Vascular surgery	Overtime (min)	108	4.3	13	2.06	3.52	104	112
	Utilization (%)	87.7	0.31	13	2.06	0.25	87.4	90.0
	Cancellations (%)	4.4	0.15	13	2.06	0.12	4.2	4.6

Table 5.3: Calculation of significant difference

5.2.2 Guaranteed surgery schedule

The effect of a guaranteed surgery schedule is summarized in Table 5.5 and Table 5.6. We see that the utilization increases with 0.3 or 0.4 percentage point if no surgeries are cancelled because of delay of surgeries (intervention Guaranteed-URO-1 and Guaranteed-VAT-1). The amount of overtime increases with more than 10 minutes per day on average.

In intervention Guaranteed-URO-2 and Guaranteed-VAT-2, the overtime stays approximately equal, but the utilization decreases with 1.5 percentage point. This would be the price we need to pay for halving the amount of cancellations if no other measures are taken. We achieved these figures by setting the capacity target (see Section 4.3.3) to 101% for urology and 100% for vascular surgery. The cancellation parameters are set to 80% for urology and 83% for vascular surgery.

Urology			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
Current-URO	55	87.9	4.8
Guaranteed-URO-1	84	88.2	0.0
Guaranteed-URO-2	54	86.5	2.3

Table 5.4: Results of intervention Guaranteed-URO

Vascular surgery			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
CurrentVAT	108	87.7	4.4
Guaranteed-VAT-1	179	88.1	0.0
Guaranteed-VAT-2	114	86.2	2.2

Table 5.5: Results of intervention Guaranteed-VAT

5.2.3 No MSS

We see from the results of intervention NoMSS-VAT (see Table 5.7) that the absence of an MSS would lead to a lower utilization of the OR, lower overtime, and less cancellations. This may indicate that the MSS surgery days tend to have a higher daily surgery load than non-MSS surgery days.

Vascular surgery			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
Current-VAT	108	87.7	4.4
NoMSS-VAT	84	86.3	3.4

Table 5.6: Results of intervention NoMSS-VAT

5.2.4 Different day length

The results of intervention DayLength-URO and DayLength-VAT are given in Appendix H. We see that the average amount of overtime is lower, if the number of hours per day is larger (see Illustration 5.8). Some large surgeries, which typically take over 8 hours of surgery time, have a large effect on the amount of overtime when an OR-day has a duration of 6 hours for urology.

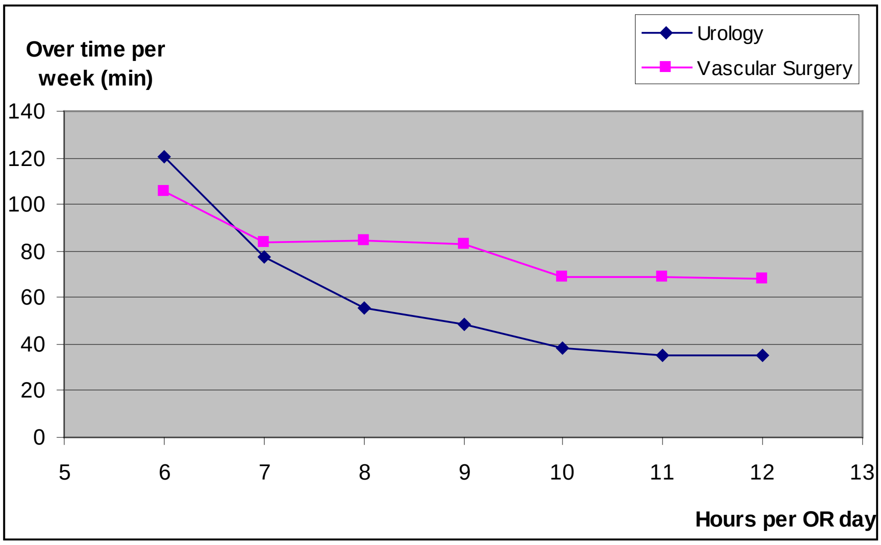


Illustration 5.7: Overtime in intervention DayLength-URO and DayLength-VAT

The utilization tends to be larger if the number of working hours per day is larger (see Illustration 5.9). The percentage of surgeries cancelled does not seem to be correlated with the number of hours per OR-day (see Illustration 5.10).

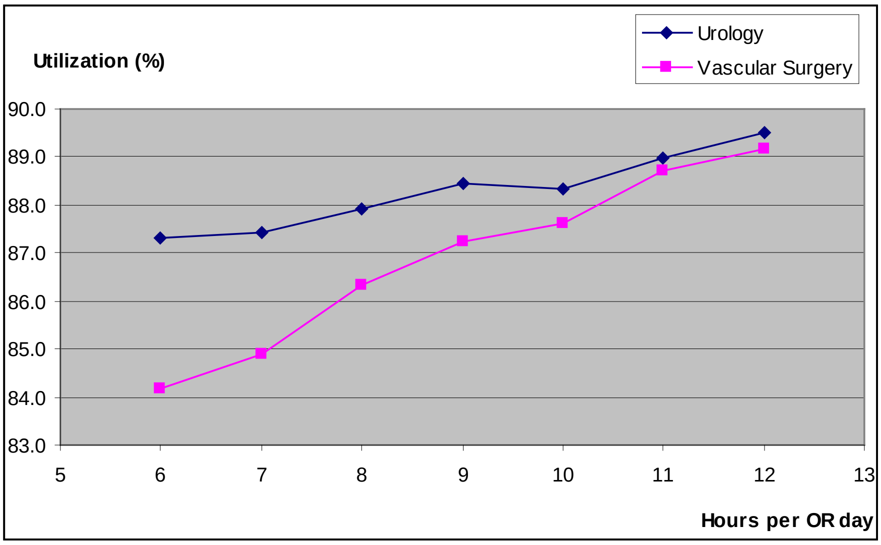


Illustration 5.8: Utilization in intervention DayLength-URO and DayLength-VAT

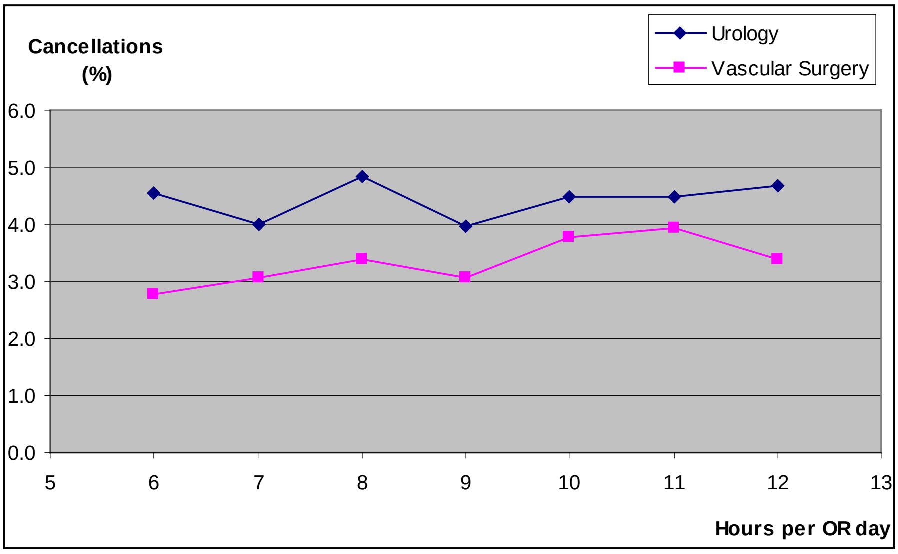


Illustration 5.9: Cancellations in intervention DayLength-URO and DayLength-VAT

5.2.5 Adapt working hours to MSS

The results of intervention AdaptHours-VAT are summarized in Table 5.11. We can see that the percentage of cancellations is halved if the number of working hours is 9 (intervention AdaptHours-VAT-9) or more. This leads to a utilization of 91% and an average overtime of 38 minutes per Tuesday.

Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
AdaptHours-VAT-8	49	92.6	12.8
AdaptHours-VAT-8.5	45	92.1	9.0
AdaptHours-VAT-9	38	91.0	6.2
AdaptHours-VAT-9.5	31	89.3	4.3
AdaptHours-VAT-10	25	87.1	3.0
AdaptHours-VAT-10.5	19	84.5	2.1
AdaptHours-VAT-11	14	81.8	1.5
AdaptHours-VAT-11.5	11	78.9	1.0
AdaptHours-VAT-12	8	76.2	0.7

Table 5.10: results of intervention AdaptHours-VAT

5.2.6 Two ORs per day, move surgeries at end of day

Table 5.12 shows the result of intervention MoveSurg-URO. Moving a delayed surgery to another OR may increase the utilization, decrease the percentage of cancellations and does not have a significant effect on the overtime (see Section 5.2.1).

Urology			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
Current-URO	55	87.9	4.8
MoveSurg-URO	57	88.7	3.4

Table 5.11: Results of intervention MoveSurg-URO

5.2.7 Schedule on different surgery selection criterion

The results of interventions Heuristic-URO and Heuristic-VAT are displayed in Table 5.13 and Table 5.14 for both urology and vascular surgery. We see that earliest due date first (Heuristic-URO-1 and Heuristic-VAT-1) causes a 0.2 or 0.3 percentage point lower utilization and 0.1 or 0.3 percentage point more cancellations, compared to the current situation (largest surgery duration first). This means that earliest due date performs worse than largest surgery duration first. The results of largest standard deviation first (Heuristic-URO-2 and Heuristic-VAT-2) are similar to the current situation; existing differences are not significant (see Section 5.2.1).

Urology			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
Current-URO	55	87.9	4.8
Heuristic-URO-1	53	87.7	5.1
Heuristic-URO-2	56	88.0	4.7

Table 5.12: Results of intervention Heuristic-URO

Vascular surgery			
Intervention	**Overtime per week (min)**	**Gross Utilization (%)**	**Cancellations (%)**
Current-VAT	108	87.7	4.4
Heuristic-VAT-1	106	87.4	4.5
Heuristic-VAT-2	109	87.8	4.5

Table 5.13: Results of intervention Heuristic-VAT

5.2.8 Combination of interventions

In the previous sections, we presented several results. In Table 5.15, we indicate which interventions may lead to performance improvement. We will combine these interventions into one new intervention.

Intervention	**Improvement?**	
	Urology	Vascular surgery
Guaranteed	✓	✓
NoMSS		
DayLength	✓	✓
AdaptHours		✓
MoveSurg	✓	
Heuristic		

Table 5.14: Do the interventions result in improvements of performance?

For urology, we want to combine longer working days with moving surgeries between ORs and fine tune this in such a way that the overtime is equal to the current situation. If we schedule two longer ORs on one day however, all urological surgeries would be on one day in the week. This would cause major problems on the ward. Therefore, we want to schedule these surgeries on at least two days. Furthermore, long working days may be more difficult to realize with respect to personnel. We choose to simulate a week in which one day has one OR operating 9 hours and another day has two ORs operating 8 hours. The extra working hour can be compensated by decreasing the number of OR-days per week by one periodically. We fine tune this situation in such a way that the overtime per week is equal to the current situation. Note that the overtime per day has increased, because the number of days has decreased. The result of this intervention is given in Table 5.16. The capacity target is set to 104% and the cancellation parameter is set to 71 in this intervention.

Specialty	Intervention	Overtime (min)	Utilization (%)	Cancellations (%)
Urology	Current-URO	55	87.9	4.8
	Combi-URO	54	88.8	2.4
Vascular surgery	Current-VAT	108	87.7	4.4
	Combi-VAT	110	89.2	2.2

Table 5.15: Results of intervention Combi-URO and Combi-VAT

For vascular surgery, we want to combine longer days and an adaptation to the MSS and fine tune this in such a way that the overtime is equal to the current situation. We choose for a regular working day of 9 hours, because this is easy to realize with respect to personnel (see Section 2.1.1). On Tuesday, we add another hour, because this results in less overtime and cancellations. To compensate the extra hours, we schedule one OR-day per week less, the Friday. Finally, we fine tune this intervention in such a way that the overtime is equal to the current situation. The result of this intervention is given in Table 5.16. The capacity target is set to 107% and the cancellation parameter is set to 95 in this intervention.

5.3 Conclusions

From the results of the interventions (see Section 5.2), we draw several conclusions:

- A guaranteed surgery schedule causes a large increase of overtime and a small increase of utilization. A more relaxed version reduces the amount of cancellations and keeps the overtime approximately equal, but reduces the utilization with 1.5%.
- Adapting working hours to the MSS helps to reduce the number of cancellations by 1 percentage point, with a loss of utilization of 1.4 percentage point.
- Longer working days allow a higher utilization with a lower amount of overtime, while the number of cancellations is not influenced. Utilization increases up to 5 percentage point for vascular surgery and overtime decreases up to 68% for urology, when twelve hours of surgery are scheduled per OR per day.
- Moving delayed surgeries at the end of the day from one OR to the other helps to decrease the number of cancellations by 1.4 percentage point and increase utilization by 0.8 percentage point.

- The differences between three scheduling heuristics, earliest due date first, largest surgery duration first, and largest standard deviation first, are small.
- A combination of the interventions can reduce the number of cancellations by 50%, does not increase overtime and at the same time increase the utilization by 0.9 to 1.5 percentage point.

Chapter 6 Conclusions and Discussion

In Section 6.1, we draw the conclusions of this research. In Section 6.2 we discuss the implementation of the interventions that showed improvement of OR performance (see Section 5.2). In Section 6.3 we describe several interesting directions for future research. We conclude with a discussion of this research (Section 6.4).

6.1 Conclusions

The first goal of this research was to *“Decrease the percentage of cancelled surgeries and increase utilization while not increasing overtime”*. We researched several interventions that may contribute to reach this goal (see Table 6.1). The last intervention, number seven, is a combination of the most promising interventions.

	Intervention	**Abbreviation**
1	Guaranteed surgery schedule	Guaranteed
2	No MSS	NoMSS
3	Different day length	DayLength
4	Adapt working hours to MSS	AdaptHours
5	2 ORs per day, move surgeries at end of day	MoveSurg
6	Scheduling heuristic	Heuristic
7	Combination of interventions	Combi

Table 6.1: summary of the proposed interventions

To evaluate the effect of the interventions, we co-developed an event based simulation tool of the operating department of UMC Utrecht, OR Manager. This was the second goal of the research. The simulation tool schedules surgeries based on a waiting list and is able to incorporate an MSS. We generated input of surgeries based on historic elective surgeries in 2008. The resulting model proved to be valid.

From the computational results, we draw several conclusions:

- A guaranteed surgery schedule causes a large increase of overtime and a small increase of utilization. A more relaxed version halves the amount of cancellations and keeps the overtime approximately equal, but reduces the utilization with 1.5%.

- Adapting working hours to the MSS helps to reduce the number of cancellations by 1 percentage point, with a loss of utilization of 1.4 percentage point.
- Longer working days allow a higher utilization with a lower amount of overtime, while the number of cancellations is not influenced. Utilization increases up to 5 percentage point for vascular surgery and overtime decreases up to 68% for urology, when twelve hours of surgery are scheduled per OR per day.
- Moving delayed surgeries at the end of the day from one OR to the other helps to decrease the number of cancellations by 1.4 percentage point and increase utilization by 0.8 percentage point.
- The differences between scheduling heuristics, earliest due date first, largest surgery duration first, and largest standard deviation first, are small.
- A combination of the interventions can reduce the number of cancellations by 50%, does not increase overtime and at the same time increase the utilization by 0.9 to 1.5 percentage point.

For the implementation in the entire OR department, we advise to widen the scope and research the proposed interventions with more, or even better, all specialties.

6.2 Implementation

In Chapter 5, we suggested a combination of interventions for both specialties. A straightforward implementation of these interventions is not advisable. More research to the implications for other departments in the hospital is necessary, as well as the extension of this research to more specialties. In this section, we describe the steps necessary to enable implementation.

Nine hour working day

The “Anders Roosteren” project has researched the willingness of personnel to adopt a nine hour working day (see Section 2.1.1). They concluded that 35% of the personnel prefers a nine hour working day. OR management will be able to implement a nine hour working day in corporation with surgeons, anesthesiologists, the team leads of the surgery technologists, and the team leads of the anesthesia assistants. On a small scale, Urology and Vascular surgery represent a small part of the total surgery load in UMC Utrecht, it will be easy to find volunteers for nine hour working days. A full scale implementation will cause more aversion amongst personnel. Note that also supporting facilities may need longer working days, for example the recovery and the cleaners.

Adapt working hours to MSS

The adaptation of working hours to the MSS can be implemented in the same way as the nine hour working day. However, longer working hours may cause a larger risk of errors because of fatigue. More research may be performed to establish the maximum duration of a working day. This should also take possible overtime into account.

Move surgeries between ORs

Moving surgeries between ORs causes more problems in the implementation, mainly because there are two ORs of the same specialty on one day. This may cause a peak in the use of various resources. Therefore, we recommend performing further research on the effects of this intervention on the schedules of surgeons, usage of beds in the wards, and usage of beds in the IC. This research should be performed by, or in close cooperation with, the specialty itself. Furthermore, more research is needed to determine how to decide whether a surgery is moved or not in practice. Who takes the decision, when is it taken, and on which grounds? Finally, the scheduler needs to schedule a surgery at the end of the day, which another surgeon can take over.

Adaptation of the cancellation parameter

The adaptation of the cancellation parameter can be translated into practice as a smaller chance a surgery gets cancelled because of delays. If a surgery can start before the end of the day, it will start. Surgeries that cannot start before the end of the day are cancelled. OR management should clearly communicate this rule as part of a pilot project and the rule is part of the deal for all personnel. The OR coordinator is in charge of the execution of this rule.

6.3 Future

Currently, this research is being extended to the other specialties of UMC Utrecht. For all specialties, surgery groups are being constructed. These data can be used as the basis for further research. We list several interesting fields of further research.

- The interventions we suggest for urology and vascular surgery can be applied to other specialties.

- Resources can be incorporated in the simulation model, for example surgeons, IC, wards and instruments. This leads to even more realistic scheduling, enabling the next interesting field of research.
- Construction of an MSS for several specialties that do not have an MSS. The MSS could spread resources usage equally and simplify scheduling on a weekly basis.
- The handling of emergency surgeries. Several decision rules can be analyzed, and measurement of medical intervals (the interval in which an emergency patient needs to be operated) can be added to the model. Interesting interventions to research may include:
    - Closing the emergency OR and reserving time for emergency surgeries in the regular ORs.
    - Several priority rules for (semi-)emergency surgeries.
    - Rules to decide whether a semi-emergency surgery takes place during the night or whether it is postponed to the next day.
    - Determining the amount of time reserved for emergency surgeries and when this time is available.
- The model can be extended to other departments of UMC Utrecht: the outpatient department and the pediatric hospital.

Without the simulation model, many other possible improvements can be researched. Some research that may improve OR performance includes:

- Research on the causes of cancellations not caused by delay of surgeries.
- Research on the cause of delay of surgeries.
- Research on the processes during the surgery. It may be possible to reduce surgery duration.
- Research on the time used for anesthesia. If anesthesia is applied before the patient enters the OR, valuable time of surgeons and surgery technologists may be saved. The effect on the work of anesthesiologists and anesthesia assistants also needs attention in this research.

6.4 Discussion

Despite the effort we have made to create a valid simulation study, some issues may arise. In this section we discuss several of these issues.

The utilization in the simulation is lower than in practice, mainly because gaps in the schedule that occur during the simulation because of no-show, are not filled with emergency surgeries or extra elective surgeries, which does happen in practice. The decision to add an extra surgery to fill a gap in the surgery schedule in practice depends on many factors, such as the availability of a suitable surgery and a surgeon for this surgery. Some gaps will be filled with a surgery and some gaps will not. It is hard to simulate this. Therefore, we chose to leave all gaps unfilled, which results in a lower utilization than in practice.

In practice, we cannot distinguish the difference between a large changeover time and a gap caused by a cancelled surgery. Therefore, we chose to consider all gaps between surgeries longer than 30 minutes as changeover time. The 30 minutes are set in such a way that gaps caused by cancelled surgeries are not likely to appear in the changeover figures. The same yields for keeping a surgery room free because an emergency surgery will arrive in short notice.

Grouping surgeries results in a limited number of expected surgery durations for the surgery groups, whereas the expected surgery durations in practice are more multiform. This may lead to a puzzle in the simulation model that is less flexible than in practice. For example, if a surgery of type X does not fit at the end of the day, but only just, in practice an ‘easy surgery’ of type X can be scheduled, to make it fit.

In the simulation model, surgeries in the MSS are scheduled first. If the waiting list contains more surgeries than slots in the MSS of a certain surgery type, the model may schedule the surgery outside the MSS. In practice, these surgeries are usually postponed to the next week. This causes fewer surgeries to be scheduled within the MSS in the simulation. We expect that the effects to the simulation results are limited.

We compared the simulation to only 1 year of results from practice. This has the same reason as stated before. Surgery data and working procedures may change over time, which causes

OR performance to change. The disadvantage of using one year of data from practice is that OR performance may depend on coincidence more than it would if figures would be averaged over several years.

Discussion on implementation

Parallel to this research and the development of the simulation model, we have made a start with the adoption of the simulation model and its results in the UMC Utrecht. A crucial factor for this was a good first result, which can be used to persuade the people involved. Since we researched Urology and Vascular surgery, it was important to get the cooperation of the staff of both specialties. Therefore, we kept close contact with one of the surgeons and organized a meeting for the urologists to present the results of the simulation.

This meeting however, did not have the intended effect. Two of the urologists felt attacked by our presentation. They experienced the “how can you outsider know what we should do”-feeling. This feeling was probably caused by a lack of knowledge about the tools we use and the urge to protect their own interests.

This example shows how careful we should be while promoting the OR Manager in practice. Important players need to be involved in an early stadium. And since the UMC Utrecht has a decentralized organization structure, almost everyone that will be involved should be considered as an important player. This means that for every possible improvement in the organization, we need to make the people involved aware of the problems occurring, the need for improvement, and the validity of the tools we use. This leads to a better understanding and the willingness to contribute to the improvement of the situation under consideration, and ultimately to a contribution to the improvement of organization of the UMC Utrecht as a whole.

Appendix A Literature Cited

Allen M., M.J. Wigglesworth. 2009. Innovation leading the way: application of lean manufacturing to sample management. Journal of Biomolecular Screening 14(June (5)):515–22.

Altman, D. G. 1991. Practical statistics for medical research. Chapman and Hall/CBC.

Armitage, P., and G. Berry. 1994. Statistical Methods in Medical Research. 3rd ed. Blackwell.

Ashby, M., D. Ferrin, M. Miller, N. Shahi. 2008. Discrete event simulation: Optimizing patient flow and redesign in a replacement facility. Simulation conference 1632-1636.

Blake, J.T., J. Donald. 2002. Mount Sinai Hospital Uses Integer Programming to Allocate Operating Room Time. Interfaces 32(2):63-73.

Belien, J., E. Demeulemeester, B. Cardoen. 2009. A decision support system for cyclic master surgery scheduling with multiple objectives. J Sched 12: 147–161.

Cardoen, B. 2009. Optimizing a multiple objective surgical case sequencing problem. Int. Journal of Production Economics 112:354-366.

Collins, G. 2006. New ways of working in theatres. Three session working days. J Perioper Pract. 16(1):43-51.

England, W., S.D. Roberts. 1978. Applications of computer simulation in health care. Proceedings of the 10th conference on Winter simulation - Volume 2:665-677.

Fei, H. 2009. Solving a tactical operating room planning problem by a column-generation-based heuristic procedure with four criteria. Annals of Operations Research 166:91-108.

Hans, E. W. 2008. Robust surgery loading. European Journal of Operational Research 185:1038–1050.

Hans, E. W., and G. Wullink.2006. A framework for Hospital Planning and Control.

Hoorn, A. F., and I. Wendt. 2008. Benchmarking: een kwestie van leren. project Benchmarking OK.ase, K., and K. Kanefuji. 1994. Estimation for 3-Parameter Lognormal-Distribution with Unknown Shifted Origin. Statistical Papers 35:81-90.

Jun, J.B., S.H. Jacobsen, J.R.Swisher. 1999. Application of discrete-event simulation in health clinics: a survey. J Oper Res Soc 50:109–123.

Law, A. M., and W. D. Kelton. 2000. Simulation modeling and analysis. third ed. McGraw-Hill, Singapore.

Los, A.2004. Een opslagsysteem voor hechtmaterialen.

Oostrum, J.M. van, E. bredenhof, and E. W. Hans. 2009. Suitability and managerial implications of a Master Surgical Scheduling approach. Annals of Operations Research 178(1):91-104.

Persson, M.J., J.A.Persson. 2009. Analyzing management policies for operating room planning using simulation. Health Care Manag Sci 13:182–191.

Ramwadhdoebe, S., E. Buskens, R.J.B. Sakkers, J.E. Stahl. 2009. A tutorial on discrete-event simulation for health policy design and decision making: Optimizing pediatric ultrasound screening for hip dysplasia as an illustration. Health Policy 93:143–150.

Shapiro, S. S., and M. B. Wilk. 1965. An Analysis of Variance Test for Normality (Complete Samples). Biometrika 52:591-&.

Stepaniak, P. S., C. Heij, G. H. Mannaerts, Q. M. de, and V. G. de. 2009. Modeling procedure and surgical times for current procedural terminology-anesthesia-surgeon combinations and evaluation in terms of case-duration prediction and operating room efficiency: a multicenter study. Anesth.Analg. 109:1232-1245.

Strum, D. P., J. H. May, A. R. Sampson, L. G. Vargas, and W. E. Spangler. 2003. Estimating times of surgeries with two component procedures: comparison of the lognormal and normal models. Anesthesiology 98:232-240.

Appendix B Simulation settings

This section is meant as a guideline for future users of OR Manager. We describe the settings of OR manager and the choices we made. We will use the steps defined within OR manager in this description. These steps are different than the steps described in Section 4.1.

Step 1

We choose to simulate a duration of one year. This period is easy to compare with registrations in practice. We divide the year in 52 *periods* of one week.

The *number of patients* in this step is not the number of patients we will simulate, but is only used for the calculation of the initial waiting list. It is set to an amount of patients that would use approximately 100% of the available surgery time in the simulation model, i.e. 690 patients per year.

The *maximum number of waiting weeks,* which is the maximum number of weeks a patient is allowed to be on the waiting list, is described in step 4.

The *start of the working day* will be 8:00, as it is in practice. The simulation model does not take the startup time into account. It does however count one changeover time too many, because the duration of every surgery, including the first and the last surgery, includes the changeover time. To keep the calculation of the results easy, we assume that the changeover time and start up time are both equal to 15 minutes, which is approximately the case in practice (see Table 2.15). In this way, the startup and the extra changeover time cancel each other out with respect to the available surgery time. The gross utilization (see Section 2.3) is however not registered correctly automatically, because changeover is included in the utilized time and start up time is not. Therefore, we need to subtract the warm up time, approximately 15 minutes, from the utilized time in the simulation. The end of the working day in the simulation is equal to the end of the working day in practice: 16:00.

In Section 4.2 we describe how we derive the surgery types from historical data. We will not need emergency surgeries and staffing data, because these are out of our scope.

The *no-show percentage* is assumed to be equal for all surgeries of the same specialty. This figure represents all surgeries that are cancelled because of external factors. These factors include patient reasons (i.e. a patient does not show up), medical reasons (i.e. the patient is ill) and cancellations because of a capacity shortage (i.e. x-ray or surgeon shortage). The no-show percentage of Urology is 3.5 and the no-show percentage of vascular surgery is 3.3 (see Table 2.16).

Step 2

The *number of OR-days per week* is equal for every week. For simplicity, we use the typical number of OR-days per week of each specialty for the simulation. The number of OR-days per specialty is rounded to an integer number of ORs per week. In case of vascular surgery, this is 5 OR-days per week and for urology, this is 3 OR-days per week. This causes the capacity in the model to be larger than in practice. If necessary, the resulting figures can be adjusted to be compared with the actual workload.

The *capacity target* is the percentage of available surgery time the simulation model tries to plan surgeries in. We will determine the capacity target as part of the fine-tuning (Section 4.3.3). This number represents the maximum fill rate per OR-day.

Step 3

For vascular surgery, we will use the MSS in the same way as it is used in practice (see Section 2.2.3). We mentioned that 2 or 3 Abdominal Aneurysms are performed on Tuesdays. In the simulation, we will create 3 MSS slots for Abdominal Aneurysms. This will result in some days on which 3 abdominal aneurysms are performed. But on other days, the number of Aneurysms performed will be 2 or less, because the number of Aneurysms we need to schedule is less than 3 per week. The MSS we use is given in Table A. 1.

Day	**Surgeries**
Monday	Open Aneurysm + Small surgeries
Tuesday	2 or 3 * Abdominal Aneurysm
Wednesday	Nefrectomy + Kidney transplant
Thursday	3 * Carotid
Friday	Other surgeries (if Friday is assigned)

Table A. 1: Vascular surgery MSS

For Urology, we will not use an MSS. Opening times are equal for every OR-day per specialty. In step 1 we described which times we use.

Step 4 surgery generation

To generate a new set of surgeries, the tool has three options. One option generates a *number of surgeries*, which is defined by the user. The specialty and type of surgery of each surgery are generated randomly, based on the historical division of surgeries between specialties and surgery types. This option generates an unbalanced amount of surgeries per week, causing an unbalanced surgery schedule.

The second option generates a number of surgeries to *fill a certain percentage* of the available OR capacity per specialty. The surgery type of each surgery is generated randomly, based on the historical division of surgery types. This results in changing amounts of surgeries per surgery group per week, which in turn causes many empty MSS slots in some weeks and a shortage of slots in some other weeks.

The third option *generates a waiting list*, which is used as input for the schedule. The waiting list is replenished after a period is planned. All surgeries need to have a maximum waiting time that needs to be longer than the initial weeks of waiting list. One week of waiting list equals the average amount of surgeries the OR handles within one week, which is the total number of patients per year, divided by the number of weeks. The *initial weeks of waiting list* need to be at least two. This ensures that there are enough patients to be scheduled in every week. The *maximum number of waiting weeks* needs to be sufficiently larger that the *initial weeks of waiting list*. Otherwise all patients would be on the waiting list equally long, which would ruin the principle of the waiting list. A too long *maximum number of waiting weeks* however, would cause a high variation in waiting time per patient. Therefore, a small *maximum number of waiting weeks* would be best. We chose 4 weeks, which satisfies both criteria and is similar to current practice. Please note that the waiting list we use in the simulation model is not the same as the waiting list in practice. In its current form, it represents the last couple of weeks of the waiting list in practice, in which a patient may be scheduled.

We will choose the option that generates a waiting list, because this method represents the current planning method in practice best, and it creates a schedule that is most similar to the schedules in practice. We use a waiting list of 2 weeks and a maximum number of waiting weeks of 4. We select patients from the waiting list based on largest surgery duration first.

Schedule construction

With the generated surgeries, the tool can make a surgery schedule. The simulation tool generates surgery schedules on a weekly basis. The built-in constructive heuristics consists of two parts:

1. Surgery selection
2. OR selection

To start with, the heuristic selects a surgery based on a selection criterion. Built in options are selection based on *expected surgery duration*, *surgery duration standard deviation* and *random selection*. We adapted the existing selection method in such a way that due date critical surgeries have priority when waiting list replenishment is used as a generation technique for surgeries. We choose for longest surgery duration first in combination with the rule that surgeries with a critical due date have priority, because this is most similar to the selection criterion in practice.

The next part assigns an OR for the selected surgery. The OR selection is also possible in different ways. *Random fit* selects a random OR from the ORs where the selected surgery fits. *First fit* assigns the first OR where the surgery fist in to the surgery. *Best fit* selects the OR in which the least amount of surgery time is left idle after assigning the surgery to the OR.

The constructive heuristics produce a schedule which is often sub optimal. The constructed schedule can be improved using the steepest descent local search algorithm. This algorithm tries swapping or moving surgeries within a week. It accepts the change if the solution improves or with a certain chance if the solution deteriorates. The improvement heuristic does not take in to account which constructive heuristic was used. Therefore the resulting schedules get less dependent on the constructive schedule that was used, as the number of swaps increases. Additionally, the improvement heuristic does not take the MSS into account. Therefore, the surgeries in the MSS are shuffled, causing a non-MSS surgery schedule.

A different built in way to create a surgery schedule is regret based random sampling. This produces a schedule which is similar to the schedules that are produced by a constructive heuristic and the improvement heuristic together [Hans 2008].

We choose the scheduling algorithm that is most similar to current practice, *best fit descending*. This algorithm works well in combination with an MSS and uses the available time in a proper way. We will not use the improvement heuristic, because this does not work well with the MSS.

To spread the Break In Moments (BIM) equally over the day, the schedule can be improved with BIM optimization. We will not use this option, because most emergency surgeries will be performed in the emergency OR and because this is only interesting with several ORs running at the same time, which is not the case with the two specialties we chose in this research.

Step 5

OR manager has several different options for decision rules during the simulation. We will not use the options for (semi-)emergency surgeries. We will use the other options to match the simulation with the situation in practice. Delayed elective surgeries can not be moved to another OR. In practice, there are some exceptions to this rule, but most often, no movement is possible. Elective surgeries may start before its planned start time. This is the case in practice, since all patients are inpatient and patients are called to the OR by the OR personnel based on the progress of the previous patient.

Appendix C Surgery cancellation

Some of the processes used in practice in UMC Utrecht are not yet built in OR manager. In this section, we will mention the functionality we need to add to the tool. We describe why we need to add these components and how we have built them.

Currently, the OR coordinator (see Section 2.2.4) cancels a delayed surgery, if she expects it to cause an 'unacceptable' amount of overtime. 'Unacceptable' is not defined and subject to the judgment of the OR coordinator. It depends on many soft constraints, i.e. the urgency of the surgery, the willingness of the personnel to work in overtime on that specific moment, the overtime of other ORs on the same moment, etc. OR manager tool currently is not able to cancel patients. Thus, we cannot imitate cancellation figures and the absence of the possibility to cancel patients causes deviating overtime and occupation figures. We need to add the functionality to cancel surgeries to OR manager.

For the construction of the cancellation function, first we need to construct a set of decision rules that resembles the complex set of rules in practice. These are the most important factors that influence the decision to cancel a surgery:

1. Medical urgency
2. Recent occurrence of overtime of a specialty
3. The willingness of personnel to work in overtime
4. Expected amount of overtime
5. The idle time caused by a cancellation

Some of the above measures would need many adaptations to the model, others need fewer adaptations. The medical urgency for example, is not registered for elective surgeries and can therefore not be a factor in the simulation model. The recent occurrence of overtime of a specialty is probably a factor that does not have a large influence. The willingness of personnel to work in overtime probably differs over time, but we do not expect that the use of the average willingness affects model performance in a negative way. The number of ORs where overtime is expected on the same day is a factor which does have influence in practice, but it is not easy to implement in the model. The expected amount of overtime and idle time on the contrary, are factors with greater influence. These factors are easy to determine in the simulation. Hence, we will use these factors in the simulation model.

An interview with the OR coordinator indicates that more overtime is accepted when more idle time would result from canceling the surgery. For example, when the start of a surgery is 3 hours before the end of the day, an expected overtime of 1 hour may be accepted, but the same amount of overtime may not be accepted when the cancellation causes 1 hour of idle time (see Illustration A. 2). The cancellation figures shown in Illustration A. 2 are derived from an interview with one of the OR coordinators, so the situation in practice may be slightly different. The upper line represents the situation in which the coordinator would cancel a surgery, the lower line represents the cases in which the OR coordinator would let the surgery take place. The straight line in the middle represents the boundary between the 'cancel' and the 'do not cancel' area. We can see that the points of the upper and lower line form a reasonable straight line. This indicates that ratio between the expected overtime and the idle time can be used in the model as a parameter for the cancellation of surgeries.

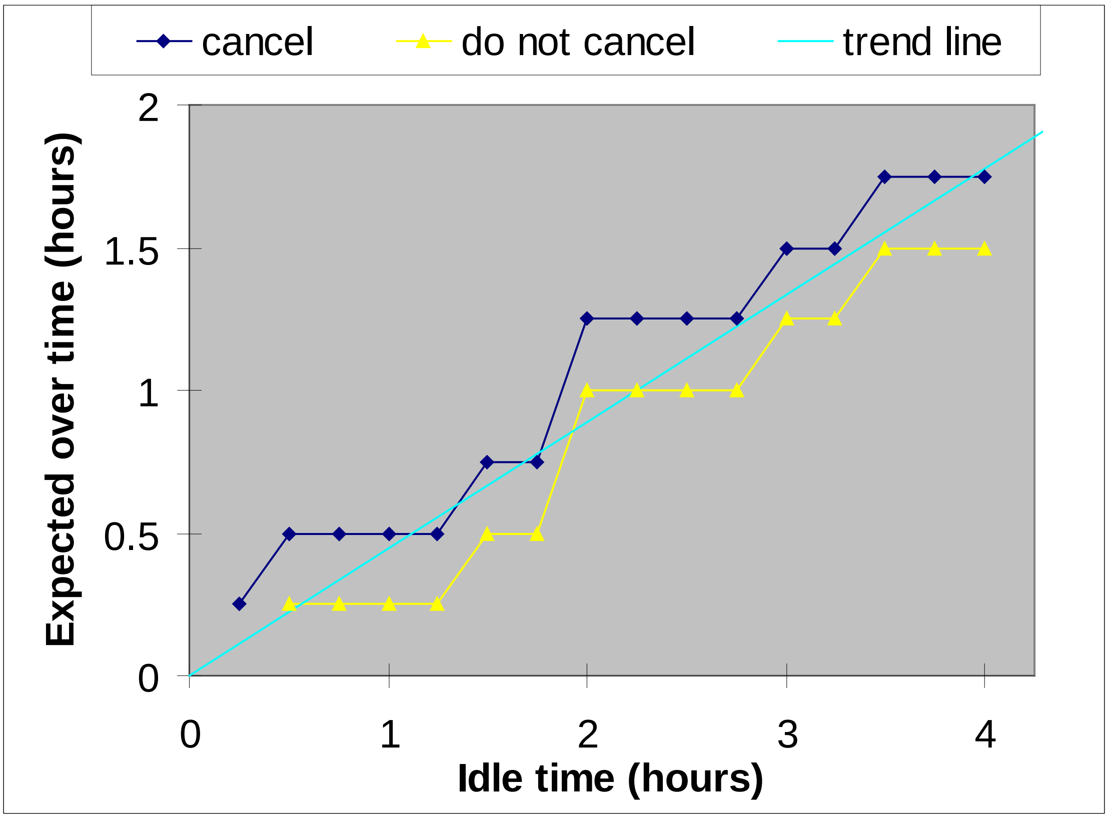


Illustration A. 2: to cancel or not to cancel a surgery?

We have implemented this parameter in OR manager tool. A user can select the option to cancel surgeries and select which percentage of the expected surgery duration in overtime is the critical level. We call this the cancellation parameter. Surgeries with an expected overtime percentage above the cancellation parameter are cancelled. Surgeries with an expected overtime percentage below the cancellation parameter take place as planned.

Surgeries that are cancelled, are cancelled permanently. They are not rescheduled. The reason for this is that OR manager makes the schedule for the whole year in advance. This leaves no room for the rescheduling of elective surgeries. In practice, many surgeries are rescheduled. This is possible because the schedule is constructed in the week before execution. This difference is not a problem, because for the simulation model, it makes no difference whether a surgery in the schedule is a rescheduled cancelled surgery, or a new surgery.

In our simulation study, we will select the option that surgeries are cancelled. We will determine the critical overtime percentage when we fine tune the simulation.

Appendix D Surgery grouping

Many surgeries are of a unique type and many surgery groups are too small for a good estimation of parameters. Therefore, we need to reduce the number of groups. In this appendix, we apply a numerical method, in which we try to deduce which surgical procedures contribute most to the duration of a surgery. These surgical procedures should be leading when constructing surgery groups based on surgical procedures. Surgeries with little contribution can be omitted to reduce the number of groups.

We define v_m^i as the contribution factor of surgical procedure *m* after iteration *i*. The surgery duration S_n is a constant for every surgery *n*. We define the number of surgical procedures *m* per surgery *n* as $a_{n,m}$. The contribution factors of all surgical procedures are equal at iteration *i*=0, we set them to 1.

$$v_m^o = 1 \qquad \forall m$$

The contribution factor of surgical procedure *m per surgery* after iteration *i*=1 is c_m^i .

$$c_m^i = Sn \cdot \frac{v_m^{i-1} \cdot a_{m,n}}{\sum_m v_m^{i-1} \cdot a_{m,n}} \qquad \forall m, n, i \geq 1$$

The contribution factor of surgical procedure *m* is the average of all contribution factors of surgical procedure *m* per surgery.

$$v_m^i = \frac{\sum_n c_m^i}{\sum_n a_{m,n}} \qquad \forall m, i \geq 1$$

At *i*=1, the differences between the $v^i{}_m$'s are small. These differences increase when *i* increases. We made a grouping based on surgeries with a contribution more than 25% of total surgery duration for different *i*'s. This did however not lead to a workable grouping. Using a different percentage of contribution did not improve the grouping, so we have to conclude that we are not able to group surgeries merely based on the surgical procedures.

Appendix E Surgery groups

Table A. 3 and Table A. 4 show the surgery groups and their parameters for vascular surgery and urology.

Code	Description (in Dutch)	% of surgery volume	Average duration*	Stdev of duration	Shift
A1	Amputatie bovenbeen	1,2	104	18	78
A2	Amputatie	5,8	77	26	15
AA1	Aneurysma - Endovasculaire Buisprothese	13,6	201	65	113
AA2	Aneurysma – Open	6	313	81	15
C0	Carotis - overige	2	183	40	15
C1	A.Carotis - Desobstructie	18,2	181	32	15
CAPD1	CAPD	1,6	108	42	15
D1	Toegangschirurgie	3,6	121	25	15
EX1	Ext.Antat.Bypass	1,4	206	44	15
F1	A.Femoralis	1,8	236	49	15
F2	A.Femoralis - Herstel Aneurysma	1,4	152	42	15
F3	A.Femoralis - Endarteriectomie	4,6	168	59	27
FC1	Femorcrurale bypass autologe vene	1	244	38	215
FP1	Femorpopliteale bypass	2,4	224	68	25
H1	Huid	2,2	62	15	35
I0	A.Iliaca - overige	1,4	186	31	15
N1	Nefrectomie laparotomie	6,4	192	27	15
N4	Nefrectomie getransplanteerde nier	1,2	91	16	15
NTX1	Niertransplantatie	7,2	164	21	114
VO1	Overige klein	6,2	109	30	15
VO2	Overige groot	6,6	260	83	158
P1	A.Poplitea – Herstel Aneurysma	1,8	199	84	85
TA1	Thoracaal Aneurysma - Percutaan	1	264	78	177
TOC1	Thorax	1,4	111	26	68

*Table A. 3: Vascular surgery types (*duration includes anesthesia and changeover time)*

Code	Description (in Dutch)	% of surgery volume	Average duration*	Stdev of duration	Shift
Blaas1	Cystectomie	3,5	555	78	15
Blaas2	Blaas klein	2,6	54	11	24
Lymf1	Retroperitoneale lymfklierdissectie	2,4	388	71	15
Nier1	Nier alle operaties	11,2	278	62	15
Penis1	Biopt penis en laser	3,2	56	10	32
Penis2	Reven penis / penoplicatie / Nesbit + circumcisie	1,8	143	52	15
Pros1	RALP	5,9	411	49	15
Testis1	Vasovasostomie	4,4	184	23	15
Testis2	Orchidectomie	2,6	103	33	69
Testis3	varico-/hydro-/spermatocele	8,5	85	22	41
Testis4	Microscopisch denervatie	1,8	154	26	15
Tur1	TUR(P/blaas)	3,8	100	27	49
Ureter1	Ureterreimplantatie	2,1	234	63	15
Ureter2	JJ splint	2,1	95	27	15
Ureter3	Uretorenoscopie (+evt. jj splint)	2,9	138		95
Urethr1	AMS-sfincterprothese bulbair	3,2	133	13	15
Urethr2	Urethraplastiek	4,4	240	36	75
Urethr3	Sachse/OTIS	4,4	70	23	15
Urethr4	Urethra klein	1,8	53	12	16
Urethr5	Urethra groot	1,8	170	43	15
Vas1	Vasectomie	1,8	75	17	15
UO1	Overige klein	13,2	79	21	15
UO2	Overige middel	5,0	174	40	123
UO3	Overige groot	5,6	292	82	15

*Table A. 4: Urology surgery types (*duration includes anesthesia and changeover time)*

Appendix F Number of replications

	Overtime			Gross utilization			% cancelled surgeries			half-length / average		
Rep nr	**Av.**	**cum av**	**cum stdev**	**Av.**	**cum av**	**cum stdev**	**%**	**cum av %**	**cum stdev**	**Overtime**	**Utili-zation**	**cancel**
1	49,59	49,59	-	88,05	88,05	-	5,69	5,69	-	-	-	-
2	57,05	53,32	5,28	87,96	88,00	0,064	4,78	5,24	0,64	0,8889	0,0065	1,1044
3	56,57	54,40	4,18	88,08	88,03	0,062	4,7	5,06	0,55	0,1907	0,0018	0,2702
4	58,78	55,50	4,05	87,73	87,95	0,158	5,36	5,13	0,47	0,1162	0,0029	0,1469
5	51,63	54,72	3,91	88,33	88,03	0,217	5,15	5,14	0,41	0,0888	0,0031	0,0992
6	60,24	55,64	4,16	87,82	87,99	0,212	4,45	5,02	0,46	0,0785	0,0025	0,0965
7	52,58	55,21	3,97	87,89	87,98	0,197	5,17	5,04	0,43	0,0665	0,0021	0,0780
8	66,78	56,65	5,50	88,12	87,99	0,189	4,76	5,01	0,41	0,0812	0,0018	0,0678
9	51,48	56,08	5,43	88,20	88,02	0,190	4,89	4,99	0,38	0,0744	0,0017	0,0588
10	47,25	55,20	5,83	87,35	87,95	0,277	4,52	4,95	0,39	0,0755	0,0023	0,0564
11	55,36	55,21	5,53	87,97	87,95	0,263	4,73	4,93	0,38	0,0673	0,0020	0,0512
12	68,44	56,31	6,51	88,24	87,97	0,264	5,02	4,94	0,36	0,0735	0,0019	0,0463
13	54,7	56,19	6,25	87,89	87,97	0,254	4,27	4,88	0,39	0,0672	0,0017	0,0483
14	56,22	56,19	6,00	88,57	88,01	0,292	5,63	4,94	0,43	0,0617	0,0019	0,0497
15	53,74	56,03	5,82	88,19	88,02	0,285	4,68	4,92	0,42	0,0575	0,0018	0,0467
16	55,62	56,00	5,62	87,72	88,00	0,286	4,39	4,89	0,42	0,0535	0,0017	0,0460
17	60,77	56,28	5,57	88,40	88,03	0,292	4,92	4,89	0,41	0,0509	0,0017	0,0430
18	57,1	56,33	5,40	87,71	88,01	0,294	4,7	4,88	0,40	0,0477	0,0017	0,0407
19	55,55	56,29	5,25	87,95	88,00	0,286	4,49	4,86	0,40	0,0450	0,0016	0,0395
20	53,38	56,14	5,16	87,90	88,00	0,279	5,15	4,87	0,39	0,0430	0,0015	0,0377
Adjusted gamma (γ')										**0,0448**	**0,0023**	**0,0394**

Table A. 5: 20 replications of urology. Cells in the last three columns are marked grey if the value in it is below γ'.

Rep nr	Overtime Av.	Overtime cum av	Overtime cum stdev	Gross utilization Av.	Gross utilization cum av	Gross utilization cum stdev	% cancelled surgeries %	% cancelled surgeries cum av %	% cancelled surgeries cum stdev	half-length / average Overtime	half-length / average Utili-zation	half-length / average cancel
1	110,1	110,1	-	88,10	88,10	-	4,42	4,42	-	-	-	-
2	113,8	112,0	2,62	88,48	88,29	0,27	4,45	4,44	0,02	0,2100	0,0273	0,0430
3	104,0	109,3	4,97	88,02	88,20	0,25	4,04	4,30	0,23	0,1130	0,0069	0,1319
4	106,9	108,7	4,23	88,12	88,18	0,20	4,41	4,33	0,19	0,0620	0,0037	0,0713
5	107,3	108,4	3,72	87,26	87,99	0,45	4,54	4,37	0,19	0,0426	0,0063	0,0547
6	108,9	108,5	3,34	87,90	87,98	0,40	4,16	4,34	0,19	0,0323	0,0048	0,0466
7	112,3	109,0	3,36	88,35	88,03	0,39	4,57	4,37	0,20	0,0285	0,0041	0,0417
8	106,7	108,7	3,22	87,92	88,01	0,37	4,35	4,37	0,18	0,0247	0,0035	0,0349
9	116,1	109,6	3,88	88,10	88,02	0,34	4,32	4,36	0,17	0,0272	0,0030	0,0302
10	114,5	110,6	3,98	88,20	88,04	0,33	4,56	4,38	0,17	0,0259	0,0027	0,0283
11	103,7	109,9	4,23	88,33	88,07	0,32	4,32	4,38	0,17	0,0260	0,0025	0,0254
12	103,7	109,0	4,36	87,85	88,05	0,31	4,39	4,38	0,16	0,0254	0,0023	0,0229
13	113,3	109,3	4,34	88,27	88,06	0,31	4,38	4,38	0,15	0,0240	0,0021	0,0208
Adjusted gamma (γ')										**0,0421**	**0,0023**	**0,0437**

Table A. 6: 13 replications of vascular surgery. Cells in the last three columns are marked grey if the value in it is below γ'.

Appendix G Interventions

description	intervention	urology	vascular surgery	
Current situation	Current-	URO	VAT	
Reduce cancellations	Guaranteed	URO-1	VAT-1	No cancellations
		URO-2	VAT-2	Half the cancellations
No MSS	NoMSS-	-	VAT	
adjust working day duration	DayLenght-	URO-1	VAT-1	6 hours
		URO-2	VAT-2	7 hours
		URO-3	VAT-3	8 hours
		URO-4	VAT-4	9 hours
		URO-5	VAT-5	10 hours
		URO-6	VAT-6	11 hours
		URO-7	VAT-7	12 hours
Adapt working hours to MSS	AdaptOurs-	-	VAT-1	8.5 hours
		-	VAT-2	9 hours
		-	VAT-3	9.5 hours
		-	VAT-4	10 hours
		-	VAT-5	10.5 hours
		-	VAT-6	11 hours
		-	VAT-7	11.5 hours
		-	VAT-8	12 hours
Move surgeries between ORs	MoveSurg-	URO	-	
Different scheduling heuristic	Heuristic-	URO-1	VAT-1	Earliest due date first
		URO-2	VAT-2	Largest standard deviation first
Combination of interventions	Combi-	URO	VAT	

Table A. 7: Interventions

Appendix H Results intervention DayLength

Urology			
Intervention	**Overtime per 24 hours OR time (min)**	**Gross Utilization (%)**	**Cancellations (%)**
DayLength-URO-1	121	87.3	4.5
DayLength-URO-2	77	87.4	4.0
DayLength-URO-3	55	87.9	4.8
DayLength-URO-4	49	88.4	4.0
DayLength-URO-5	39	88.3	4.5
DayLength-URO-6	35	89.0	4.5
DayLength-URO-7	35	89.5	4.7

Table A. 8: Results of the interventions on urology

Vascular surgery			
Intervention	**Overtime per 40 hours OR time (min)**	**Gross Utilization (%)**	**Cancellations (%)**
DayLength-VAT-1	106	84.2	2.8
DayLength-VAT-2	83	84.9	3.1
DayLength-VAT-3	84	86.3	3.4
DayLength-VAT-4	83	87.2	3.1
DayLength-VAT-5	69	87.6	3.8
DayLength-VAT-6	69	88.7	4.0
DayLength-VAT-7	68	89.2	3.4

Table A. 9: results of the interventions on vascular surgery