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Constructing schedules for the Operation Room Department while considering the influence on the Intensive Care Unit

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Abstract

The Operation Room (OR) and the Intensive Care Unit (ICU) are two departments at the hospital that interact with each other. Some patients require post-operative care at the ICU and their surgical operations can only be performed if there is capacity available at the ICU. This thesis proposes a scheduling algorithm which incorporates the ICU in constructing an OR schedule. Two objectives are used which either level the occupation of the ICU or the flow of patients from the OR to the ICU. Data of the Erasmus MC is used to construct OR schedules for this hospital. In this hospital currently the schedule of the OR is constructed without considering the interaction between the OR and the ICU. The constructed schedules are compared with the current OR schedule and show a more smooth occupation of the ICU and less variance in the flow of patients from the OR to the ICU.

To analyze the interaction between the OR and the ICU in more detail, the ICU is modeled as a queueing model. Different types of patients require admission to the ICU, for example patients from the OR, from the wards of the hospital or from the emergency department. Patients from scheduled surgical operations are one of these types. Their arrival at the ICU is determined by the OR schedule. With a simulation model the influence of the new OR schedules on the ICU is analyzed. The performance of the ICU is compared to the performance under other OR schedules. The constructed OR schedules result in a better performance on the ICU than a random schedule. The results show an increase in performance if the flow of patients from the OR to the ICU is more levelled. However, in general the differences in performance between the diffent OR schedules are small. The conclusion therefore is that there is not much room for improvement, although the ICU performance sligthly increases under OR schedules with a more smooth flow of patients from the OR to the ICU. The ICU performance is thus not very sensitive to the OR schedule. Apart from levelling the flow of patients from the OR to the ICU, we can thus focus on other criteria while constructing the OR schedule, such as optimal use of the OR capacity.

Keywords: Operation Room Scheduling, Mathematical Modeling, Intensive Care Unit, Queueing Theory, Simulation

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Chapter 1

Introduction

In the past decades the use of Operations Research in health care has increased considerably (Brailsford and Vissers (2010)). Hospitals do not only focus on providing service to the patients, but they become more cost orientated. Also the aging of the population will raise the costs for health care, which forces hospitals to think more about efficiency and cost savings. For these questions Operations Research is used and different studies have been done in this area. Mathematical models and simulation models are used for scheduling and planning, for analyzing patient flows and for the allocation of resources like capacity, nurses and hospital beds. These methods can help to analyze the performance of the hospital and to organize the hospital more efficiently, which can save costs. Examples are the analysis and improvement of the inventory control policy of medication and the scheduling of patient appointments to reduce the waiting time and expected over time in the doctor's consultation hours.

A class of papers in the field of Operations Research for health care focuses on the Operation Rooms (ORs). ORs are considered as one of the most expensive parts of the hospital, but they also generate the most profit (Jackson (2002)). The department of Operation Rooms (the OR) also influences many other departments in the hospital, such as the Intensive Care Unit (ICU). Operations Research has been used to study the scheduling of the ORs, the modeling of the ICU and the interaction between the OR and the ICU. This thesis focuses on these two departments in the hospital: the OR and the ICU. Data from the Erasmus Medical Centre in Rotterdam (Erasmus MC) is used to analyze the current performance. The Erasmus MC collects data of all the patients, including the length of stay at the hospital, the deparments of the hospital where the patient was treated et cetera. With these data information about the ICU and the OR is obtained. A scheduling model for the OR is constructed, which considers the capacity of both the OR and the ICU. The objective is to optimally use these limited capacities, since both over and under usage of the departments is costly.

1.1 Problem description

The Operation Rooms (ORs) and the Intensive Care Unit (ICU) are both costly departments in the hospital with limited capacity. Capacity can be measured in terms of beds, operation rooms, time, personnel, material et cetera. The limited capacities require a well thought schedule and use of the available capacity, considering both the care for the patients and the costs. For the OR this means that the surgical operations need to be scheduled such that the capacity is used as efficient as possible. Efficient use is the minimization of overtime and under time, which are both costly. At the OR two different groups of patients arrive: elective and emergency patients. To construct an OR schedule, information is needed about the number of surgical operations to perform and their duration. However both types of information are subject to variability. A surgical operation may take longer than expected and emergency surgical operations may come in, which cannot be scheduled beforehand. Therefore the schedule of the OR usually contains slack, time in which no surgical operations are scheduled. This time can then be filled with emergency surgical operations or used when elective surgical operations exceed their expected duration. The amount of time reserved for slack is difficult to determine and depends on the exact situation of the hospital.

The patients need post-operative care after the surgical operation. Some of them can immediately return to the ward, where others may need extra care, at the ICU or the PACU (Post Anaesthesia Care Unit). The flow of patients in and out of the OR and the ICU is showed in Figure 1.1. The ICU is also a department with limited capacity, where the actual number of arriving patients varies. A part of the patients demanding care at the ICU comes from the OR, but also patients from the wards within the hospital or emergency patients from outside may demand care at the ICU. Another source of variability at the ICU is the Length of Stay (LOS) of a patient. Some patients stay only one day, where others occupy an intensive care bed for a very long time. The variability makes the planning for the use of the ICU capacity complicated. If there is no bed available for a patient at the ICU, the patient is rejected. If that patient comes from the OR, the surgical operation must be cancelled. Over usage of the ICU capacity will thus result in the rejection of patients, while under usage of ICU beds is costly. The scheduling of the ICU therefore focuses on optimal use of the limited capacity. Different hospitals assign different priorities to patients to determine the ICU admission or rejection. Some hospitals give preference to emergency patients over patients from scheduled surgical operations. In case of shortage of capacity, surgical operations then may be cancelled, which reduces the part of incoming patients from the OR at the ICU. Other hospitals put high priority to the continuation of the scheduled surgical operations. Then emergency patients may be rejected at the ICU and, when necessary, transported to other hospitals.

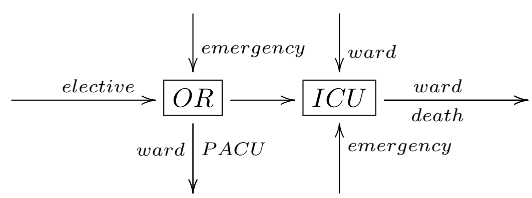

Figure 1.1: The arriving and departing groups of patients from the OR and ICU.

The scheduling of the surgical operations in the ORs and the admission of patients to fill the capacity of the ICU are correlated problems. When all ICU beds are occupied, scheduled surgical operations may have to be cancelled. Also the schedule of the OR determines a part of the demand for ICU beds. The problem addressed in this thesis is to analyze the influence of the OR schedule on the ICU. A model is constructed for the scheduling of surgical operations into the ORs, which also incorporates the demand for ICU beds caused by those surgical operations. The main objective is to use the capacity of both the OR and the ICU optimally and reduce the variability in the demand for ICU beds from patients out of the OR. A more constant and less variable flow of patients from the ICU to the OR is more convenient for the ICU. Less peaks in this demand and thus smoothing the amount of incoming patients from the OR at the ICU, is thought to reduce the probability that all the ICU capacity is used and that patients must be rejected. A simulation model of the ICU is constructed to analyze the actual influence of the OR schedule on the ICU.

1.2 Relevance and motivation

The topic of OR scheduling is analyzed more theoretically. One of the main aspects is to construct a scheduling model for the OR, which takes the demand for ICU beds into account. In literature the scheduling of the OR and performance of the ICU are usually considered separately. However there are some studies performed with a more joined analysis. Some of them are described in the literature review. They differ mostly in the way the ICU capacity is introduced in the model. Also the variability in duration of surgical operations and in length of stay at the ICU is taken into account in different ways. This thesis constructs a scheduling method for the OR, based on methods from literature, considering the demand for ICU beds and the variability in the problem. In contribution to literature, the influence of the OR schedule on the ICU occupation and the actual benefits of the new OR schedule for the ICU department are analyzed with simulation models.

The thesis is performed in cooperation with the Erasmus MC. At the Erasmus MC the planning of the OR and the admission of the ICU are determined separately. This results in an unevenly distributed demand for ICU beds from patients out of the OR and sometimes in lack of ICU capacity. The number of patients from the OR which needs an ICU bed, both from elective and emergency surgical operations, is very variable over time. Management assumes that this leads to (unnecessary) cancellation of surgical operations. The ICU department would benefit from a more smooth arrival of these patients. However the group of elective patients from the OR is the only incoming group at the ICU which can be regulated. Emergency patients cannot be scheduled and thus the variance in ICU bed demand can only be reduced for elective patients. The actual benefit of a more smooth arrival of elective OR patients at the ICU thus depends on the emergency patients as well. The department Spoed en Intensief [in English: Emergency and Intensive Care] of the Erasmus MC requested a joined analysis of scheduling of the OR and the admission of the ICU. The data of the Erasmus MC is used and an OR schedule is constructed for the specific situation of the Erasmus MC, using methods from literature. After constructing this schedule, the consequences for the ICU are analyzed via simulation. The assumption that a more smooth distribution of patients from the OR to the ICU leads to fewer cancellations of elective surgical operations, is tested. The benefits of the new OR schedule for the ICU department are analyzed. This means that the results of the study are relevant for the Erasmus MC. However, the focus of the thesis is more theoretical than practical. Therefore the results of the thesis must be translated afterwards for implementation and perhaps some adjustments should be made for the actual practical use.

1.3 Research question and structure of the thesis

This thesis focuses on the construction of OR schedules. The objective in the OR scheduling is to influence the patients going from the OR to the ICU. The OR schedules try to influence the flow of these patients, such that it is advantageous for the ICU.

The research question can be formulated as follows:

How can we construct OR schedules that incorporate the patients going from the OR to the ICU and what is the actual influence of these OR schedules on the ICU performance?

To answer the research question, first different studies from literature are investigated in the Literature Review in chapter 2. These studies describe methods that are used for comparable problems. Some of these methods are used to formulate the problem in this thesis. The data used in this thesis is from the Erasmus MC. The characteristics of the OR and ICU departments of this hospital are described in chapter 3. Based on the methods used in literature the OR scheduling problem is formulated in chapter 4. In this problem OR schedules are constructed while considering the influence of these schedules on the ICU.

The actual influence of the OR schedules on the ICU is analyzed by modeling the ICU. In chapter 5 the ICU is modeled as a queueing model. A simulation study of the ICU is performed, which analyzes the influence of the different OR schedules on the ICU. In chapter 5 the results of the simulation study are presented. Based on these results the OR schedules can be compared together with their influence on the performance of the ICU. In the final chapter, chapter 6, a short summary of the performed research is given. This chapter also gives the final conclusions, suggestions for further research and some recommendations for the Erasmus MC.

Chapter 2

Literature review

Literature about Operations Research in health care analyzes different aspects of the health care system and the hospital. One field mainly studied is the planning of the Operation Rooms (ORs). The Operation Room department (the OR) is one of the most expensive departments of the hospital and interacts with many other departments, such as the Intensive Care Unit (ICU). The scheduling of the OR is a difficult problem and many studies focus on this problem.

2.1 The planning and scheduling of Operation Rooms

Cardoen et al. (2010) describe different types of patients for surgical operations. We can distinguish between elective and non-elective patients. Elective patients have a surgical operation which is scheduled in advance and non-elective patients undergo a surgical operation because of urgency or emergency. The elective patients can be partitioned in inpatients, which stay in the hospital for more than one day, and outpatients, which come and leave at the same day. Only the surgical operations of the elective patients can be scheduled, since they are known in advance. This is the reason that the OR schedule in chapter 4 is only constructed for elective patients. The scheduling of surgical operations in the ORs can be done on three levels (Blake (2010)). At the strategic level the scheduling and needed capacity for the long term are investigated. At the tactical level a general schedule is determined for the intermediate term and thirdly, the individual surgical operations on the short term are scheduled at the operational level. This thesis considers scheduling on the tactical level. Planning at operational level can be done both offline and online, where offline planning means that the planning is done before the schedule starts and online planning are the adjustments made while the schedule is already in progress.

The scheduling system for an OR can be a blocked or a non-blocked system. In blocked systems the available OR time is split in time intervals, called blocks, with a length of usually a day or half a day. These blocks are assigned to surgical services, which are the specialisms in the hospital which perform surgical operations (general surgery, plastic surgery, neurosurgery et cetera). These surgical services are then free to plan their patients in their own blocks. Non-blocked systems simply assign all patients based on first come first served basis. Formerly completely non-blocked systems were used (Magerlein and Martin (1978)), but nowadays blocked-systems are preferred (Blake (2010)). The Erasmus MC is also using a blocked system. Those blocked systems allow a better allocation of the resources over the different surgical services and reduce the probability of time conflicts, which may occur due to the variability in duration of surgical operations. According to Gupta (2007) sometimes a combination of blocked and non-blocked systems is used. The elective patients are scheduled in blocks, but the emergency cases are scheduled according to a non-blocked system. For a blocked system there are two main decisions which have to be made. A priori there must be identified how the available OR time should be allocated to the different surgical services. After that allocation is done, the blocks must be scheduled and the actual patients need to be determined and scheduled in the blocks. Cardoen et al. (2010) refer to the first step as the planning and to the second step as the scheduling of the ORs. This thesis focuses on the second step.

Different methods are used to plan the OR and to determine which amount of time is assigned to each surgical service. Blake and Donald (2002) start with a given target allocation of the available time over the different surgical services. This target is based on the allocation over the surgical services in the existing schedule. They then use an integer programming problem, which schedules the given surgical operations, minimizing the deviation in time allocation from the target allocation. Kuo et al. (2003) use a linear programming approach to adjust the allocation of the OR time among a group of surgeons. They allocate the available time such that the weekly revenue is maximized. The OR schedule constructed in this thesis uses the data of the surgical operations performed in 2011. Assumed is that the allocation of the OR time over the different surgical services in 2011 is representative for the future. Different articles incorporate the variability in surgical duration. Usually this duration is assumed to follow a lognormal distribution (Strum et al. (2000)). Hans et al. (2008) also consider which part of the available OR time must be left unscheduled. These empty time periods are called slack and they are used as buffer, such that the probability of overtime is reduced. The article uses the portfolio effect, which states that the variance in the total duration of the surgical operations on an OR day can be reduced if surgical operations with comparable variances are scheduled after another. The sum of durations of the surgical operations on one day is assumed to follow a normal distribution according to the central limit theorem. Different constructive and local search methods are used to make the OR schedules.

Different articles refer to the schedule of the OR with the term Master Surgical Schedule (MSS), which is a cyclical schedule for the operating rooms. This cyclical schedule holds for a limited time period and it starts again when the end of that time period is reached. The MSS is related to the master production schedule in a production environment. Beliën and Demeulemeester (2007) construct an MSS with a blocked system and take the required number of blocks for each surgical service as input information. The formulation of the OR scheduling problem in chapter 4 is comparable to the problem formulation in Beliën and Demeulemeester (2007). Van Oostrum et al. (2008) consider the surgical operations to be added in the MSS as given, together with their duration. The objective then is to minimize the use of the OR capacity. Both articles therefore do not study the allocation of time over the different surgical services, but assume that this allocation is already given. The same assumption is used in this thesis. In Van Oostrum et al. (2011) a clustering method for surgical operations is proposed. The article constructs a cyclical schedule which consists of recurrent surgery types, which are clusters of surgical operations. Comparable surgical operations are clustered together in surgery types. Dummy surgery types are added for the remaining surgical operations. The objective is to minimize the volume of dummy surgeries and the variability within a cluster. In chapter 4 another method is used to place surgical operations in groups. The proposed method is a contribution to literature, because it is a new way of combining surgical operations for the construction of the OR schedule.

Van Oostrum (2009) uses a seven-step approach to construct an MSS. The first step focuses on the determination of the scope of the MSS, which includes the types of surgical services that should be included in the MSS. Surgical services which have to perform surgical operations on a regular basis, are included in the cyclical schedule. Surgical services which rarely use the OR can plan their surgical operations in the time which is left unscheduled.

Once the allocation of OR time over the different surgical services is determined, usually combinatorial optimization methods are used to construct the schedule for the OR. The linear programming model of Kuo et al. (2003) is relatively simple and can be solved to optimality. Beliën and Demeulemeester (2007) propose different MIP heuristics and a Simulated Annealing approach to solve the problem for the construction of the MSS. Van Oostrum et al. (2008) construct an MSS in two steps and also include the levelling of the demand for hospital beds. First an optimal combination of Operating Room Day Schedules (ORDSs) is determined, with the objective to minimize the usage of the OR capacity. An ORDS is a set of surgical operations feasible for a specific OR on one day. A column generation approach is used to generate these ORDSs. The second step determines how these ORDSs should be scheduled into the MSS, such that the maximum requirement for hospital beds is minimized. The problem in this second step is formulated as an MILP. Pham and Klinkert (2008) propose a surgical operations scheduling model based on the job shop scheduling problem. The development of heuristics to solve this problem is left to further research. Vargas et al. (2009) formulate the OR scheduling as a bin packing problem, where OR time must be filled with surgical operations. The bin packing problem is NP-hard and therefore different heuristics are proposed, all based on the context of bin packing.

2.2 The Intensive Care Unit

The OR interacts with many other departments in the hospital, such as the Intensive care unit (ICU). The patients at the ICU need specialized care, because their vital functions are threatened. The hospital aims to provide the required care to those patients, because their lives may be in danger. However, since the capacity at the ICU is limited and this department is extremely costly (Mallor and Azcárate (2011)), choices should be made about the admission and scheduling of patients. Kim et al. (1999) distinguish four different types of incoming patients at the ICU: patients out of the operating room, both elective and non-elective, patients from the ward and patients who must visit the ICU because of emergency and accidents. Other studies use comparable groups. In chapter 5 the same four groups are used to describe the patients at the ICU.

The different types of patients arrive according to different arrival patterns. The arrival of patients from elective surgeries is known in advance and can be determined out of the OR schedule. The arrival of other groups is usually assumed to be Poisson (for example Ridge et al. (1998) and Kim et al. (1999)).

Ridge et al. (1998) assumes that emergency patients arrive according to the Poisson distribution with an arrival rate independent of the day of the week. The arrival rate of planned patients however does depend on the day of the week, but it is assumed that these patients arrive at random during a day.

Mallor and Azcárate (2011) use the translated Poisson distribution, which seem to fit the patient arrivals during the week better. In the weekends, when no scheduled surgical operations are performed, the Poisson distribution is used to describe the total arrival pattern of patients at the ICU.

Different articles are written about the modeling of the ICU and often queueing models are used for that (Griffiths et al. (2006) among others). For these models the arrival process, the service process and the number of servers must be defined. ICU beds are considered as servers and the service time is the time a patient stays at the ICU. The arrival of patients has been described before. Patients are discharged from the ICU when their condition has improved or when they have died. These patients do no longer need the intensive care and the first group can be transported to the ward. The time between arrival and departure at the ICU is called the length of stay (LOS). Zhu et al. (2012) use discrete event simulation to analyze the capacity usage at the ICU.

The main difficulty in analyzing the ICU is the large variability in Length of Stay (LOS). Bruin et al. (2005) state that averages of the LOS cannot be used, because of this large variability. Van Houdenhoven et al. (2007) focus on the prediction of the individual LOS. They use patient characteristics in multivariable linear regression models and are able to improve the predictions of the LOS of individual patients. The distribution of the LOS is heavily tailed towards the right, which means that a small amount of patients stays at the ICU for a long time. Suggested is that these patients should be considered as outliers and perhaps be removed from the dataset. However these patients require a large amount of resources (ICU beds and nurses) and are therefore very important in the analysis (Mallor and Azcárate (2011)). Marazzi et al. (1998) study the fitting of the distribution of the LOS and consider the Lognormal, Weibull and Gamma distribution. Concluded is that the lognormal distribution fits the LOS best in most cases. Other articles commonly use distributions like the negative exponential distribution and the Weibull distribution (Ridge et al. (1998)). This thesis assumes that the LOS follows a lognormal distribution.

Many articles analyze the ICU by modeling the movement of patients in and out the ICU and analyzing performance measures, such as the percentage of capacity used. However less is written about the optimization of the planning and admission to the ICU. Some simulation studies describe admission rules and investigate the changes in performance by adjusting these rules (Ridge et al. (1998)). For the admission rules elective and non-elective (or emergency) patients are separated. Elective surgery patients are often considered to be of less importance than emergency patients. When the elective patients are rejected at the ICU, their surgical operation has to be cancelled. These elective patients are only admitted if the number of free beds is above a certain minimum level, such that there remains room available for emergency patients. The elective patients can only be rejected a number of times, after that they reach the emergency status. Emergency patients are always admitted if there is a free bed. Other studies use similar rules. Litvak et al. (2008) also describe the possibility to transport emergency patients to hospitals in the region. They conclude that cooperation between hospitals can result in less rejection of patients and that fewer beds are required.

Mallor and Azcárate (2011) remark that the LOS depends on the occupancy of the ICU. They reason that the occupancy of the ICU influences the admission and discharge decisions made by the personnel. The assumption is that the LOS is shorter when the occupancy of the ICU is high, which means that patients are allowed to move to the ward after a shorter period of time to make room for other patients. The article adjusts the admission rules in the simulation model to incorporate the occupancy of the ICU. The personnel of the ICU in the Erasmus MC also reported that the LOS is influenced by the occupancy of the ICU. However, for simplicity in chapter 5 the assumption is made that the LOS is independent of the ICU occupancy.

Kim et al. (2000) describe different bed reservation schemes and compare the performance of the different scenarios. These scenarios differ mostly by the reservation of some ICU beds for elective patients. The number of rejected patients and the average bed occupancy is determined via simulation. They conclude that there is no dominant optimal bed reservations scheme, but the constructed frontier can be used for tradeoffs between different objectives. In chapter 5 two reservation schemes are proposed which also favour the patients from elective surgical operations.

Shmueli et al. (2003) use a simple queueing model to compare different rules for admission to the ICU. Patients with good prognoses for recovery are preferred to patients with poor prognoses. They conclude that the proposed rules could increase the survival benefits. Kozan (2008) models the ICU as a job shop scheduling problem and uses this model to determine the optimal scheduling and admission of patients. Only the elective patients are considered and a selected number of ICU beds is reserved for them. The model takes the arrival times and LOSs as given parameters and minimizes the number of rejected patients or the waiting time for the admitted patients.

2.3 The joint analysis of Operation Rooms and the Intensive Care Unit

In the previous studies, most of the time the planning of the OR and the modeling and scheduling of the ICU are considered separately. However these problems interact, since a part of the incoming patients at the ICU comes from the OR and the ICU capacity restricts the continuation of the OR schedule. Therefore different studies focus on the integration of ICU and OR scheduling.

McManus et al. (2003) describe two types of variability with which the ICU has to cope: natural and artificial variability. Natural variability occurs due to emergency patients and due to the variability in the course of diseases. Artificial variability however is caused by the planning of elective patients in the ORs. The authors conclude that this artificial variability is larger than the natural variability. Therefore reconsidering the OR schedules will potentially reduce the variability in the arrival process of patients at the ICU.

The demand for ICU resources, like beds and nurses, can be incorporated in the planning of the OR in different ways. A very straight forward method is to add a constraint for the resources in the mathematical programming for the OR scheduling. For example, for every surgical operation the demand of ICU beds is determined and a constraint is added to the planning of the operation rooms, such that the capacity of the ICU is not exceeded at any moment. Adan and Vissers (2002) and Santibáñez et al. (2007) use this approach amongst others. Pham and Klinkert (2008) use a large job shop scheduling problem, where not only the required OR room is considered, but also other resources that are needed for a surgical operation, such as nurses, surgeons and beds. Every surgical operation needs some specific resources and the job shop scheduling problem minimizes the total make span of all jobs, where the required resources do not exceed the capacity. A disadvantage of this way of incorporating the ICU capacity into the OR scheduling, is that the available capacity of ICU beds must be determined beforehand. As seen before, different types of patients demand ICU beds and the patients from elective surgical operations are only one group of them. Using a capacity constraint requires the theoretical reservation of some ICU beds especially for this group of patients.

There is also a class of papers which incorporates the bed occupancy of the ICU in the objective function. Ozkarahan (2000) uses goal programming with multiple objectives. Minimizing both OR underutilization and overtime and levelling the use of the ICU capacity are two of them. Pol et al. (2006) propose a four step scheduling method for the OR at an operational level. The surgical operations are scheduled such that the expected number of cancelled surgical operations due to lack of ICU bed capacity is minimized. At every step a certain type of surgical operations is scheduled given the OR and the ICU capacity. Results of this approach are not given, but it is expected to have a positive effect on the use of the ICU capacity and to reduce the number of cancelled surgical operations. Beliën and Demeulemeester (2007) construct an MSS with the objective to minimize the total expected bed shortage. Several linearization methods are proposed to construct a linear objective function. Also the variance of the expected bed occupancy is added and minimized. However to keep the model linear the LOS at the ICU is assumed to follow a multinomial linear distribution. It is not clear whether the constraints remain linear when other distributions are used for the LOS. Van Oostrum et al. (2008) construct an MSS with a weighted objective function, in which the use of OR capacity is minimized and the ICU bed requirement is levelled. The authors add the ICU bed occupancy in the model with a min max objective, which means that the maximum use of the ICU capacity is minimized. They propose a two-step solution approach. In the first step Operation Room Day Schedules (ORDSs) are scheduled and the ICU bed capacity is ignored. These day schedules are constructed using column generation as described before. Then the optimal ORDSs need to be selected and sequenced, with the objective to level the ICU bed demand. The authors use the mean ICU length of stay for each surgical service. They remarkably show that both objectives do not seem to conflict. The minimizing of the used OR capacity also leads to a reduction of peak demands at the ICU. Adan et al. (2009) introduce variables in the OR scheduling model for the under and over usage of different resources, including the ICU capacity. These variables for the ICU capacity depend on the OR schedule and the distribution of the LOS. The objective is to minimize the over and under usage, such that there is a levelled use of the resources. In contrast to the method of Van Oostrum et al. (2008), this approach is less general and focuses more on the used ICU capacity on a single day. In the OR scheduling problem in chapter 4 a formulation similar to Adan et al. (2009) is used to incorporate the use of the ICU capacity.

Finally one paper is found in which the OR and the ICU are modeled together as a tandem queue. Van Dijk and Kortbeek (2009) use this queueing system to analyze the interaction between the two departments and to determine the total rejection probability at the ICU. Analytical expressions are derived for both a lower bound and an upper bound on this rejection probability.

To sum up, we can say that the ICU can be incorporated in the OR planning in different ways. There is a class of papers which considers the ICU occupancy as a constraint. For every surgical operation the required ICU capacity is determined and a constraint is added to the OR planning model such that the ICU capacity will not be exceeded. Other papers use a multi-objective approach in which the minimization of the used OR capacity is combined with the levelling of the ICU demand. These objectives can be considered at the same time or sequentially.

The usage of the ICU capacity can thus be incorporated in the OR schedule in different ways. The articles from this section usually determine the influence of the OR schedule on the ICU by analyzing the

OR schedule. However, at the ICU there are different types of patients. Only one group of them is influenced by the OR schedule. To determine the actual influence on the ICU, the total ICU must be analyzed. The articles in section 2.2 analyze the performance of the ICU with simulation models or with expressions from queueing theory. Then all types of patients at the ICU are considered. This gives a better indication of the performance of the ICU, then when only the OR schedule is analyzed. Therefore, in addition to literature, in chapter 5 simulation models of the total ICU are used to determine the actual influence of the OR schedule on the ICU.

Chapter 3

Erasmus MC

This thesis uses data of the Erasmus MC in Rotterdam. To get more information about the characteristics of the OR and ICU departments at the Erasmus MC, short interviews have been taken with coordinators of those departments.[1] The current scheduling and planning is discussed as well. This chapter describes the OR and the ICU department in more detail.

3.1 The Operation Room Department

The OR department at the Erasmus MC consists of 16 operation rooms. Due to personnel restrictions not all rooms can be used at the same time. The aim is to use 12 rooms on Monday until Wednesday and 11 rooms on Thursday and Friday. There are no elective surgical operations scheduled in the weekend. The ORs can be used on weekdays between 08.00h and 15.30h. Sometimes the opening times are extended and surgical operations can be performed until 17.30h or 20.00h. Every day approximately two ORs have an extended opening time, these ORs are then mainly used for long-lasting surgical operations. Not all surgical operations can be performed in each OR, which has mostly to do with restricted available material. The OR planning coordinators know these restrictions and consider them while constructing the OR schedule.

The surgical operations are performed by different surgical services. The distribution of the available OR time over the different surgical services is determined by the board of the hospital and is made on a yearly basis. The decisions for the distribution are based on budget restrictions and performance objectives. The OR schedule is then constructed in two steps. First the OR planning coordinators assign operation rooms to the surgical services. For every day they determine which OR can be used by which surgical service. The outline for this schedule is made for the entire year. The schedules differ per week, but around 50 to 60% of the schedule is the same each week. The schedule can thus be considered cyclical with a time cycle of a week. An OR is assigned to a surgical service for an entire day. This schedule has to take into account on which days the surgical services have their outpatient consultations and on which days they can perform surgical operations. In the second step, the actual patients are scheduled. This scheduling is done by the surgical services themselves.

In Appendix A examples are given of the OR schedules from the Erasmus MC. Both a schedule on the level of the surgical services is presented and a schedule on the level of the individual patients.

The main objective in the planning of the OR is the optimal use of the available time, which is measured in the minimization of overtime. The duration of surgical operations is determined based on norm times, which are averages of the duration of performed surgical operations of the same type over some time period.

[1] The following people from the Erasmus MC have been interviewed:
M. Mendes and N. Stassen (OR)
W. Borst and B. Ruit (ICU)

These averages are adjusted after every surgical operation. Sometimes surgical services choose to keep some OR time unscheduled, to prevent overtime which might occur if a surgical operation takes longer than expected. However, usually just the norm times are considered in the schedule and all available time is used to schedule surgical operations.

Emergency patients who arrive at the OR are classified according to urgency. Some patients have to be operated immediately, where others can wait some hours. To operate the most urgent patients, the OR department tries to schedule these emergency operations in a room where another surgical operation has just finished. This means that the next scheduled surgical operation is postponed or cancelled. If there is no changing of surgical operations when the emergency patient arrives, sometimes another surgical operation can be interrupted, such that the personnel can operate the emergency patient first. The less urgent emergency patients can be operated at the end of the day, when there is available OR time left. This can also result in the cancellation of other surgical operations. But for the less urgent emergency patients there are no surgical operations interrupted.

The OR department is content with the current way of scheduling and could not report possibilities for substantial improvements.

3.2 The Intensive Care Unit

The patients at the ICU come from different locations. About one third of them is brought in from outside, because of emergency. Another third of the patients comes out of the OR and the other patients come from the ward. After staying at the ICU around 80% of the patients is moved back to the ward. The other 20% passes away at the ICU. At the beginning of each day there is a consultation at the ICU about the patients. There is determined whether patients can leave the ICU, which depends on their medical condition and on the demand for ICU beds. If there is a large demand for ICU beds, patients can be moved back to the ward after a shorter period of time than if there would be less demand for ICU beds.

There are standard rules for the admission of patients at the ICU. This intensive care is only available for patients whose condition meets specific medical requirements. Still this group of patients is larger than the available ICU capacity. The ICU therefore assigns priorities to the different types of patients and determines the admission based on these priorities. Patients from scheduled and emergency operations have the highest priority. The aim of the ICU admission decisions is that the surgical operations can always be performed. Patients from the ward get the second highest priority. They are already in the hospital and are admitted at the ICU if possible. Patients from emergency have the lowest priority, they are admitted selectively. The Erasmus MC is a specialized university hospital and there are also other hospitals in Rotterdam or in the neighbourhood (Ikazia ziekenhuis, Havenziekenhuis, Ijsselland ziekenhuis et cetera). Emergency patients can be transported to other hospitals if they do not necessarily have to stay at the Erasmus MC.

The schedule for the ICU is made on a weekly basis. At the beginning of the week for each day the expected incoming patients arriving from the OR are known and then the ICU tries to reserve capacity for those patients. The main objective is to admit all patients from the scheduled surgical operations. At the beginning of each day the departments of the OR and the ICU contact each other to check whether there is ICU capacity available for the patients from the surgical operations. If there is no room available, the ICU tries to move patients back to the ward earlier. If that cannot be done, the patient from the OR cannot arrive at the ICU and the surgical operation must be cancelled. If other patients, from the ward or from emergency, request for an ICU bed, they are admitted if there are beds available or if room can be created by moving other patients. If there is no ICU bed available, the patient is rejected. The ICU tries to minimize the rejection of patients and especially focuses on the minimization of cancellations of surgical operations.

There are possible improvements for the interaction between the OR and the ICU. Some organisational points were mentioned and improvements could be made in the schedule of the OR. The ICU would mostly benefit from more synchronisation with the OR. The schedule of the OR is now made independently of the ICU. There could be more alignment about the personnel planning, for example during the holidays. However this is beyond the scope of this thesis. Another improvement, which can be analyzed in this study, is the objective to create a more levelled flow of patients from the OR to the ICU. The number of patients arriving at the ICU from the OR is now very variable during the week. At some days more patients arrive and at other days none. If these patients could be more evenly spread, the arrival of patients at the ICU would be less variable and therefore easier to plan. This could result in less rejections of patients and less cancellations of surgical operations due to lack of ICU bed capacity.

3.3 The data of the Erasmus MC

The data of the Erasmus MC is used for this thesis. The information of all patients who had a surgical operation or who stayed at the ICU in 2011 is used. In 2011 there are around 15000 surgical operations performed. Arond 2000 of them were emergency surgical operations. In total around 600 patients had to go to the ICU after their surgical operation. Almost 400 of these patients had an emergency surgical operation. This means that around 200 patients in 2011 required post-operative care at the ICU after an elective surgical operation. The arrival of these patients at the ICU is influenced by the OR schedule. On average less than 5 patients per week go to the ICU after an elective surgical operation.

The Erasmus MC has different ICU departments. This thesis considers the 5 ICU departments at the Central Location (16CD, 16TH, 3ZBE, AZIC and B3IC). These departments are considered as one large department by adding the patients and the capacities together. The distribution of the patients over the different ICU departments can be found in Appendix B. In 2011 there were almost 5000 stays at the ICU. Almost 60% of the patients came from the wards of the hospital. The second largest group comes in from emergency and accounts for almost 30%. The remaining patients come from the OR department. Patients from elective surgical operations are the only patients that are influenced by the OR schedule. At the ICU less than 5% of the patients fall into this category. In Table 3.1 the exact patient numbers are given for the OR and the ICU of the Erasmus MC in 2011.

type of patients	**number**	**percentage**
Operation Room		
elective	12407	85.78
emergency	2056	14.22
total	14463	100
Intensive Care Unit		
OR elective	215	4.38
OR emergency	381	7.75
ward	2922	59.48
emergency	1395	28.39
total	4913	100

Table 3.1: The number of patients at the OR and the ICU in the Erasmus MC in 2011.

As mentioned in the previous sections the Erasums MC currently does not take the ICU into account in the OR planning. This results in a high variance in the flow of patients from the OR to the ICU. Figure 3.1 shows this flow in January 2011. The demand for ICU beds is very variable, both for elective as for emergency surgical operations. The OR schedule only considers the elective surgical operations, since it cannot be known when emergency surgical operations arrive.

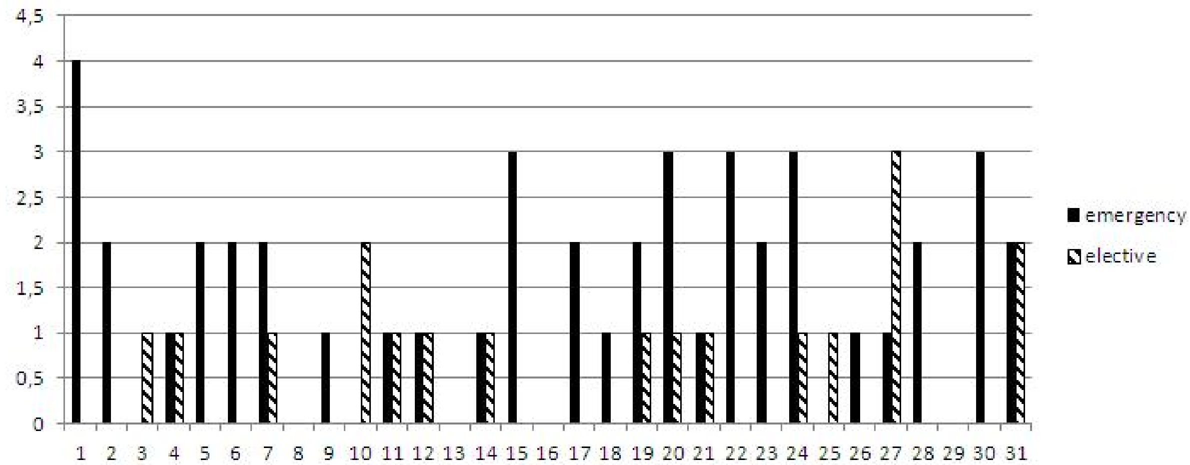

Figure 3.1: The distribution of patients from the OR to the ICU in January 2011.

This study focuses on the interaction between the OR and the ICU. An OR schedule is constructed which takes the ICU into account. After a first look on the data of the Erasmus MC some remarks kan be made. First there is a very small number of patients going to the ICU after an elective surgical operation. In 2011 it came down to less than 5 patients per week. On the total ICU these patients account for less than 5%. The OR sents patients to the ICU from both elective and emergency surgical operations. The variance in demand for ICU beds at the ICU is mainly caused by emergency surgical operations, which can be seen in Figure 3.1. Only the variance in demand from elective surgical operations can be reduced by the OR schedule. Even if this variance is reduced, the variance from the emergency surgical operations still exists.

Considering these remarks, it seems that constructing an OR schedule which incorporates the ICU will not lead to major improvements. However, this expectation cannot be proved until research has been done. The results of this study show what the actual possibilities for improvement are.

Chapter 4

OR scheduling problem

This chapter considers the OR scheduling problem. First the concept of sub surgical services is explained, which is used in the OR schedule. In section 4.3 the actual OR scheduling model is proposed. Some adjustments to the theoretical model have to be made for the case of the Erasmus MC. These adjustments can be found in section 4.4. The OR scheduling model is used to construct OR schedules. The results and the constructed schedules are presented in section 4.5. This chapter closes down with the conclusions and discussion.

4.1 Surgical services

In medical science doctors are specialized in different areas, which are called the surgical services. Examples of surgical services are general surgery, gynecology, neurology et cetera. Table 4.1 contains the list of the surgical services of the Erasmus MC which are used in this thesis. Some of these surgical services also require Operation Room time to perform their surgical operations.

The current Operation Room schedule of the Erasmus MC assigns operation rooms to the surgical services. The surgical services themselves can then decide how to use this time and when they want to operate which patients. This means that there are two OR schedules: one on the aggregate level of the surgical services and one on the level of the individual patients. In Appendix A examples of those two OR schedules are given.

This study focuses on the interaction between the Operation Room department (OR) and the Intensive Care Unit (ICU) and therefore needs to determine the patients going to the ICU after their surgical operation. For some surgical services a large fraction of patients needs post-operative care at the ICU. For other surgical services this fraction is much smaller. Also within a surgical service different types of surgical operations are performed. Some of these operations require post-operative care at the ICU and others do not.

To analyze the interaction between the OR and the ICU in more detail, a new way of constructing the OR schedule is used. The next subsection motivates and describes this new method further.

Abbreviation	**Dutch name**	**English name**
ANE	Anaesthesiologie	Anesthesiology
CAR	Cardiologie	Cardiology
CHI	Chirurgie	General surgery
DER	Dermatologie	Dermatology
GER	Geriatrie	Geriatrics
GYN	Gynaecologie	Gynecology
HAE	Hematologie	Haematology
INW	Inwendige Geneeskunde	Internal medicine
ISV	Intensivisten	Intensive-care medicine
KAA	Kaakchirurgie	Oral and maxillofacial surgery

KGA	Kindergeneeskunde Algemeen	Pediatrics
KNO	Keel-, Neus- en Oorheelkunde	Otolaryngology (ENT)
LON	Longziekten	Pulmonology
MDL	Maag-, Darm- en Levergeneeskunde	Gastroenterology and Hepatology
NEC	Neurochirurgie	Neurosurgery
NEU	Neurologie	Neurology
ONC	Interne Oncologie	Oncology
ONG	Ongevalsheelkunde	Traumatology
OOG	Oogheelkunde	Opthalmology
ORT	Orthopaedie	Orthopedic surgery
PLC	Plastische Chirurgie	Plastic surgery
REU	Reumatologie	Rheumatology
RTH	Radio Therapie	Radiotherapy
TBV	Thuisbeademing Volwassenen	Mechanical ventilation
THC	Thorax Chirurgie	Cardiovascular surgery
URO	Urologie	Urology

Table 4.1: The names of the surgical services in Dutch and English, with the corresponding abbreviations.

4.2 The sub surgical services

This thesis analyzes the interaction between the OR and the ICU. To do this, a schedule for the OR is constructed which tries to take the flow of patients going from the OR to the ICU into account. In the current OR schedule the available operation rooms are assigned to the surgical services mentioned in section 4.1. There are some disadvantages to this way of scheduling, which will be explained in this section. We have proposed a new concept of scheduling as a possible solution for the disadvantages.

4.2.1 The motivation for the usage of sub surgical services

The current OR schedule is made on the level of the surgical services. The planning coordinators of the OR department decide for every day how many operation rooms each surgical service can use. A surgical service then gets an operation room for the entire day. The individual patient schedule for the use of an operation room is made by the surgeons of the surgical service. The different surgical services do not cooperate in constructing the schedule on the individual patient level. This has consequences for the flow of patients from the OR to the ICU. The lack of cooperation between the surgical services, results in a high variance in the flow of patients from the OR to the ICU. On some days none of the surgical services performs surgical operations on patients who require post-operative ICU care, while on other days there may be more patients going from the OR to the ICU. To analyze the flow of these patients in more detail, the scheduling of the different surgical services must be aligned.

Another disadvantage of the current schedule is that it is difficult to determine the flow of patients from the OR to the ICU. For each surgical services there are different types of surgical operations. For some of these operations many patients need to go to the ICU after their surgical operation, while patients from other surgical operations rarely require post-operative ICU care. If a surgical service can use more than one operation room during the week, the surgeons of that surgical service can decide themselves on which day they want to perform which surgical operations. The scheduling of the individual patients on a day is thus made by the surgeons and not by the OR planning coordinators. Apart from the restriction that the available time in an operation room may not be exceeded, there are no restrictions on the scheduling of the individual patients. This means that patients who need to stay at the ICU after their surgical operation can be scheduled on different moments of the week. Also from week to week the flow of patients from the OR to the ICU can vary a lot. To be able to analyze this flow in more detail, it would be better to control the scheduling of the individual patients more. If the schedule allows the performance of some types of surgical operations only on specific days, the flow of patients from the OR to the ICU can be influenced more.

Some surgical services (like CHI, NEC and ORT) require an operation room (almost) every day. If the operation rooms are assigned to surgical services, this requirement makes the scheduling less flexible. It also limits the possibilities of determining and influencing the flow of patients to the ICU. This flow could be determined better, if there would be more information available about which surgical operations would be performed on which day. Scheduling on the level of surgical services does not provide enough of this information, since the surgeons are completely free in the scheduling of the patients.

To solve this problem, this thesis proposes to split each surgical service in groups consisting of different types of surgical operations. In the current situation all the surgical operations that have to be performed by a surgical service can be performed in any of their operation rooms. In the new situation we allow every type of surgical operation only at one moment in the OR schedule. Thus if a surgical service gets assigned an operation room, they can only perform specific types of surgical operations in that room. At other moments in the OR schedule, in other operation rooms, the other types of surgical operations are allowed. The group of surgical operations that is allowed to be performed in the same room is called a sub surgical service. All the surgical operations performed by a surgical service are assigned to one of these sub surgical services. The OR schedule can then be made on the level of sub surgical services. An operation room is no longer assigned to a surgical service, but to a sub surgical service. Then still all surgical operations are included in the OR schedule, but the moment when they can be performed is more restricted.

To make this way of scheduling possible the number of sub surgical services depends on the required number of operation rooms per cycle for the corresponding surgical service. If a surgical service requires three operation rooms per cycle, it is split into three sub surgical services, which all require one operation room per cycle. The surgical operations of the corresponding surgical service are then devided over these three sub surgical services.

The objective in the construction of the OR schedule is to determine the flow of patients from the OR to the ICU. Therefore the surgical services are split in groups based on the fraction of patients going to the ICU. Surgical operations with a high probability that the patients need to go to the ICU, are put in the same sub surgical service. This results in sub surgical services with a high percentage of patients going to the ICU and sub surgical services with a low percentage. These sub surgical services are then used to construct the OR schedule. In this way the influence of the OR schedule on the ICU occupation can be determined more precise.

For example, the surgical service gynecology requires about four operation rooms per week. Only a small fraction of the surgical operations performed concern patients who need post-operative care at the ICU. In the current schedule gynecology gets assigned four operation rooms per week and the gynecologists schedule their patients in the available time. Every surgical operation can be scheduled in one of these four operation rooms. There are no restrictions on the scheduling. This also means that the patients who need to go to the ICU after their surgical operation can be scheduled unrestrictedly. The moment that these surgical operations are performed can also vary from week to week. This is disadvantageous for the ICU, because the flow of patients from gynecological surgcial operations to the ICU thus varies from week to week.

Now the concept of sub surgical services is introduced. Gynecology still gets assigned four operation rooms, but restrictions are added to constraint which surgical operations can be performed when. The group of all the surgical operations which have to be performed is split into four groups. In any operation room only one of these group of surgical operations is allowed to be performed. The surgical operations which are expected to sent patients to the ICU are placed together in a group. This results in four sub surgical services of which only one contains patients going to the ICU. These four sub surgical services can be used to construct the OR schedule. Now gynecology still gets four operation rooms per week, but there are restrictions on the scheduling of the individual patients. The operation room is now available for a sub surgical service, which is a group of surgical operations. Only these surgical operations can be performed in the assigned OR. For this example it means that in only one of the four operation rooms patients can be operated that require post-operative care at the ICU. In this way the flow of patients from the OR to the ICU can be determined in more detail.

The duration and the variance in duration of the surgical operations are also considered in grouping them together. The surgical operations are placed in the sub surgical service, such that each sub surgical service has a comparable average duration and variance in duration. This even spread of duration and variance in duration has two advantages. First, to fill up all the available time in an operation room it is preferred to have surgical operations of different durations. Longer surgical operations can then be scheduled together with short surgcial operations. If only long during surgical operations are allowed in an operation room, it could be that many time remains unused. Secondly, the advantage of the even spread of variance in duration, is that it reduces the probability of over time.

The construction of the sub surgical services restricts the scheduling of the individual patients. It could be that some surgical operations cannot be performed on the same day or on the other hand that some surgical operations must be performed on the same day. This could be caused by personnel restrictions. For this thesis, these restrictions are not considered. It is assumed that all surgical operations from the same surgical service can be performed on the same day.

The problem in the current OR schedule is that the flow of patients from the OR to the ICU cannot be determined and varies from week to week. The concept of sub surgical services is presented as a solution to this problem. Theoretically, this concept has potential advantages. It increase the possiblilities of determining and influencing the flow of patients from the OR to the ICU. This makes it possible to incorporate the patients going to ICU in the OR schedule. Because of the even spread of duration and variance of duration, the sub surgical services also reduce the probability of over time.

The next subsection will describe the actual construction of these sub surgical services.

4.2.2 The construction of the sub surgical services

The construction of the sub surgical services is similar to filling boxes. The sub surgical services can be seen as boxes, that have to be filled with surgical operations. All surgical operations of a surgical service must be placed in one of these boxes. The number of boxes is the number of operation rooms required per cycle by a surgical service. This number is given beforehand. The size of each box depends on the opening times of an operation room, which limits the time that can be used for surgical operations. The sizes of the boxes are predefined as well. This subsection gives more information about the construction of the sub surgcial services.

Sub surgical services are groups of surgical operations from the same surgical service. They differ in the fraction of patients who need post-operative care at the ICU. Other characteristics of a surgical operation are the duration of the surgical operation and the code for the medical treatment. Surgical operations with the same code must be placed in the same sub surgical service to use the cyclic schedule. In that way the same medical treatments can be performed every cycle. All surigcal operations with the same code are thus assigned together. For each code the average duration of a surgical operation and the variance in duration is determined. The objective in constructing the sub surgical services is to spread the duration and the variance in duration evenly over the sub surgical services. A sub surgical service preferably contains surgical operations of different durations, to make it easier to fill up an OR completely for one day with surgical operations from the sub surgical service. The variance in duration is a measurement for the probability that overtime occurs. If the variance is low, the duration can be predicted quite accurately. If the duration has a high variance, this is more difficult. The sub surgical services must have a comparable variance. If the differences in variance would be large, the differences in probability of overtime would be large as well.

The sub surgical services are constructed with the data of all the surgical operations performed in 2011. The assumption is made that this data is representative for the near future. All the surgical operations of one surgical service are divided over different groups. Each group is then called a sub surgical service. In the OR department there are two types of surgical operations: elective surgical operations and emergency surgical operations. The sub surgical services are used for the schedule and must therefore contain surgical operations which are known beforehand. This is the reason that only the elective surgical operations are used to construct the sub surgical services.

The schedule no longer assign an OR to a surgical service, as is currently used, but to a sub surgical service. In this schedule the available ORs are assigned per day, such that a sub surgical service can use an OR for the entire day. The size of a sub surgical service could be defined as the sum of the durations of the surgical operations in that sub surgical service. The sub surgical services are scheduled in the cyclic OR schedule. The cycle time of the schedule is seven days. Therefore every sub surgical service should be at least large enough to fill up an OR completely once a week. This means that both the number of sub surgical services per surgical service and the size of these sub surgical services are limited beforehand.

Some studies in literature analyze combining surgical operations in groups. Van Oostrum et al. (2011) propose a hierarchical clustering method to cluster surgical operations in surgery types. These surgery types contain surgical operations which are comparable in terms of the use of resources (duration of surgical operation, requirements for post-operative care et cetera). The clustering method used is hierarchical, which means that the number of clusters is not determined in advance. Also the size of a cluster cannot be predefined. This is not useable for the context of this study. If ORs are assigned for an entire day to the clusters of surgical operations, the number and size of sub surgical services is limited. For simplicity therefore this thesis uses a heuristical approach to construct the sub surgical services. The objective is to construct the sub surgical services such that every sub surgical service requires exactly one OR per cycle.

The preferred size of a sub surgical service depends on the type of operation room assigned to it. If a sub surgical service can use an operation room with extended opening times every week, more surgical operations can be performed and the sub surgical service can be larger than if an OR with normal opening times would be available. Therefore the preferred size of the sub surgical services is determined by the requirements for the different types of operation rooms for the corresponding surgical services. These requirements are determined from the data of 2011 and assumed is that this data is representative for the future. In general, surgical operations are preformed in ORs which are open from 08.00h until 15.30h. However, sometimes the opening times are extended. The surgical services NEC and ORT require twice a week an OR from 08.00h until 17.30h and CHI requires three times a week such an OR. Two times a week an operation room is opened until 20.00h, one time this is for the surgical service KNO and once for PLC. The other surgical services only require operation rooms with general opening times.

These ORs with extended opening times can be used for all kinds of surgical operations. However, some surgical operations take too long to be performed in an OR with general opening times. Therefore long during surgical operations must be placed into sub surgical services which are constructed for ORs with extended opening times, if possible.

For each surgical service, the surgical operations are placed into sub surgical services. A heuristic is used to do this. The surgical operations are first ordered in a list. Every surgical operation has a code for the corresponding medical treatment, surgical operations with the same codes are placed after another. The list is ordered per code based on the duration of the surgical operation with that code and the variance in duration.

The construction of the sub surgical services is in some way comparable to a job-shop scheduling problem. Every sub surgical service can be seen as a machine and the surgical operations as the jobs. Since surgical operations with the same code must always be placed in the same sub surgical service, a group of surgical operations with the same code can be seen as a job. Then these jobs are assigned one by one to that surgical service which has the most capacity left. In this way the sub surgical services are filled up evenly, they consists of surgical operations with different durations and they have a comparable mean duration. The heuristic used for the construction of the sub surgical services can be found in section 4.2.3.

4.2.3 The heuristic

Let P be the set of all surgical services, with $p \in P$. The heuristic is performed for each surgical service p separately. Define C as the set of all the codes of surgical operations. $C_p \subset C$ is the set of all codes for surgical operations performed by surgical service p. For every code $c \in C$ there is a number of surgical operations with that code. These surgical operations have some characteristics: define d_c as the average duration of all surgical operations with code c and var_c as the variance in duration for these surgical operations. The total duration of all the surgical operations with code c is given by the variable g_c. The variable f_p^{ICU} indicates the fraction of patients going to the ICU in surgical service p and f_c^{ICU} describes this fraction for patients from a surgical operation with code c.

The number of surgical services to construct depends on the requirements of the surgical service. The set R is the set of all the types of operation rooms. The available OR time per day in an operation room of type r is described by the variable v_r, per year de available time is defined as V_r. This thesis uses three different types of operation rooms (a, b and c), which only differ in opening times. Surgical operations in all types of rooms can start at 08.00h. The rooms of type a, b and c close at 15.30h, 17.30h and 20.00 respectively. The OR schedule is constructed with a cycle time of a week and the assumption is that there are 49 weeks in a year, to correct for holiday periods. This means that $V_r = 49v_r$. The calculation and explanation of this number of weeks can be found in section 4.4. Let $n_{r,p}$ be the number of operation rooms of type r required by surgical service p. This number can be split into $n_p^{extended}$ (type a) and $n_p^{general}$ (type b and c), respectively the number of required ORs with extended opening times or with general opening times.

Define S as the total set of sub surgical services which will be constructed. The set $S_p \subset S$ describes the sub surgical services of surgical service p. Every sub surgical service is constructed for an operation room of a specific type $r \in R$. The number of sub surgical services for surgical service p , $|S_p|$, is equal to $\sum_{r \in R} n_{r,p}$. Every sub surgical service $s \in S_p$ can be related to an operation room of a specific type r. This also means that every sub surgical service s has an amount of available OR time per year V_s. This variable is equal to V_r if sub surgical service s is constructed for an operation room of type r.

The following sets and parameters are used in the heuristic:

P	the set of all surgical services
C	the set of all codes for surgical operations
C_p	the set of all codes for surgical operations of surgical service p
R	the set of types of operation rooms
S	the set of all sub surgical services
S_p	the set of all sub surgical services from surgical service p
d_c	the average duration of surgical operations with code c
var_c	the variance in duration of surgical operations with code c
g_c	the total duration of all the surgical operations with code c
f_p^{ICU}	the fraction of patients going to the ICU in surgical service p
f_c^{ICU}	the fraction of patients going to the ICU after a surgical operation with code c
v_r	the amount of operation room time per day in an operation room of type r
$v_{general}$	the amount of operation room time per day in an operation room with general opening times
V_r	the amount of operation room time per year in an operation room of type r
$n_{r,p}$	the number of operation rooms of type r required by surgical service p
$n_p^{extended}$	the number of operation rooms with extended opening times required by surgical service p
$n_p^{general}$	the number of operation rooms with general opening times required by surgical service p
V_s	the amount of operation room time per year in sub surgical service s

The following heuristic is used for each surgical service $p \in P$. First determine the number of sub surgical services to construct, based on the requirements for the different types of operation rooms for surgical service p.

1. Split the surgical operations into two groups:
   - Group 1: all surgical operations with a code c, with $f_c^{ICU} \geq f_p^{ICU}$
   - Group 2: all surgical operations with a code c, with $f_c^{ICU} < f_p^{ICU}$
2. Divide the sub surgical services $s \in S_p$ over the two groups. Determine the number of sub surgical services needed for group 1 and 2, based on the size of the two groups. Try to devide sub surgical services for extended ORs, if they exists, evenly over the two groups.
3. If $n_p^{extended} > 0$, go to step 4. Else, go to step 5.
4. Place as many as possible surgical operations with a code c, for which $d_c \geq v_{general}$, in the sub surgical services s which corresponds to operation rooms with extended opening times. The total duration in a sub surgical service is the sum over g_c for all c assigned to that sub surgical service. This total duration may not exceed the total available OR time, V_s.
5. Order the list of all surgical operations based on $\frac{var_c}{d_c}$.
6. Take the next code c in the list. If all codes have been assigned, go to step 12.
7. If the surgical operations of code c have already been placed in a sub surgical service, return to step 6. Else, go to step 8.
8. Determine for every sub surgical service s the remaining OR time. This is the difference between the total available time V_s and the time already used. The time already used is the sum over g_c for all c assigned to sub surgical service s. Go to step 9.
9. If $f_c^{ICU} \geq f_p^{ICU}$, go to step 10. Else, go to step 11.
10. Determine which of the sub surgical services for group 1 has the maximum remaining OR time. Assign the surgical operations with code c to that sub surgical service. Return to step 6.
11. Determine which of the sub surgical services for group 2 has the maximum remaining OR time. Assign the surgical operations with code c to that sub surgical service. Return to step 6.
12. All sub surgical services are constructed and the heuristic is finished.

4.2.4 The sub surgical services

The described heuristic is used to construct sub surgical services of the data of all the surgical operations performed in the Erasmus MC in 2011. The amount of sub surgical services needed for each surgical service is determined based on the used number of operation rooms per surgical service in 2011.

Every surgical service p is split into several sub surgical services. For each sub surgical service s the duration of the surgical operations is analyzed, D_s. The probability that a patient needs post-operative care at the ICU is determined, p_s^{ICU} and the corresponding length of stay at the ICU, L_s. There are n_s surgical operations in sub surgical service s. The total duration of all these surgical operations in sub surgical service s is given by the parameter K_s.

Table 4.2 shows the sub surigcal services. Sometimes the total duration of the surgical operations in a sub surgical service exceeds the available OR time. This occurs because a sub surgical service is only constructed if it can completely filled up an OR per cycle. Usually there are some surgical operations left which could fill up a OR partially. In practice, these surgical operations are not performed during every cycle of the OR schedule, but for example every other cycle. In the cyclic OR schedule these surgical operations are not incorporated. They can be added when needed. However, the data of these surgical operations is useful. Therefore they are added to the other sub surgical services and considered in the calculation of the duration of surgical operations, percentage of patients going to the ICU and in the LOS. This does result in a larger total duration per sub surgical service.

The sub surgical services therefore do not cover all the surgical operations that need to be performed. They only give information about the number of surgical operations that have to be performed every cycle. If every sub surgical service from Table 4.2 gets assigned an OR per cycle, 96.8% of the time of all the surgical operations is covered. This value can be calculated according to formula 4.1. This means that the actual usage of the OR deparment will be sligthly higher than if only the sub surgical services are scheduled.

$$\left(1-\frac{\sum_{s\in S}K_s-V_s}{\sum_{s\in S}K_s}\right)100\%=96.8\% \tag{4.1}$$

The sub surgical services										
					D_s		p_s^{ICU}		L_s	
s	p	n_s	K_s	V_s	mean	var	mean	var	mean	var
1	CHI	148	22812	22050	154.14	17142	0.068	0.063	262.70	1185962
2	CHI	135	22387	22050	165.83	17197	0.081	0.075	373.33	2660489
3	CHI	135	22815	22050	169.00	20559	0.119	0.105	885.33	19435672
4	CHI	145	22066	22050	152.18	15687	0.090	0.082	546.21	4437186
5	CHI	145	22190	22050	153.03	18633	0.110	0.099	883.86	18523762
6	CHI	114	22107	22050	193.92	17094	0.088	0.081	378.95	1763574
7	CHI	207	22549	22050	108.93	6714	0	0	0	0
8	CHI	184	22905	22050	124.48	9562	0	0	0	0
9	CHI	191	22959	22050	120.20	8324	0	0	0	0
10	CHI	154	28039	27930	182.07	19411	0.130	0.114	953.77	12637325
11	CHI	169	28470	27930	168.46	13162	0.112	0.100	494.20	2519111
12	CHI	173	28614	27930	165.40	24815	0.110	0.098	590.98	4169639
13	DER	672	29612	22050	44.07	520	0	0	0	0
14	GYN	73	12708	22050	174.08	44321	0.068	0.065	927.12	26171704
15	GYN	227	22510	22050	99.16	7942	0	0	0	0
16	GYN	236	24197	22050	102.53	8433	0	0	0	0
17	GYN	250	26782	22050	107.13	8880	0	0	0	0
18	KAA	306	34363	22050	112.30	4524	0	0	0	0
19	KNO	164	27821	22050	169.64	27521	0.037	0.035	439.02	8024146
20	KNO	152	22672	22050	149.16	21098	0.020	0.019	369.47	14267925
21	KNO	201	23568	22050	117.25	4051	0	0	0	0
22	KNO	214	23615	22050	110.35	4409	0	0	0	0
23	KNO	271	35445	35280	130.79	13729	0.004	0.004	10.63	30606
24	NEC	102	22102	22050	216.69	17365	0.069	0.065	352.94	2727965
25	NEC	103	21641	22050	210.11	15532	0.068	0.064	265.63	1046866
26	NEC	112	23656	22050	211.21	21095	0.054	0.051	205.71	779267
27	NEC	128	22076	22050	172.47	11251	0	0	0	0
28	NEC	122	27587	27930	226.12	17161	0.074	0.069	684.59	12208983
29	NEC	104	27632	27930	265.69	37029	0.096	0.088	581.54	5013651
30	ONG	106	15692	22050	148.04	26680	0.123	0.109	2472.45	79814037
31	ONG	188	22763	22050	121.08	8954	0	0	0	0
32	ONG	185	23330	22050	126.11	9068	0	0	0	0
33	OOG	411	26558	22050	64.62	1488	0	0	0	0
34	OOG	525	26458	22050	50.40	783	0.002	0.002	13.71	98742
35	OOG	510	26594	22050	52.15	838	0	0	0	0
36	ORT	153	22467	22050	146.84	7265	0.026	0.026	169.41	2726816
37	ORT	170	22166	22050	130.39	7102	0.006	0.006	33.88	195162

38	ORT	179	22223	22050	124.15	4726	0	0	0	0
39	ORT	220	24328	22050	110.58	3394	0	0	0	0
40	ORT	217	28488	27930	131.28	6056	0.028	0.027	544.15	29232132
41	ORT	189	27981	27930	148.05	7296	0.021	0.021	236.19	4499219
42	PLC	109	16745	22050	153.62	25204	0.046	0.044	224.59	1158693
43	PLC	187	22044	22050	117.88	17053	0	0	0	0
44	PLC	206	22346	22050	108.48	14725	0	0	0	0
45	PLC	191	22308	22050	116.80	16835	0	0	0	0
46	PLC	200	22420	22050	112.10	14693	0	0	0	0
47	PLC	211	22730	22050	107.73	14906	0	0	0	0
48	PLC	327	36940	35280	112.97	16346	0	0	0	0
49	URO	80	12172	22050	152.15	18624	0.088	0.081	306.00	1716297
50	URO	207	23038	22050	111.29	7712	0	0	0	0
51	URO	210	25292	22050	120.44	10091	0	0	0	0
52	URO	189	22427	22050	118.66	8638	0	0	0	0
53	URO	231	23903	22050	103.48	7360	0	0	0	0

Table 4.2: The sub surgical services with their characteristics.

4.2.5 Reserving slack

In the construction of the sub surgical services all the available OR time is used for surgical operations. There is no time left unscheduled, which is called slack, for emergency operations or for reducing the risk of overtime. At the Erasmus MC this is the commonly used method. The surgical services themselves can fill up their OR time in the way they prefer. But in general they aim to use all the available time. Emergency surgical operations are performed with the personnel available and in the operation room available at the arrival of the emergency patient. Sometimes another surgical operation then has to be interrupted, postponed or even cancelled. This is because all time is used for surgical operations and no slack is scheduled.

However, in literature sometimes a fraction of the available OR time is left unscheduled (see Hans et al. (2008)). This slack minimizes the risk of overtime. Reservation of slack can be added by adjusting the sub surgical services. The available time for surgical operations in an operation room is reduced, if time is reserved for slack. This means that the size of the sub surgical services also reduces. To be able to perform all the surgical operations, the number of sub surgical services must then be increased. In this way new sub surgical services can be constructed, which can be used to make the OR schedule.

For the flow of patients from the OR to the ICU, it does not make much difference whether slack is reserved or not. If time is reserved for slack, the same surgical operations are performed. They are only spread over a larger number of operation rooms. The flow of patients from the OR to the ICU is not influenced. This is the reason that this thesis only considers OR schedules in which no time is reserved for slack.

4.3 The OR scheduling model

The elective surgical operations are scheduled in a cyclical schedule with a cycle time of T_c, measured in days. A cyclic schedule is easy to implement and can be motivated by the fact that many surgical operations are recurrently performed. Only elective surgical operations are considered in the OR schedule, since emergency surgical operations cannot be scheduled in advance. For every day $i \in T$ in the cycle, where $T = \{1, 2, \ldots, T_c\}$ at most B_i^{OR} operation rooms can be used for surgical operations. There are in total N different types of operation rooms, which can differ in available material, opening times et cetera. There are v_r hours available for surgical operations in an operation room of type $r \in R$, where $R = \{1, 2, \ldots, N\}$. The available number of operation rooms of type r on day i is $C_{r,i}^{OR}$. A small example is used to illustrate these variables. Assume that at most 10 of the hospital's operation rooms can be assigned on day 1 ($B_1^{OR} = 10$). Let there be two types of operation rooms, type a and type b, which differ only in opening times. Type a is open during regular opening times and for type b the opening times are extended. Now assume that $C^{OR}_{a,1} = 9$ and $C^{OR}_{b,1} = 2$. This means that at most 9 operation rooms can be open on regular times and at most 2 operation rooms can have the extended opening times. Remark that it is possible that $C^{OR}_{a,1} + C^{OR}_{b,1} > B^{OR}_{1}$, because type b is an optional extension of type a. Therefore two constraints are required to restrict the used OR capacity on day i. One constraint makes sure no more than B^{OR}_{i} rooms are assigned on day i and another constraint restricts the number of assigned operation rooms per type r on day i to $C^{OR}_{r,i}$.

One of the objectives in the OR scheduling model is to level the usage of the ORs. The OR department prefers to use every day about the same number of operation rooms and not on one day many ORs and on another day only a few. Define O^{OR}_{i} as the number of operation rooms occupied on day i. The preferred usage of the OR on day i is PU^{OR}_{i}. To obtain a levelled usage, both the over and under usage are minimized. The corresponding variables are respectively OU^{OR}_{i} and UU^{OR}_{i}.

The available OR time is assigned to M different sub surgical services. These sub surgical services are constructed with the heuristic described in section 4.2. Every sub surgical service $s \in S$, where $S = \{1, 2, \ldots, M\}$, requires one operation room of type r per cycle if $m_{s,r} = 1$. The binary parameter $m_{s,r}$ indicates whether the sub surgical service s is constructed for an operation room of type r. Operation rooms are assigned to a sub surgical service for an entire day. The binary decision variable $X_{s,r,i}$ determines whether an operation rooms of type r is assigned to sub surgical service s on day i. If $m_{s,r} = 0$ the variable $X_{s,r,i}$ also has to be 0. The surgical services themselves plan the individual patients within the available OR time. In the OR schedule described here, no room is left unscheduled for emergency surgical operations. These operations can be added to the schedule.

Every surgical service $p \in P$ in the hospital has some requirements and preferences about the scheduling of their operation rooms. Operation rooms are assigned to sub surgical services and the set S_p contains all sub surgical services of surgical service p. Some surgical services prefer an even spread of their assigned operation rooms over the week. Other surgical services cannot perform surgical operations on some days, because of consulting hours. The total number of assigned operation rooms on day i to surgical service p is thus restricted and can only take integer values between $b^1_{p,i}$ and $b^2_{p,i}$.

The number of patients that can be operated by sub surgical service s on a day in an operation room of type r is the integer variable $n_{s,r}$, which can be calculated by dividing the available OR time, v_r, over the duration of a surgical operation. The duration of a surgical operation of sub surgical service s, D_s, is assumed to follow a lognormal distribution according to Strum et al. (2000), with parameters μ^D_s and σ^D_s. This duration can be used in many different ways in the calculation of $n_{s,r}$. Using the mean duration gives a distortion, because the lognormal distribution has large tails when σ^D_s is large. The mean duration would then be very large and the number of patients that could be operated would be underestimated. However using the median duration, does not reflect the large variety in durations of surgical operations. This study proposes to use an approximation and to calculate $n_{s,r}$ as the average of the number of patients determined with the mean duration and the median duration of surgical operations. The average is rounded down, since it is not possible to operate patients partially on one day. Formula 4.2 is proposed to approximate $n_{s,r}$, where the analytical expressions for the mean and the median of the lognormal distribution are used. Appendix C uses different ways to calculate $n_{s,r}$. The calculated values are compared to the data of the sub surgical services in order to test the correctness of the proposed formula.

$$n_{s,r} = \left\lfloor \frac{1}{2} \left(\frac{v_r}{exp\left(\mu^D_s + \left(\frac{(\sigma^D_s)^2}{2}\right)\right)} + \frac{v_r}{exp\left(\mu^D_s\right)} \right) \right\rfloor \tag{4.2}$$

Sometimes an elective surgical operation cannot be performed, although it was scheduled. This can be caused by many different reasons. To reduce overtime sometimes surgical operations are cancelled if the other operations on that day took longer than expected. Cancellation can also be caused by medical reasons or by lack of material or shortage of capacity at a post-operative destination. Finally, an operation cannot be performed in case of a no-show, which means that the patient did not show up. Since the OR is a very costly department, the coordinators usually try to fill up the time which has become available because of a cancellation. Therefore the assumption is made that all the surgical operations that are scheduled are also performed. This thesis does not consider no-shows and other reasons for cancellations.

The schedule for the OR also takes into account the patients going to the ICU after their surgical operation. This interaction between the OR and the ICU can be incorporated in the OR scheduling model in two ways. The occupation of the ICU by patients from the OR can be used or the flow of patients from the OR to the ICU. In literature usually the first method is used. The objective is then to level the occupation on the ICU. The second method analyzes the flow of patienst from the OR to the ICU and aims to level this flow. Both methods are used in this thesis. First the OR scheduling model is described, considering the occupation of the ICU. In subsection 4.3.2 the adjustments to the model are given, which are needed to analyze the flow of patients.

The available number of beds on the ICU for patients from the OR on day i is C_i^{ICU}. The variable O_i^{ICU} is the amount of ICU capacity occupied at day i by patients from the OR. The occupation of the ICU is determined based on Beliën and Demeulemeester (2007). The cyclical aspect of the schedule is incorporated in the factor $\left\lceil \frac{d}{T_c} \right\rceil$. This factor adjusts the demand for ICU beds when the length of stay is longer than the cycle time. For example assume that $T_c = 7$ and that a patient stays 10 days at the ICU, starting at day 1. If we consider the ICU occupation on the first day of the cycle (day 1), this patient occupies a bed at day 1. However the patient from the previous cycle, operated on day -6, also occupies a bed on day 1. Therefore the ICU occupancy for this type of patient must be counted double. The factor $\lceil \frac{d}{T_c} \rceil$ incorporates the cyclical aspects and adjusts the ICU occupation if $d > T_c$.

The variables UU_i^{ICU} and OU_i^{ICU} compare the occupation of the ICU to the capacity and determine respectively the under and over usage of the ICU at day i. The objective in the OR schedule is to minimize both the under and over usage of the ICU, which is also used in Adan et al. (2009). The number of occupied beds is determined based on the length of stay (LOS) of a patient at the ICU. The individual LOS of every patient is not considered, but an average LOS per sub surgical service is used. The variable L_s represents the length of stay at the ICU of a patient of sub surgical service s and is measured in minutes. According to Marazzi et al. (1998), L_s is assumed to follow a lognormal distribution with parameters μ_s^L and σ_s^L. Not all sub surgical services contain patients who need post-operative care at the ICU. Define the set $S^{ICU} \subset S$ as the set of sub surgical services containing ICU patients. Then the variables L_s with parameters μ_s ans σ_s are only defined for sub surgical services $s \in S^{ICU}$. Define $p_{d,s}$ as the probability that a patient of sub surgical service s stays at the ICU until d days after the operation. Since d is measured in days and L_s in minutes, $p_{d,s}$ cannot be exactly obtained from the distribution of L_s. The day on which the surgical operation takes place is considered as the first day of the LOS. The ICU bed occupancy is determined per day, independent of the actual time of a day until a patient stays at the ICU. Both the patients who leave the ICU in the morning and the patients who stay the entire day at the ICU are considered to stay at the ICU that day. $p_{d,s}$ can then be calculated according to formula 4.3, where 1440 represents the number of minutes in a day. The time between the day in the cycle of the OR schedule that the ICU occupancy is determined, i, and the day in the cycle on which the surgical operation was performed, j, is defined as $dist(i, j)$. For $j \leq i$; $dist(i, j)$ is equal to $i - j$ and for $j > i$; $dist(i, j)$ equals $T_c + i - j$. The total number of patients at the ICU d days after their surgical operation of surgical service s in an operation room of type r is assumed to follow a binomial distribution with parameters $n_{s,r}$ and $p_{d,s}$. This means that the ICU occupation on day i, O_i^{ICU}, can be defined according to formula 4.4.

$$p_{d,s} = P(d * 1440 \leq L_s \leq (d + 1) * 1440) \quad \forall s \in S^{ICU} \tag{4.3}$$

$$O_i^{ICU} = \sum_{s \in S} \sum_{r \in R} \sum_{j=1}^{T_c} X_{s,r,j} \left\{ \sum_{d=dist(i,j)}^{\infty} \left\lceil \frac{d}{T_c} \right\rceil n_{s,r} p_{d,s} \right\} \quad \forall i \in T \tag{4.4}$$

The OR scheduling model is constructed as a multi-objective scheduling model, comparable to Van Oostrum et al. (2008). There are mainly two objectives: levelling the OR usage and one objective related to the ICU. The model in subsection 4.3.1 uses the objective to reduce the variance in the ICU occupation. In subsection 4.3.2 an alternative is proposed in which the flow of patients from the OR to the ICU is levelled. For both the OR occupation and the ICU occupation the under and over usage on every day are calculated. These variables are minimized with the corresponding weights. Other studies use as an objective the minimization of OR usage. This cannot be used in this thesis, since the ORs are assigned to sub surgical services and each sub surgical service requires exactly one OR per cycle. The total usage of the OR department is thus fixed.

4.3.1 Problem formulation

The previous subsection describes the problem in words and explains the used parameters and variables. In this subsection the problem is formulated formally.

The following sets are used in the OR schedule:

$T = \{1, 2, \ldots, T_c\}$	$i \in T$	the days in the OR schedule
$P = \{1, 2, \ldots, K\}$	$p \in P$	the surgical services
$S = \{1, 2, \ldots, M\}$	$s \in S$	the sub surgical services
$S_p \subset S, \cup_{p \in P} S_p = S$	$s \in S_p$	the sub surgical services of surgical service p
$R = \{1, 2, \ldots, N\}$	$r \in R$	the operation room types

The following parameters are used in the OR schedule:

T_c	cycle time
B_i^{OR}	maximum number of operation rooms that can be used on day i
$C_{r,i}^{OR}$	capacity of operation rooms of type r on day i
v_r	amount of opening hours in an operation room of type r
$n_{s,r}$	number of patients operated by sub surgical service s in an operation room of type r
$m_{s,r}$	binary parameter indicates whether sub surgical service s is constructed for an operation room of type r
D_s	the duration of a surgical operation of sub surgical service s, lognormally distributed with parameters μ_s^D and σ_s^D
$b_{p,i}^1$	minimum number of operation rooms that can be assigned to surgical service p on day i
$b_{p,i}^2$	maximum number of operation rooms that can be assigned to surgical service p on day i
C_i^{ICU}	capacity of the ICU on day i
PU_i^{OR}	preferred usage of the OR department on day i
L_s	the LOS of a patient of sub surgical service s, lognormally distributed with parameters μ_s^L and σ_s^L
$p_{d,s}$	probability that a patient of sub surgical service s occupies an ICU bed d days after the surgical operation
w_1	weight corresponding to the under usage of the ICU capacity
w_2	weight corresponding to the over usage of the ICU capacity
w_3	weight corresponding to the under usage of the OR rooms
w_4	weight corresponding to the over usage of the OR rooms

The following variables are used in the OR schedule:

$X_{s,r,i}$	binary variable indicating whether sub surgical service s gets assigned an operation room of type r on day i
O_i^{ICU}	occupation of the ICU on day i
UU_i^{ICU}	under usage of the ICU capacity on day i
OU_i^{ICU}	over usage of the ICU capacity on day i
O_i^{OR}	occupation of the OR on day i
UU_i^{OR}	under usage of the OR capacity on day i
OU_i^{OR}	over usage of the OR capacity on day i

The total OR scheduling model is formulated as a mathematical programming problem. The model is based on the formulation of Beliën and Demeulemeester (2007) and Adan et al. (2009).

min

$$\sum_{i \in T} \left(w_1 UU_i^{ICU} + w_2 OU_i^{ICU} + w_3 UU_i^{OR} + w_4 OU_i^{OR} \right) \tag{4.5}$$

s.t.

$$\sum_{r \in R} \sum_{i \in T} X_{s,r,i} = 1 \quad \forall s \in S \tag{4.6}$$

$$\sum_{s \in S} \sum_{r \in R} X_{s,r,i} \leq B_i^{OR} \quad \forall i \in T \tag{4.7}$$

$$\sum_{s \in S} X_{s,r,i} \leq C_{r,i}^{OR} \quad \forall r \in R, \forall i \in T \tag{4.8}$$

$$O_i^{ICU} = \sum_{s \in S} \sum_{r \in R} \sum_{j=1}^{T_c} X_{s,r,j} \left\{ \sum_{d=dist(i,j)}^{\infty} \left\lceil \frac{d}{T_c} \right\rceil n_{s,r} p_{d,s} \right\} \quad \forall i \in T \tag{4.9}$$

$$C_i^{ICU} - UU_i^{ICU} \leq O_i^{ICU} \leq C_i^{ICU} + OU_i^{ICU} \quad \forall i \in T \tag{4.10}$$

$$O_i^{OR} = \sum_{s \in S} \sum_{r \in R} X_{s,r,i} \quad \forall i \in T \tag{4.11}$$

$$PU_i^{OR} - UU_i^{OR} \leq O_i^{OR} \leq PU_i^{OR} + OU_i^{OR} \quad \forall i \in T \tag{4.12}$$

$$b_{p,i}^1 \leq \sum_{s \in S_p} \sum_{r \in R} X_{s,r,i} \leq b_{p,i}^2 \quad \forall p \in P, \forall i \in T \tag{4.13}$$

$$X_{s,r,i} \in \{0,1\} \quad \forall s \in S, \forall r \in R, \forall i \in T \tag{4.14}$$

$$X_{s,r,i} \leq m_{s,r} \quad \forall s \in S, \forall r \in R, \forall i \in T \tag{4.15}$$

$$UU_i^{ICU} \geq 0 \quad \forall i \in T \tag{4.16}$$

$$OU_i^{ICU} \geq 0 \quad \forall i \in T \tag{4.17}$$

$$UU_i^{OR} \geq 0 \quad \forall i \in T \tag{4.18}$$

$$OU_i^{OR} \geq 0 \quad \forall i \in T \tag{4.19}$$

The objective of the schedule is to minimize the weighted under and over usage of both the ICU bed capacity and the usage of the OR department (4.5). Constraint (4.6) states that each sub surgical service should be assigned an OR per cycle. The number of assigned rooms and the capacity of the OR is restricted by (4.7) and (4.8). The occupation of the ICU is determined in constraint (4.9). The over and under usage of the ICU is calculated in (4.10). Constraint (4.11) determines the usage of the OR per day. The over and under usage of the OR is determined in constraint (4.12).

The number of assigned operation rooms must be within the required interval for each surgical service p ((4.13)). The integrality of the variables $X_{s,r,i}$ is guaranteed by constraint (4.14). An operation room of type r can only be assigned to a sub surgical service s, if that sub surgical service s is constructed for an operation room of type r. Constraint (4.15) requires this. The last constraints ((4.16), (4.17),(4.18) and (4.19)) determine the non-negativity of the variables UU_i^{ICU},OU_i^{ICU},UU_i^{OR} and OU_i^{OR}.

4.3.2 Flow of patients

The OR scheduling model described in the previous section considers the occupation of the ICU. In general this is the way literature incorporates the interaction between the OR and the ICU. However, the variance in occupation of ICU beds by patients from elective surgical operations does not seem to be the largest problem in the hospital. The ICU coordinators at the Erasmus MC pointed at another type of variability: the variance in arrival. They admit or reject a patient upon arrival and this decision is mainly based on the occupation of the ICU at that moment. The expected occupation in the future is not considered, since this is very difficult to determine. The focus on arrival of patients can be incorporated in the OR scheduling model.

Define F_i^{ICU} as the flow of patients from elective surgical operations to the ICU on day i. This variable can be calculated with formula (4.20). The average flow, AF^{ICU}, is the total flow divided over the cycle time ((4.21)). Now the under and over flow can be modeled in the same way as under and over usage. The variables UF_i^{ICU} and OF_i^{ICU} describe respectively the under and over flow of patients to the ICU on day i. These variables are related to the average flow in formula (4.22). The under and over flow cannot be negative, which is required in (4.23).

$$F_i^{ICU} = \sum_{s \in S^{ICU}} \sum_{r \in R} X_{s,r,i} p_s^{ICU} n_{s,r} \quad \forall i \in T \tag{4.20}$$

$$AF^{ICU} = \frac{1}{T_c} \sum_{i \in T} F_i^{ICU} \tag{4.21}$$

$$AF^{ICU} - UF_i^{ICU} \leq F_i^{ICU} \leq AF^{ICU} + OF_i^{ICU} \quad \forall i \in T \tag{4.22}$$

$$UF_i^{ICU} \geq 0, \quad OF_i^{ICU} \geq 0 \quad \forall i \in T \tag{4.23}$$

The equations (4.20), (4.21), (4.22) and (4.23) can be added to the OR scheduling problem. To level the flow of patients, the objective function needs to be adjusted. The new objective function can be found in (4.24). It is a multi-objective weighted objective function, in which the under and over flow is minimized as well as the under and over usage of the OR. The weights for under and over flow are respectively w_5 and w_6.

$$\sum_{i \in T} (w_5 UF_i^{ICU} + w_6 OF_i^{ICU} + w_3 UU_i^{OR} + w_4 OU_i^{OR}) \tag{4.24}$$

The additional variables for the determining of the flow of patients to the ICU are listed below:

F_i^{ICU}	flow of patients from the OR to the ICU on day i
AF^{ICU}	average flow of patients per day from the OR to the ICU
UF_i^{ICU}	under flow of patients from the OR to the ICU on day i
OF_i^{ICU}	over flow of patients from the OR to the ICU on day i
w_5	weight corresponding to the under flow of patients from the OR to the ICU
w_6	weight corresponding to the over flow of patients from the OR to the ICU

The OR schedule can now be constructed with two objectives: levelling the occupation of the ICU ((4.5)) or levelling the flow of patients to the ICU ((4.24)). Both objectives are used and for both objectives schedules for the OR department are constructed. The results can be found in section 4.5.

4.4 The Erasmus MC case

In the previous section the problem is formulated in a general way. For the specific situation at the Erasmus MC some extra assumptions need to be made.

The OR schedule is constructed with a cycle time of a week, which is also used in the current operating schedule. Elective surgical operations are only performed during weekdays, which would suggest a cycle time $T_c = 5$ days. But then the cycles are not completely subsequent, because the weekend days are in between. This will give problems in determining the ICU occupation, since patients occupy ICU beds on all days of the week. Therefore T_c is set equal to 7 and $i \in 1, 2, \dots, 7$, where $i = 1$ corresponds to Monday and $i = 7$ to Sunday. Then an extra restriction is needed to require that elective surgical operations are only performed during weekdays and not in the weekends. The variable $X_{s,r,i}$ can be limited by adjusting the variables $b_{p,i}^1$ and $b_{p,i}^2$ which describe respectively the minimum and maximum number of operation rooms that can be assigned on day i to surgical service p. Equation (4.25) defines the adjusted variables.

$$b_{p,i}^1 = b_{p,i}^2 = 0 \quad \forall s \in S, \forall r \in R, \forall i \in \{6, 7\} \tag{4.25}$$

The other values for the parameters $b_{p,i}^1$ and $b_{p,i}^2$ can be found in table 4.3. These values are based on the data of all surgical operations performed in the Erasmus MC in 2011.

	Monday		**Tuesday**		**Wednesday**		**Thursday**		**Friday**	
Surgical service	$b_{p,i}^1$	$b_{p,i}^2$	$b_{p,i}^1$	$b_{p,i}^2$	$b_{p,i}^1$	$b_{p,i}^2$	$b_{p,i}^1$	$b_{p,i}^2$	$b_{p,i}^1$	$b_{p,i}^2$
CHI	2	4	2	4	2	4	2	4	2	4
DER	0	0	0	0	0	1	0	0	0	1
GYN	0	2	0	0	0	2	0	2	0	1
KAA	0	0	0	2	0	1	0	2	0	0
KNO	1	2	1	2	1	2	1	2	1	2
NEC	1	2	1	2	1	2	1	2	1	2
ONG	0	1	0	1	0	0	0	1	0	1
OOG	0	1	0	1	0	1	0	1	0	1
ORT	1	3	1	3	1	3	1	3	1	3
PLC	1	3	1	3	1	3	1	3	1	3
URO	1	2	1	2	1	2	1	2	1	2

Table 4.3: This table shows the values of the parameters $b_{p,i}^1$ and $b_{p,i}^2$.

Assumed is the schedule operates less than 52 weeks per year, in order to accommodate for holiday periods in which less or even no elective surgical operations are performed. Define M as the set of all months, with $j \in M$. Define M_1 as the non-holiday months and M_2 as the holiday months, with $M_1 \cup M_2 = M$. The months July, August and December are considered as holiday months, since the number of elective surgical operations performed per working day in these months is lower than in the other months. Let d_j be the number of days in month j that elective surgical operations can be performed. The average number of elective surgical operations performed per working day in the non-holiday months, A_1, is calculated with formula (4.26), where O_j is the amount of elective surgical operations performed in month j. With this average, the effective number of weeks in a year in which elective surgical operations can be performed, W, can be determined with formula 4.27. The effective number of weeks is defined as the number of weeks that could completely be used for elective surgical operations, without accounting for holidays. The assumption is made that a week consists of five working days. Using the data from the Erasmus MC gives $W = 49$. Therefore this study constructs a schedule with the assumption that there are 49 weeks in a year.

$$A_1 = \frac{\sum_{j \in M_1} O_j}{\sum_{j \in M_1} d_j} \tag{4.26}$$

$$W = \left\lceil \frac{1}{5} \frac{\sum_{j \in M} O_j}{A_1} \right\rceil \tag{4.27}$$

The different types of operation rooms are defined by the set R in the problem formulation. For the Erasmus MC the operation rooms are assumed to differ in opening times only. There are three types of operation rooms: a, b, and c, thus $R = \{a, b, c\}$. All types of operation rooms start at 08.00h, but differ in closing times and thus also in opening times. The ORs of type a, b and c close at 15.30h, 17.30h and 20.00h respectively. The variable v_r indicates the amount of minutes an operation room of type r is open: $v_r = \{450, 570, 720\}$. The central location of the Erasmus MC has in total 16 operation rooms, but the number of ORs that can be used is smaller due to personnel restrictions. This thesis uses $B_i^{OR} = 13 \quad \forall i \in T$. All these operation rooms can be open during the normal opening times, from 08.00h until 15.30h. Per day at most two operation rooms can have an extended opening time, until 17.30h or 20.00h. This leads to the extra restriction (4.28). Per day also at most one operation room can be open until 20.00h. This means that $C_{a,i}^{OR} = 16$, $C_{b,i}^{OR} = 2$ and $C_{c,i}^{OR} = 1 \quad \forall i \in T$.

$$X_{s,b,i} + X_{s,c,i} \leq 2 \quad \forall i \in T \tag{4.28}$$

In practice there are some material restrictions on the different operation rooms as well, which means that some instruments are only available in a limited number of rooms. However the available material per operation room and the needed material per surgical operation are not properly documented. Therefore these material restrictions are neglected and the assumption is made that, as far as the material is concerned, every surgical operation can be performed in every operation room.

The parameter C_i^{ICU} indicates the ICU capacity on day i for patients from the OR. This capacity is difficult to determine, since it is not exactly defined in the hospital. On average three ICU beds are occupied by patients from elective surgical operations. Therefore we set $C_i^{ICU} = 3 \quad \forall i \in T$.

The OR scheduling model has a weighted objective function, with w_1 and w_2 the weights for respectively the under and over usage of the ICU capacity. The weights w_3 and w_4 are used for the under and over usage of the OR capacity. According to Adan et al. (2009) w_1 is set equal to w_2. For simplicity the same value is used for the other weights (w_3, w_4, w_5 and w_6).

The following sets are used in the OR scheduling model:
$T = \{1, 2, 3, 4, 5, 6, 7\}$
$R = \{a, b, c\}$
$S = \{1, 2, \ldots, \text{M}\}$
$P = \{$CHI, DER, GYN, KAA, KNO, NEC, ONG, ORT, OOG, PLC, URO$\}$
S_p = the set of sub surgical services from surgical service p

The following parameters are used in the OR scheduling model:
$T_c = 7$
$B_i^{OR} = 13 \quad \forall i \in T$
$C_{a,i}^{OR} = 13, C_{b,i}^{OR} = 2, C_{c,i}^{OR} = 1 \quad \forall i \in T$
$v_a = 450, v_b = 570, v_c = 720$
$b_{p,i}^1, b_{p,i}^2$ these values can be found in Table 4.3
$C_i^{ICU} = 3 \quad \forall i \in T$
$w_1 = w_2 = w_3 = w_4 = w_5 = w_6 = 1$

4.5 Results

The OR scheduling model described in section 4.3 is implemented in AIMMS and solved as an MIP. The problem could be solved to optimality, although the solution is not unique. This section presents the constructed OR schedules.

4.5.1 The current situation at the Erasmuc MC

The schedules can be compared based on their influence on the ICU. Therefore for each schedule the average occupation of ICU beds per day is determined. Also the number of patients going to the ICU on every day is calculated. These statistics can be determined for the current situation in the Erasmus MC as well. Table 4.4 gives the mean and variance in occupation of ICU beds by patients from elective surgical operations. In the same table the average number of patients from the OR the the ICU can be found. Very rarely a patient has arrived on Saturday or Sunday. But in general elective surgical operations are only performed on weekdays.

	Occupation ICU		**Flow from OR to ICU**	
Day	mean	variance	mean	variance
Monday	1.72	1.31	0.87	0.55
Tuesday	2.22	1.51	1.04	0.55
Wednesday	2.59	1.98	0.56	0.60
Thursday	2.44	2.05	0.79	0.60
Friday	2.49	2.15	0.77	0.85
Saturday	2.17	2.32	0.02	0.02
Sunday	1.63	1.55	0.10	0.09
total	2.18	1.93	0.59	0.59

Table 4.4: The occupation of patients from elective surgical operations at the ICU and the flow of these patients from the OR to the ICU based on the data of the Erasmus MC in 2011.

4.5.2 The OR schedules

As mentioned the OR schedule can be constructed with two different objectives. The first objective is to level the occupation of the ICU. Table 4.5 shows the corresponding optimal OR schedule.

Another OR schedule is constructed with the second objective: levelling the flow of patients from the OR to the ICU. The optimal schedule can be found in Table 4.6.

Both OR schedules show an average ICU occupation of around 3 patients per day. The schedule in Table 4.5 shows a more levelled occupation, which was the objective. On average between 4 and 5 patients per week have to go to the ICU after their elective surgical operation. In the schedule in Table 4.6 these patients are more evenly spread over the week. The flow fluctuates more in both the schedule in Table 4.5 and in the current schedule of the Erasmus MC.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	CHI (5) KNO (21) NEC (25) NEC (29) ONG (30) ORT (37) ORT (38) PLC (47) URO (53) CHI (10) CHI (11)	CHI (1) CHI (8) KAA (18) KNO (19) ONG (32) OOG (34) PLC (42) PLC (45) URO (49) NEC (27) ORT (40)	CHI (2) CHI (3) GYN (15) GYN (16) KNO (20) NEC (24) OOG (33) PLC (44) URO (50) ORT (39) PLC (48)	CHI (4) CHI (9) GYN (14) ONG (31) OOG (35) ORT (36) PLC (43) URO (51) NEC (28) KNO (23)	CHI (6) CHI (7) DER (13) GYN (17) KNO (22) NEC (26) ORT (41) PLC (46) URO (52) CHI (12)		
total	11	11	11	10	10		
O_i^{ICU}	3.01	3.00	3.00	2.98	3.02	2.64	2.03
F_i^{ICU}	1.66	0.69	0.74	0.62	0.72	0	0

Table 4.5: An OR schedule for the sub surgical services. The objective in this schedule is to level the occupation of the ICU.

The ICU occupation for both schedules is sligthly higher than in the current situation at the Erasmus MC (see Table 4.4). There can be several reasons for this. First the constructed schedules operate for 49 weeks per year, where the real life data cover all 52 weeks of 2011. Then the same number of patients must be spread over a shorter period of time, which increases the occupation. Another reason can be that the modelling with distributions for Length of Stay at the ICU and probabilities for the need of post-operative ICU care sligthly overestimates the ICU occupation. However, the main objective here is to see whether the interaction between the OR and the ICU can be influenced by the OR schedule. From the differences between the two OR schedules in variables O_c^{ICU} and F_c^{ICU}, we can conclude that the schedule indeed has an influence on the ICU. The actual influence and the actual occupation of the ICU are analyzed in the simulation model of the ICU in chapter 5.

4.5.3 Total comparison

In subsection 4.5.2 two different OR schedules are presented:
a = levelled occupation
b = levelled flow

The performance of these OR schedules can be compared with the current situation (Table 4.7).

The constructed schedules have a lower variance in both the occupation of the ICU and the flow of patients from the OR to the ICU. This means that incorporating the ICU in the OR schedule reduces the variance. A more detailed comparison of the influence of the OR schedules on the performance of the ICU is given in chapter 5.

Table 4.7 shows that the constructed OR schedules (schedule a and schedule b) result on average in a higher ICU occupation and a higher flow of patients from the OR to the ICU. This can be explained by the fact that the schedules are constructed for 49 weeks in a year, while the current situation contains the data of 52 weeks in a year. Another reason is that the current situation gives actual data. To obtain the numbers for schedule a and schedule b different assumptions are made for calculation. This can explain the differences between the calculated numbers and the real data.

Another remarkable result is that the variance in occupation of the ICU for schedule b is lower than for schedule a, while schedule a was constructed to level the ICU occupation. The OR scheduling problem

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	CHI (6)	CHI (2)	CHI (1)	CHI (5)	GYN (17)		
	CHI (7)	CHI (3)	CHI (4)	KAA (18)	KNO (19)		
	GYN (15)	CHI (9)	CHI (8)	KNO (22)	NEC (25)		
	GYN (16)	NEC (29)	DER (13)	NEC (24)	ONG (31)		
	KNO (20)	OOG (33)	GYN (14)	NEC (26)	ORT (36)		
	ONG (30)	ORT (37)	KNO (21)	ONG (32)	PLC (42)		
	OOG (35)	PLC (43)	OOG (34)	ORT (41)	PLC (44)		
	PLC (45)	URO (49)	ORT (38)	PLC (46)	URO (53)		
	URO (51)	ORT (39)	URO (52)	PLC (47)	CHI (10)		
	NEC (28)	KNO (23)	NEC (27)	URO (50)	CHI (12)		
	ORT (40)		PLC (48)	CHI (11)			
total	11	10	11	11	10		
O_i^{ICU}	2.22	2.56	2.66	3.00	3.05	2.99	2.41
F_i^{ICU}	0.80	0.96	0.68	0.91	1.07	0	0

Table 4.6: An OR schedule for the sub surgical services. The objective in this schedule is to level the flow of patients to the ICU.

	Occupation ICU		**Flow to ICU**	
OR schedule	mean	variance	mean	variance
Current situation	2.1790	1.9312	0.5890	0.5889
Schedule a	2.8124	0.1377	0.6321	0.3122
Schedule b	2.6986	0.1048	0.6321	0.2018

Table 4.7: Comparison between the different OR schedules.

in section 4.3 levels the occupation by minimizing the deviation from a given capacity level. Apparently, the minimization of this deviation does not directly corresponds to minimizing the variance of the ICU occupation.

4.6 Conclusions and discussion

The main objective in constructing the OR schedules is trying to influence the interaction between the OR and the ICU. From the differences between the two OR schedules in variables O_c^{ICU} and F_c^{ICU}, we can conclude that the schedule indeed has an influence on the ICU. There are two objectives used in the OR scheduling problem. The first objective aims to level the ICU occupation. This objective is commonly used in literature in studies where the ICU is considered in the OR schedule. The second objective focuses on the flow of patients from the OR to the ICU and aims to create a smooth flow. Using this objective is a contribution to literature. Expected is that a smooth flow of patients arriving at the ICU will in practice be preferred to a levelled occupation of the ICU. The personnel at the ICU of the Erasmus MC also reported the variance in arrivals of patients from the OR as the main problem in the interaction between the OR and the ICU. Therefore, the objective to level the flow is added. Using the first objective results in a stable occupation of around 3 patients from elective surgical operations per day on the ICU. If a stable flow of patients from the OR to the ICU is preferred, an OR schedule can be constructed which results in an arrival of around 1 patient per day at the ICU.

The constructed OR schedules can be compared with the current OR schedule. They are compared based on their influence on the ICU. Both in terms of ICU occupation and flow of patients to the ICU, the constructed schedules perform better. They result in a more stable occupation and flow with less variance. The occupation of the ICU is more smooth, if that objective is used. With the second objective the flow of patients from the OR to the ICU is more levelled. In literature usually a levelled occupation is used. Theoretically a smooth occupation is preferable for the ICU. The OR schedule constructed with the first objective is then the best option. For the ICU of the Erasmus MC the large variance in arrival of patients from the OR was mentioned as a possible improvement. The time a patient stays at the ICU is very variable. Therefore the OR schedule which aims to level the flow of patients from the OR to the ICU seems to be the most advantageous for the Erasmus MC. In conclusion we can say that both schedules are improvements to the current operating schedule. Whether to choose for the levelled ICU occupation or the levelled flow to the ICU depends on the preferences of the ICU department. The constructed OR schedules show that considering the ICU in the OR scheduling problem, seems to be advantageous for the ICU. Usually this is where studies in literature stop (see Beliën and Demeulemeester (2007), Van Houdenhoven et al. (2008) and Van Oostrum et al. (2008)). The OR schedules in those studies have a positive influence on the ICU, which leads to the conclusion that a levelled ICU occupation will result in fewer cancellations of surgical operations. However, at the ICU there are many other patients who did not undergo a surgical operation. To analyze the actual influence of the improved OR schedule on the ICU, the ICU department need to be analyzed in more detail. This is done in chapter 5, where the ICU is modeled with a simulation model.

The concept of the sub surgical services is a contribution to literature. This way of constructing an OR schedule and trying to influence the flow of patients from the OR to the ICU is new. The sub surgical services are groups of surgical operations from the same surgical service. The assumption is used that there are no restrictions on combining surgical operations in a sub surgical service. Each sub surgical service gets assigned one operation room per cycle, in which the surgical operations can be performed. This means that surgical operations of the same sub surgical service must be performed on the same day. The assumption that this is possible can be questioned. It is possible that some surgical operations cannot be performed on the same day due to material, medical or personnel restrictions. This means that the practical implementation of the sub surgical services can be difficult. However, the OR schedule is made on an aggregate level. The scheduling of the individual patients is not determined. This can still be done by the surgeons and the planning coordinators of the OR. These are the people that have more detailed knowledge about scheduling restrictions of the individual surgical operations. Therefore we assume that the sub surgical services can be used in practice.

There are also some topics which could be investigated further. The cycle time used for the OR schedule is one week. However some surgical operations appear only a few times a year. In the current model they can be incorporated in one of the sub surgical services, such that they can be scheduled when needed. Perhaps a longer cycle time would be better for these surgical operations. The construction of sub surgical services could be investigated in more detail as well. This thesis uses a straight forward heurstic, but with more medical knowledge it is perhaps possible to group the surgical operations differently.

Chapter 5

ICU queueing model

This chapter analyzes the Intensive Care Unit and the influence of the OR schedule on this department. First the department of the ICU is shortly introduced. In section 5.2 the ICU model and the simulation are presented. This section also describes the total simulation setup and the different scenarios that are compared. The results of the simulation are presented in section 5.3. Some further analysis on the results is performed in section 5.4. The results are discussed in section 5.5. In that section also the conclusions are presented.

5.1 The Intensive Care Unit

The Intensive Care Unit (ICU) of the hospital is a department where different types of patients arrive. Some patients have had a surgical operation and thus come from the Operation Room department (OR). Other patients come from other departments of the hospital. Kim et al. (1999) describes four types of patients: patients from elective surgical operations which are scheduled in advance, patients from emergency surgical operations, patients from the ward and patients from the emergency department of the hospital. The flow of patients in and out of the ICU is showed in Figure 5.1.

Both the arrival of patients at the ICU and their Length of Stay (LOS) is very variable. Only the arrival of patients from elective surgical operations is known in advance, since this is determined by the OR schedule.

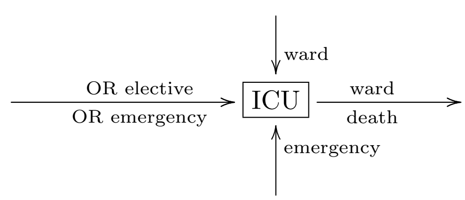

Figure 5.1: The arriving and departing groups of patients at the ICU.

Different hospitals assign different priorities to patients to determine the ICU admission or rejection. Some hospitals give preference to emergency patients over patients from scheduled surgical operations. In case of shortage of capacity, elective surgical operations then may be cancelled, which reduces the part of incoming patients from the OR at the ICU. Other hospitals put high priority to the continuation of the scheduled surgical operations. Then emergency patients may be rejected at the ICU and, when necessary, transported to other hospitals.

5.2 An ICU model

This thesis models the Intensive Care Unit (ICU) as a queueing model, which is commonly used in literature (see Griffiths et al. (2006) and Mallor and Azcárate (2011)). A queueing model has different characteristics: the arrival pattern of customers, the distribution of the service time, the number of servers, the waiting capacity and the used admission policy. To translate the ICU to a queue, patients are considered as customers. A request for admission at the ICU can be seen as an arrival of a patient. When a patient is admitted to the ICU, the time he or she stays there is called the Length of Stay (LOS). In terms of queueing theory the LOS can be seen as the service time. The available beds at the ICU are considered as servers. Some ICU queueing models in literature do not have waiting capacity and thus not allow queueing. This means that an admission policy is not needed. Patients are admitted upon their arrival if there is capacity available for them and rejected if there is not. If queueing is allowed, different admission policies can be used. Ridge et al. (1998) use a non-preemptive priority policy, where the different types of patients are admitted with different priorities. Most common is the First Come First Served (FCFS) policy (Griffiths et al. (2006)), which admits patients in the order they arrive.

5.2.1 Formal description of a queueing model

This thesis proposes a simple qeueing model to model the ICU. The assumption is made that there is no waiting capacity. This seems a realistic assumption, since patients require an ICU bed if they demand for admission, but may not require that ICU bed anymore after a period of waiting. The fact that there is no queue also means that there is no admission policy defined.

To model the ICU as a queueing model, different parameters need to be defined. The number of servers equals the total bed capacity available for patients. This capacity is assumed to be constant during the day, but to differ over the days of the week. The capacity depends both on the available beds and the available personnel. Usually, the personnel is the bottleneck resource, which is also the reason that the capacity fluctuates over the week. The parameter C_j^{ICU} is defined as the capacity of the ICU on day j, where $j = \{1, 2, \ldots, 7\}$. In the Erasmus MC the capacity is the same from Monday to Friday and is slightly lower in the weekend. This also motivates the preference for a smooth flow of patients from the OR to the ICU.

Since there is no queue, patients are admitted to the ICU, if there is capacity available upon their arrival. When the capacity is completely used, arriving patients are rejected and lost. The arriving patients at the ICU are categorized into the four categories of Kim et al. (1999): OR-elective ($ORel$), OR-emergency ($ORem$), ward (w) and emergency (em). The last three of these categories are assumed to arrive at the ICU according to homogeneous Poisson distributions (see Ridge et al. (1998) and Kim et al. (1999)) with arrival rates λ^{ORem} for emergency patients from the OR, λ^{w} for the ward and λ^{em} for emergency. Patients at the ICU can also be classified by the surgical services in the hospital, $p \in P$ with $P = \{1, 2, \ldots, K\}$. The probability that an arriving patient belongs to surgical service p, is p_p^{ORem}, p_p^{w}, p_p^{em} for patients from OR-emergency, from the ward or from emergency respectively.

The patients from elective surgical operations are classified into sub surgical services $s \in S$. Define p_s^{ORel} as the probability that a patient of sub surgical service s, who had an elective surgical operation, must visit the ICU after that surgical operation. The elective patients from the OR of sub surgical service s are assumed to arrive according to a non-homogeneous Poisson arrival pattern with arrival rate $\lambda_{s,t,i}^{ORel}$ at time t on day i. The arrival rate depends on the schedule of the OR. Assumed is that the OR-elective patients arrive with a Poisson distribution only during the times that the surgical operations are performed. We realize that this is not a realistic assumption. Poisson arrivals mean that the probability to arrive at any moment of time is the same. This is not the case in the context of surgical operations. Patients can only arrive at the ICU after their surgical operation and not before. This results in a larger probability to arrive during the day than at the beginning of the day, when the surgical operations just start. However, although assuming Poisson arrivals is unrealistic, it makes the modeling of the ICU easier. Next to that, we have no information about the actual arrival times of patients, because that depends on the OR schedule on the level of the individual patients. That schedule is not constructed in this thesis. We assume that the disadvantage of using the unrealistic assumption of Poisson arrivals is not large.

We distinquish between the different types of operation rooms to deterime the total arrival rate. The set R defines the set of types of operation rooms, with $r \in R$. Let $\lambda^{ORel}_{s,t,i,r}$ be the arrival rate at the ICU at time t on day i of OR-elective patients of sub surgical service s from an operation room of type r. Define b_r and e_r as respectively the starting and ending time of an operation room of type r and v_r as the total time between b_r and e_r.

The following sets and parameters are used in the modelling of the ICU:

$J = \{1, 2, \ldots, 7\}$	$j \in J$	the days of the week
$T = \{1, 2, \ldots, T_c\}$	$i \in T$	the days in the OR schedule
$P = \{1, 2, \ldots, K\}$	$p \in P$	the surgical services
$S = \{1, 2, \ldots, M\}$	$s \in S$	the sub surgical services
$R = \{1, 2, \ldots, N\}$	$r \in R$	the operation room types

C^{ICU}_j	total bed capacity available for patients at the ICU on day j
λ^{ORem}	arrival rate of patients from OR-emergency
λ^{w}	arrival rate of patients from the ward
λ^{em}	arrival rate of patients from emergency
$\lambda^{ORel}_{s,t,i,r}$	arrival rate of patients of sub surgical service s from OR-elective at time t of day i from an operation room of type r
$\lambda^{ORel}_{s,t,i}$	arrival rate of patients of sub surgical service s from OR-elective at time t of day i
p^{ORem}_p	probability that an arriving patient from OR-emergency belongs to surgical service p
p^{w}_p	probability that an arriving patient from the ward belongs to surgical service p
p^{em}_p	probability that an arriving patient from emergency belongs to surgical service p
p^{ORel}_s	probability that a patient of sub surgical service s must visit the ICU after the elective surgical operation
b_r	starting time of an operation room of type r
e_r	ending time of an operation room of type r
v_r	the total time an operation room of type r is available for surgical operations

The number of patients that can be operated by sub surgical service s on a day in an operation room of type r is the integer variable $n_{s,r}$. This number can be calculated by dividing the available OR time, v_r, over the duration of a surgical operation. The duration of a surgical operation of sub surgical service s, D_s, is assumed to follow a lognormal distribution with parameters μ^D_s and σ^D_s according to Strum et al. (2000). This study proposes to use an approximation and to calculate $n_{s,r}$ as the average of the number of patients determined with the mean duration and the median duration of surgical operations. The average is rounded down, since it is not possible to operate patients partially on one day. Formula 5.1 is proposed to approximate $n_{s,r}$, where the analytical expressions for the mean and the median of the lognormal distributions are used. A comparison of this approximation for $n_{s,r}$ to other approximations can be found in Appendix C.

$$n_{s,r} = \left\lfloor \frac{1}{2} \left(\frac{v_r}{exp\left(\mu^D_s + \left(\frac{(\sigma^D_s)^2}{2}\right)\right)} + \frac{v_r}{exp\left(\mu^D_s\right)} \right) \right\rfloor \tag{5.1}$$

The arrival of OR-elective patients is determined by the cyclic OR schedule. This schedule determines for each day $i \in T$ in the cycle ($T = \{1, 2, \ldots, , T_c\}$) which sub surgical services can perform surgical operations. The used variable $X_{s,r,i}$ is a binary variable indicating whether sub surgical service s is assigned an operation room of type r on day i. The arrival rate of OR-elective patients can be calculated by dividing the number of patients going to the ICU by the time in which they arrive. They can arrive only during the time surgical operations take place. The exact way to calculate $\lambda^{ORel}_{s,t,i,r}$ can be found in formula 5.2. The total arrival rate of OR-elective patients of sub surgical service s at time t on day i, $\lambda^{ORel}_{s,t,i}$, is then equal to the sum over the different types r of operation rooms (formula 5.3).

$$\lambda^{ORel}_{s,t,i,r} = \begin{cases} \frac{p^{ORel}_s n_{s,r} X_{s,r,i}}{v_r} & \text{if} \quad t \in [b_r, e_r] \\ 0 & \text{else} \end{cases} \qquad \forall s \in S, \quad \forall i \in T, \quad \forall r \in R \tag{5.2}$$

$$\lambda^{ORel}_{s,t,i} = \sum_{r \in R} \lambda^{ORel}_{s,t,i,r} \qquad \forall s \in S, \quad \forall i \in T, \quad \forall r \in R \tag{5.3}$$

The length of stay (LOS) of patients at the ICU is assumed to follow a lognormal distribution according to Marazzi et al. (1998). Assumed is that patients from the different types ($ORel, ORem, w$ and em) and from the different (sub) surgical services have a different distribution of the LOS. The LOS of a patient of surgical service p from $ORem, w$ or em is described by the variable L^{ORem}_p, L^w_p and L^{em}_p respectively. The variable L^{ORel}_s describes the LOS of a patient of sub surgical service s from an elective surgical operation.

The following parameters describe the LOS of the patients:

- L^{ORem}_p the LOS of a patient from an emergency surgical operation of surgical service p following a lognormal distribution with corresponding parameters μ^{ORem}_p and σ^{ORem}_p
- L^w_p the LOS of a patient of surgical service p from the ward following a lognormal distribution with corresponding parameters μ^w_p and σ^w_p
- L^{em}_p the LOS of a patient of surgical service p from emergency following a lognormal distribution with corresponding parameters μ^{em}_p and σ^{em}_p
- L^{ORel}_s the LOS of a patient from an elective surgical operation of sub surgical service s following a lognormal distribution with corresponding parameters μ^{ORel}_p and σ^{ORel}_p

The arrival of patients is assumed to be Poisson and the service time is lognormally distributed. There is no waiting capacity and thus no queue. Therefore the ICU model can be best seen as a $M/G/k/k$ model, where k is the capacity of the ICU.

5.2.2 The simulation model

Due to the different arrival patterns the queueing model is difficult to analyze analytically. Therefore a simulation model is built and used for the analysis. In this subsection the pseudocode for the simulation model is given. The simulation model is built as a discrete event simulation. The time units used are minutes, which means that the arrival rates are calculated per minute and that the LOS is also determined in minutes. There are three possible events that can occur. A patient can arrive or depart from the system. Departure only occurs after the LOS has completely expired. The third event is the end of a day. This is also considered as an event because some parameters may change per day. For example, for the Erasmus MC the capacity of the ICU is different during the days of the weekend. In the following list the parameters are described, which are used in the simulation.

T_{end}	the total simulation time
t	the current time in the simulation
t_e	the time of the next event
M	a very large number
$admittedPatients$	the total number of admitted Patients
$rejectedPatients$	the total number of rejected Patients
$totalArrivals$	the total number of arrived Patients
$totalDepartures$	the total number of departed Patients
$nextArrival$	the arrival time of the next arriving patient
$nextDeparture$	the departure time of the next departing patient
$nextDay$	the time of the next ending of a day
$occupationICU$	the number of patients occupying a bed at the ICU
$capacityICU$	the total bed capacity on the ICU at the current time
$ArrivalList$	a list of all the arrival times of the arriving patients

The simulation starts with an initialization. After the initialization the simulation is run for T_{end} minutes. The ICU starts empty at the beginning of the simulation. Therefore the registered performance measures at the beginning of the simulation time are not representative. To analyze the ICU in a more stable state, a warm-up period is used. During this period of time the simulation is run, but the data of this time period is not used in the calculation of the performance measures.

In the simulation the state of the ICU is registered in two ways. A list is used which contains information about all the patients who are currently occuping an ICU bed. This information consist of their origin ($ORel, ORem, w, em$), their (sub) surgical service, their arrival time and their departure time. Secondly, the simulation registers the occupation and capacity of the ICU at any moment of time. This information can be used to determine the overall usage of the capacity.

The pseudocode for the initiliazation and the simulation model for the ICU can be found below.

Initialization

1. Generate all the arrivals of patients during the simulation time T_{end}, using the distributions of the arrival times. Place them in the $ArrivalList$.
2. Start with an empty ICU, which means that $occupationICU = 0$.
3. Set $t = 0$.
4. Determine $capacityICU$ at time t.
5. Set $admittedPatients = 0, rejectedPatients = 0, totalArrivals = 0, totalDepartures = 0$.
6. Determine $nextArrival, nextDeparture$ and $nextDay$. If there are no arrivals or no departures, set the corresponding variable equal to M.
7. Determine the time of the first event, t_e, as the minimum of $nextArrival, nextDeparture$ and $nextDay$.
8. Store the state of the system: between t and t_e the system has a capacity of $capacityICU$ and an occupation of $occupationICU$.
9. Set $t = t_e$, such that t is the time of the first event.

Pseudocode of the simulation model
Do the initialization.

1. If $t \leq T_{end}$, go to step 2. Else, go to step 12.
2. Determine which event is occuring at time t. If the event is an arrival of a patient, go to step 3. If the event is a departure of a patient, go to step 7. If the event is the end of a day, go to step 8.
3. The event is an arrival. Update $totalArrivals = totalArrivals + 1$. Compare the current occupation of the ICU with the current capacity. If the occupation is higher than or equal to the capacity, the patient is rejected. Go to step 4. If the occupation is below the capacity, the patient is admitted to the ICU. Go to step 5.
4. The patient is rejected. Update $rejectedPatients = rejectedPatients + 1$. Go to step 6.
5. The patient is admitted to the ICU. Update $admittedPatients = admittedPatients + 1$. Generate a LOS for this patient, with a lognormal distribution dependent on the type and the (sub) surgical service of the patient. Add the patient to the ICU. Update $occupationICU = occupationICU + 1$. Go to step 6.
6. Remove the arriving patient from the $ArrivalList$. If there are still arriving patients in the ArrivalList, set $nextArrival$ equal to the time of the next arrival. Else, set $nextArrival = M$. Go to step 9.
7. The event is a departure. Update $totalDepartures = totalDepartures + 1$. Remove the departing patient from the ICU. Update $occupationICU = occupationICU - 1$. If the ICU is now empty, set $nextDeparture = M$. Otherwise, set $nextDeparture$ equal to the departure time of the first departing patient from the ICU. Go to step 9.
8. The event is the end of a day. Update $capacityICU$ by determining the capacity at time t. Update $nextDay = nextDay + 1440$. Go to step 9.
9. Determine the time of the next event, t_e, as the minimum of $nextArrival, nextDeparture$ and $nextDay$. Go to step 10.
10. Add to the information matrix the state of the system in the time between t and t_e. Store the occupation and capacity of the ICU. Go to step 11.
11. Set $t = t_e$ and return to step 1.
12. The simulation is finished. Use the collected information to calculate the performance measures of the simulation.

5.2.3 Priority for patients from elective surgical operations

The proposed ICU model treats all different types of patients in the same way. In queueing models it is possible to assign priorities to different types of customers. These priorities determine the way different types of customers are accepted from the queue. The proposed queueing model from subsection 5.2.1 has no waiting capacity and thus priorities cannot be assigned in the usual way.

In the Erasmus MC the patients from elective surgical operations (referred to as $ORel$ patients) have a higher priority than other patients. The arrival of these patients is less unexpected than the arrival of the other patients. The OR schedule is known and communicated with the ICU department. This means that it is known at the ICU when the patients from elective surgical operations will arrive. The ICU can thus prepare for their arrival.

These characteristics of the ICU department and the $ORel$ patients can be incorporated in the simulation of the ICU. This is done by adjusting the acceptance of $ORel$ patients. Analogous to Kim et al. (2000) some beds at the ICU can be reserved for $ORel$ patients. There are two OR schedules constructed with two different objectives. The first objective is to level the occupation of $ORel$ patients at the ICU and the second objective is to level the flow of patients from the OR to the ICU. For both objectives a reservation scheme at the ICU can be constructed. The reservation schemes match the flow of patients from that specific OR schedule, but this does not mean that the schemes cannot be applied under other OR schedules. The reservation schemes can be used under all types of OR schedules. We only assume that they give better results under specific OR schedules.

The reservations schemes and the corresponding adjustments in the simulation are described in the next paragraphs.

Reservation scheme that matches a levelled ICU occupation

The first OR schedule aims to level the occupation of ICU beds by patients from elective surgical operations. The reservation scheme that matches this schedule reserves some beds of the ICU especially for $ORel$ patients. A levelled occuption corresponds to a low variance, which means that over and under usage of the reserved beds will be small. The reserved beds are especially for $ORel$ patients. In this reservation scheme a bed is considered as reserved for $ORel$ patients both as it is occupied by an $ORel$ patient and as it is unoccupied and available for an arriving $ORel$ patient.

The simulation of the ICU needs to be adjusted for this reservation scheme. Let there be b beds reserved for $ORel$ patients. This means that there are $(capacityICU - b)$ beds left for the other types of patients. The reserved beds can only be used for $ORel$ patients. The unreserved beds are mainly meant for the other types of patients. However, if all reserved beds are occupied, an $ORel$ patient can be admitted to an unreserved bed as well. The number of reserved beds b is a parameter that can vary. This thesis does not analyze the optimal value for b, but simply assumes b to be fixed. In the simulation model b is set equal to the average occupation of the ICU by $ORel$ patients.

Step 3 in the pseudocode of the simulation model from subsection 5.2.2 has to be adjusted if this reservation scheme is used. The adjusted step can be found below.

3. The event is an arrival. Update $totalArrivals = totalArrivals + 1$. If the patient is an $ORel$ patient, go to step 3(a). If the patient is from another category, go to step 3(b).
   (a) If there are reserved beds unoccupied, admit the patient to a reserved bed and go to step 5. If all reserved beds are occupied, check whether there is capacity available on the unreserved beds. Go to step 3b.
   (b) Compare the current occupation of the unreserved ICU beds with $(capacityICU - b)$, the capacity for patients not from $ORel$. If the occupation is higher than or equal to the capacity, the patient is rejected. Go to step 4. If the occupation is below the capacity, the patient is admitted to the ICU. Go to step 5.

Reservation scheme that matches a levelled flow from OR to ICU

The second OR schedule has the objective to level the flow of patients from the OR to the ICU. This means that the arrival of $ORel$ patients at the ICU is smooth and has a small variance. To use this information in the ICU model, another reservation scheme can be proposed. This scheme reserves each day a number of beds for the arriving $ORel$ patients. In contrast to the previous reservation scheme, this scheme considers a bed only as reserved as it is unoccupied and available for an arriving $ORel$ patient.

The general idea of this reservation scheme is that a number of beds must be reserved each day for arriving $ORel$ patients. If an $ORel$ patient arrives and there are reserved beds, the patient can be admitted to one of these reserved beds. Preferably the beds are reserved at the beginning of the day. In that way the probability that arriving $ORel$ patients can be immediately admitted on these reserved beds is the highest. However, it is only possible to reserve empty beds. If there are no unoccupied beds at the beginning of the day, beds can also be reserved during the day. These beds can still be used to admit arriving $ORel$ patients, if the reservation takes place before the arrival. The simulation must then keep track of the total number of reserved beds during every day. If there are not enough beds reserved at the beginning of the day, extra beds must be reserved during the day when patients leave the ICU. Below the adjusted pseudo code for the simulation is given. Define b as the number of beds that must be reserved in total on each day. The variable $reservedBeds$ keeps track of the number of beds that has been reserved on the current day. This number starts at 0 at the beginning of each day and can only increase during the day. The number of beds that is reserved at present is given by the variable $numberReserved$. This last variable gives thus the number of beds that is currently unoccupied and can be used to admit an *ORel* patient. The same initialization can be used as described in subsection 5.2.2.

Again the number of reserved beds b can take different values. For this reservation scheme we also consider b to be fixed and set the parameter equal to the average flow of patients from the OR to the ICU.

Pseudocode of the simulation model
Do the initialization.

1. If $t \leq T_{end}$, go to step 2. Else, go to step 12.
2. Determine which event is occuring at time t. If the event is an arrival of a patient, go to step 3. If the event is a departure of a patient, go to step 7. If the event is the end of a day, go to step 8.
3. The event is an arrival. Update $totalArrivals = totalArrivals + 1$. If the patient is an $ORel$ patient, go to step 3(a). If the patient is from another category, go to step 3(b).
   (a) If there are reserved beds unoccupied, which means that $numberReserved > 0$, admit the patient to a reserved bed. Update $numberReserved = numberReserved - 1$ and go to step 5. If $numberReserved = 0$, check whether there is capacity available on the unreserved beds. Go to step 3b.
   (b) Compare the $occupationICU$ with available capacity ($capacityICU - numberReserved$), the capacity for patients not from $ORel$. If the occupation is higher than or equal to the capacity, the patient is rejected. Go to step 4. If the occupation is below the capacity, the patient is admitted to the ICU. Go to step 5.
4. The patient is rejected. Update $rejectedPatients = rejectedPatients + 1$. Go to step 6.
5. The patient is admitted to the ICU. Update $admittedPatients = admittedPatients + 1$. Generate a LOS for this patient, with a lognormal distribution dependent on the type and the (sub) surgical service of the patient. Add the patient to the ICU. Update $occupationICU = occupationICU + 1$. Go to step 6.
6. Remove the arriving patient from the $ArrivalList$. If there are still arriving patients in the ArrivalList, set $nextArrival$ equal to the time of the next arrival. Else, set $nextArrival = M$. Go to step 9.
7. The event is a departure. Update $totalDepartures = totalDepartures + 1$. Remove the departing patient from the ICU. Update $occupationICU = occupationICU - 1$. If the ICU is now empty, set $nextDeparture = M$. Otherwise, set $nextDeparture$ equal to the departure time of the first departing patient from the ICU. Check whether the emptied bed must be reserved. If $reservedBeds < b$ and $numberReserved < b$, go to step 7(a). Else, go to step 9.
   (a) Reserve the bed that has become empty because of the departure. Update $numberReserved = numberReserved + 1$ and $reservedBeds = reservedBeds + 1$. Go to step 9.
8. The event is the end of a day. Update $capacityICU$ by determining the capacity at time t. Update $nextDay = nextDay + 1440$. Update $reservedBeds = 0$, there are no beds reserved this day. Determine the number of free beds, $freeBeds = capacityICU - occupationICU$. If there are still enough reserved beds ($numberReserved \geq b$) or $freeBeds \leq 0$ it is not needed or possible to reserve beds. Go to step 9. However, if $numberReserved < b$ and $freeBeds > 0$ some beds must be reserved. If $numberReserved + freeBeds \leq b$, go to step 8(a). If $numberReserved + freeBeds > b$, go to step 8(b).
   (a) Reserve all the free beds. Update $numberReserved = numberReserved + freeBeds$ and $reservedBeds = freeBeds$. Go to step 9.
   (b) Only $b - numberReserved$ beds must be reserved. Update $numberReserved = b$ and $reservedBeds = b - numberReserved$. Go to step 9.
9. Determine the time of the next event, t_e, as the minimum of $nextArrival, nextDeparture$ and $nextDay$. Go to step 10.
10. Add to the information matrix the state of the system in the time between t and t_e. Store the occupation and capacity of the ICU. Go to step 11.
11. Set $t = t_e$ and return to step 1.
12. The simulation is finished. Use the collected information to calculate the performance measures of the simulation.

5.2.4 Simulation setup

The ICU department is analyzed with the simulation models described in the previous subsections. These subsections propose three different simulation models. The first simulation model is a straight forward model that models the ICU as a queueing model (subsection 5.2.2). The two models in subsection 5.2.3 give a higher priority to patients from elective surgical operations by reserving beds for them. The first reservation scheme matches the levelled occupation schedule and reserves a fixed number of beds for patients from elective surgical operations. Another reservation scheme is proposed which reserves every day a number of beds for arriving patients from elective surgical operations. This way of reserving beds matches the levelled flow of patients from the OR to the ICU. These three simulation models correspond to three different scenarios that are analyzed.

A fourth scenario is added as well. This scenario is similar to the simulation without reservations, but now the input parameters are adjusted. The fraction of $ORel$ patients at the ICU of the Erasmus MC is relatively small. The OR schedules therefore influences only a small number of patients. This could make it more difficult to see the actual influence of the different OR schedules on the performance of the ICU. Therefore the percentage of $ORel$ patients is artificially increased. In subsection 5.3.5 the actual adjustments to the parameters are described and the results are given. In short, the ICU is simulated and analyzed for four different scenarios.

Scenario 1	general ICU simulation model
Scenario 2	ICU simulation model with continuous reservation of a number of beds for $ORel$ patients
Scenario 3	ICU simulation model with the reservation of a number of beds every day for arriving $ORel$ patients
Scenario 4	general ICU simulation model with increased percentage of $ORel$ patients

This thesis focuses on the interaction between the OR and the ICU. Therefore the performance of the ICU is compared under different OR schedules. In chapter 4 the OR schedules are constructed with two different objectives. The first objective is to level the occupation of the ICU and the second objective is to level the flow of patients from the OR to the ICU. The two constructed schedules will be referred to as schedule 1 (occupation) and schedule 2 (flow). Two other schedules are added for comparison. Schedule 3 is an extreme schedule constructed with the same sub surgical services as schedule 1 and 2. These sub surgical services are scheduled such that the flow of patients from the OR to the ICU over the week is very variable. These patients only arrive at the ICU on Monday, Tuesday or Wednesday. This schedule is expected to have a negative influence on the admission of patients from elective surgical operations. The schedule could be used as a benchmark to see the benefits of the other two schedules. Finally, a fourth schedule is added without the usage of sub surgical services. The normal surgical services are used and they are randomly scheduled over the week. For this schedule the number of patients going to the ICU is determined by calculating the percentage of patients going to the ICU per surgical service. For schedule 1, 2 and 3 this percentage is calculated per sub surgical service. This results in a small difference in flow of patients from the OR to the ICU, which can be seen in Table D.5 in Appendix D.

The total number of operation rooms per week for each surgical service is the same in each of the four schedules. To summarize, the ICU performance under four different OR schedules is compared. The used schedules can be found in the Appendix D.

Schedule 1	OR schedule based on sub surgical services with the objective to level the occupation of the ICU by patients from elective surgical operations
Schedule 2	OR schedule based on sub surgical services with the objective to level the flow of patients from the OR to the ICU
Schedule 3	extreme OR schedule based on sub surgical services with the objective to have a very high variation in the flow of patients from the OR to the ICU
Schedule 4	random OR schedule based on surgical services

The simulation running time, T_{end} is set equal to a period of 10 years, which corresponds to 5256000 minutes. The first year is used as a warm-up period. The performance measures from the simulation vary over the different simulation runs. Therefore the simulation run of 10 years is performed 50 times. The mean and variance of the performance measures are calculated over these 50 runs.

5.2.5 Parameter values

The data used for the simulation model contains the information about the patients staying at the ICU of the Erasmus MC in 2011. Patients can stay at the ICU for more than one day. This means that there are patients who arrived in 2010 and departed in 2011 and patients who arrived in 2011 but departed in 2012. If all these patients would be considered, we would cover more than one year. To analyze the total number of patients in one year, this thesis only uses the patients who left the ICU in 2011. Table 5.1 shows the distribution of patients over the different types.

type of patient	**number**	**percentage**
OR elective	215	4,38
OR emergency	381	7,75
ward	2922	59,48
emergency	1395	28,39
total	4913	100

Table 5.1: The number of the different types of patients who left the ICU in 2011.

The arrival and departure times at the ICU of all these patients is available. This can be used to determine their arrival patterns and the distribution of their Length of Stay. The patients of $ORem, w$ and em are assumed to arrive according to Poisson processes.

The Erasmus MC only keeps track of the patients at the ICU if they are also admitted. There is no information available about the rejected patients. If arrival rates are calculated from the data, they thus only contain the arrival rates of the admitted patients. To obtain the arrival rates of all patients, including the rejected patients, backward reasoning can be used. Define p_{block} as the percentage of time all ICU capacity is used and patients who arrive are rejected. Then let $\lambda^{arrival}$ be the total arrival rate of all patients and $\lambda^{admission}$ be the arrival rate of the patients who are admitted to the ICU. From the data of the Erasmus MC thus only $\lambda^{admission}$ can be obtained.

Some simulation runs have been performed, which showed that the rejection probability is around 5%. Therefore we choose to set $p_{block} = 0.05$. Now $\lambda^{arrival}$ can be calculated using equation (5.4). The corresponding arrival rates can be found in equations ((5.5)). These arrival rates are thus the arrival rates of all the patients, both the rejected and the admitted patients. The time unit used in the simulation is minutes, but for understanding also the arrival rates per day are added.

$$\lambda^{admission} = (1 - p_{block})\lambda^{arrival} \tag{5.4}$$

$$\begin{aligned} \lambda^{ORem} &= 0.000750 \text{ per minute} &&= 1.08 \text{ per day} \\ \lambda^{w} &= 0.004621 \text{ per minute} &&= 6.65 \text{ per day} \\ \lambda^{em} &= 0.003165 \text{ per minute} &&= 4.56 \text{ per day} \end{aligned} \tag{5.5}$$

The arrival of the OR elective patients is determined with the OR-schedule. This is a cyclic schedule with a cycle time $T_c = 7$. There are 3 different types of operation rooms: a, b and c. These rooms all open at 08.00h and differ only in opening times. The ending times of the operation rooms of type a, b and c are respectively 15.30h, 17.30h and 20.00h. The total time available for surgical operations in an operation room of type r is v_r, which can be calculated with the difference between the ending and starting time. This means that $v_a = 450, v_b = 570$ and $v_c = 720$ minutes.

The Erasmus MC has different ICU departments. For this thesis 5 ICU departments at the Central Location of the hospital are considered (16CD, 16TH, 3ZBE, AZIC, B3IC). These departments are considered as one large ICU department by adding the capacities together. This results in a total capacity for patients of 46 beds during the week and 43 beds in the weekend. In Appendix B more information can be found about the joining of the ICU departments.

There are in total 25 different surgical services at the ICU. In this thesis 53 different sub surgical services are constructed in section 4.2. Table 5.2 shows the probabilities that an arriving patient belongs to a certain surgical service and presents the corresponding parameters for the LOS.

	$ORem$			w			em		
p	p_p^{ORem}	μ_p^{ORem}	σ_p^{ORem}	p_p^{w}	μ_p^{w}	σ_p^{w}	p_p^{em}	μ_p^{em}	σ_p^{em}
ANE	0.000	-	-	$3.42 \cdot 10^{-4}$	8.455	0.000	0.001	5.558	0.109
CAR	0.029	8.372	1.469	0.178	6.800	1.474	0.724	6.677	1.440
CHI	0.402	8.233	1.217	0.148	7.476	1.124	0.030	7.807	1.306
DER	0.003	7.213	0.000	$3.42 \cdot 10^{-4}$	7.778	0.000	0.000	-	-
GER	0.000	-	-	0.001	8.800	1.647	0.000	-	-
GYN	0.021	9.439	1.417	0.009	7.311	1.375	0.002	7.875	2.099
HAE	0.013	9.553	0.978	0.024	7.656	1.843	0.002	6.456	1.997
INW	0.029	8.743	1.260	0.019	8.709	1.489	0.039	7.789	1.252
ISV	0.000	-	-	0.000	-	-	0.001	6.948	1.872
KAA	0.005	8.492	0.700	$3.42 \cdot 10^{-4}$	7.363	0.000	0.000	-	-
KGA	0.000	-	-	0.001	5.858	0.667	0.000	-	-
KNO	0.013	8.435	0.880	0.054	7.482	0.931	0.003	7.553	0.949
LON	0.005	9.247	1.773	0.019	7.927	1.674	0.020	8.314	1.524
MDL	0.052	8.869	1.220	0.017	8.506	1.377	0.020	8.352	1.172
NEC	0.252	8.770	1.193	0.007	8.817	1.088	0.043	8.524	1.302
NEU	0.118	8.781	1.269	0.011	8.403	1.122	0.066	8.260	1.124
ONC	0.008	7.798	1.136	0.008	7.636	1.354	0.001	7.703	0.916
OOG	0.000	-	-	0.001	7.722	1.109	0.000	-	-
ORT	0.013	8.100	1.601	0.001	7.873	1.159	0.001	6.893	0.000
PLC	0.010	7.697	0.556	0.007	6.760	1.064	0.001	7.723	0.081
REU	0.003	8.530	0.000	$3.42 \cdot 10^{-4}$	5.670	0.000	0.000	-	-
RTH	0.000	-	-	0.004	6.663	1.253	0.001	4.500	0.000
THC	0.000	-	-	$3.42 \cdot 10^{-4}$	4.419	0.000	0.022	8.282	0.777
TBV	0.024	8.758	1.228	0.480	7.041	1.038	0.023	8.147	0.949
URO	0.000	-	-	0.013	7.161	1.179	0.001	8.324	0.000

Table 5.2: The parameters for the LOS and the percentages of patients for the different surgical services.

5.3 Results

This section presents the results of the simulation model. The ICU is simulated for four different scenario's and the performance under four different OR schedules is compared (see subsection 5.2.4). As input information the parameters of subsection 5.2.5 are used. The performance of the ICU is measured with different performance measures. Before the actual results are presented, these performance measures are explained.

5.3.1 Performance measures

To analyze the performance of the ICU, different performance measures are used. The number of admitted patients and rejected patients over a period of time are simple statistics which describe the performance. These numbers can be determined over the entire simulation time and averages per year can be determined. The total number of arrived patients is not considered. Every simulation model uses the same arrival patterns for $ORem, w$ and em patients. Only for $ORel$ patients the arrival of patients depends on the OR schedule. However, the schedule does not influence the total number of arrivals, but only the distribution of the arrivals over time.

The number of rejected patients is an important performance measure. This measure can be determined in total, but also for the different types of patients separately. For the patients from the OR ($ORel$ and $ORem$), rejection at the ICU corresponds to cancellation of the surgical operation. The rejected patients thus indicate the cancellations of surgical operations. One simulation run analyzes a period of 10 years, where the first year is the warm-up period. The average number of rejected patients per year is determined over the remaining 9 years. This gives an average rejection per year for each simulation run. The results in the next subsections show the average performance measures over 50 simulation runs.

Other performance measures are obtained from the context of queueing theory. The average number of patients in the system can be determined, which indicates the average bed occupation. The occupation of the ICU is measured by determining the average number of beds occupied over the entire simulation time. This occupation level can be determined in total and for the different types of patients ($ORel, ORem, w$ or em). Another performance measure is the occupation percentage, which indicates the percentage of capacity used on average. Both over usage and under usage of the capacity can occur and they both influence the occupation percentage. Therefore, when this percentage is used to analyze the capacity usage, the conclusion can be biased. To analyze capacity usage better, information is also needed about the percentage of time that over usage of capacity occurs. Patients are rejected when the occupation of the ICU is equal to or above the capacity. The rejection probability indicates the percentage of time that the occupation of the ICU is equal to or larger than the capacity.

The performance of the ICU in the next subsections is measured with the following performance measures:

occupation	the average occupation of ICU beds by patients of type $ORel, ORem, w$ or em
total occupation	the average occuption of the ICU for all types of patients together
occupation percentage	the percentage of the ICU capacity that is used on average
rejections	the mean number of rejected patients of type $ORel, ORem, w$ or em per year
rejection probability	percentage of time that the occupation of the ICU is equal to or higher than the capacity

For these performance measures, the mean and the variance are determined and confidence intervals are added for comparison. The central limit theorem is used, because of the sample size of 50 simulation runs. This justifies the assumption that the mean of the performance measures follows the normal distribution. The variables $\bar{x}$, $\bar{s}$ and n indicate respectively the sample mean, the sample variance and the sample size. The cumulative distribution function of the standard normal distribution is given by Φ. Equation (5.6) gives the formula for the 95% confidence interval.

$$\left[\bar{x} - \Phi^{-1}(0.975)\frac{\sqrt{\bar{s}}}{\sqrt{n}}, \quad \bar{x} + \Phi^{-1}(0.975)\frac{\sqrt{\bar{s}}}{\sqrt{n}}\right] \tag{5.6}$$

5.3.2 Scenario 1 : ICU simulation

The first scenario in the analysis of the ICU uses a general queueing model. The four different OR schedules are used as input parameters in the simulation. The results of the ICU performance can be found in Table 5.3 on page 51.

The performance of the ICU under the different OR schedules is comparable for some performance measures. All the schedules result in an average occupation of around 37 patients per day and a capacity usage of around 82%.

Performance measure	Schedule 1 mean	var	95% CI	Schedule 2 mean	var	95% CI
Occupation						
ORel	2.5360	0.0449	[2.4772 , 2.5947]	2.5617	0.0704	[2.4882 , 2.6353]
ORem	8.3599	0.1130	[8.2667 , 8.4531]	8.3648	0.0965	[8.2787 , 8.4509]
w	15.0918	0.1176	[14.9968 , 15.1869]	15.0708	0.1286	[14.9714 , 15.1702]
em	11.3128	0.1027	[11.2240 , 11.4016]	11.2530	0.0797	[11.1747 , 11.3313]
total occupation	37.3005	0.1820	[37.1822 , 37.4188]	37.2504	0.2184	[37.1209 , 37.3800]
Capacity usage						
percentage	0.8265	0.0001	[0.8238 , 0.8291]	0.8254	0.0001	[0.8226 , 0.8283]
Rejections						
ORel	8.0222	2.2817	[7.6035 , 8.4409]	8.2044	4.5192	[7.6152 , 8.7937]
ORem	18.5133	9.8770	[17.6422 , 19.3844]	18.4422	11.7050	[17.4939 , 19.3905]
w	114.0556	228.6406	[109.8643 , 118.2468]	115.1200	464.069	[109.1489 , 121.0911]
em	78.1511	135.4073	[74.9257 , 81.3765]	78.3489	194.1658	[74.4866 , 82.2112]
rejection probability	0.0476	$4.45 \cdot 10^{-5}$	[0.0457 , 0.0494]	0.0483	0.0001	[0.0459 , 0.0506]

Performance measure	Schedule 3 mean	var	95% CI	Schedule 4 mean	var	95% CI
Occupation						
ORel	2.5462	0.0516	[2.4832 , 2.6091]	2.3723	0.0099	[2.3448 , 2.3999]
ORem	8.3552	0.1047	[8.2655 , 8.4449]	8.3698	0.0710	[8.2959 , 8.4436]
w	15.1358	0.1727	[15.0206 , 15.2510]	15.0383	0.1524	[14.9301 , 15.1465]
em	11.2256	0.0725	[11.1510 , 11.3002]	11.2758	0.0703	[11.2023 , 11.3493]
total occupation	37.2627	0.1707	[37.1482 , 37.3773]	37.0562	0.2554	[36.9162 , 37.1963]
Capacity usage						
percentage	0.8254	0.0001	[0.8229 , 0.8280]	0.8211	0.0001	[0.8180 , 0.8242]
Rejections						
ORel	9.9889	4.2370	[9.4183 , 10.5594]	9.1133	2.8725	[8.6436 , 9.5831]
ORem	17.9000	9.8459	[17.0303 , 18.7697]	18.0778	7.3592	[17.3258 , 18.8297]
w	110.8844	238.1028	[106.6074 , 115.1615]	109.8067	256.36143	[105.3691 , 114.2443]
em	75.7844	13.9208	[72.5888 , 78.9801]	75.3622	156.3557	[71.8963 , 78.8282]
rejection probability	0.0461	$4.27 \cdot 10^{-5}$	[0.0443 , 0.0480]	0.0461	$4.98 \cdot 10^{-5}$	[0.0422 , 0.0481]

Table 5.3: Scenario 1 - the performance of the ICU under the four OR schedules.

There are also some differences in performance if we compare the different types of patients. Especially the performance for the *ORel* patients is of interest, because this group of patients is influenced by the OR schedule. The occupation of *ORel* patients is significantly lower for schedule 4 compared to the other three schedules. This also influences the total occupation and the usage of the capacity. These two performance measures are also significantly lower for schedule 4 in comparison with the other schedules. The lower occupation of *ORel* patients in schedule 4 could be caused by the fact that schedule 4 is constructed different from the other schedules. Schedule 1, 2 and 3 are constructed for the sub surgical services, while schedule 4 assigns the operation room time to the surgical services. This also results in a different way of determining the number of patients going to the ICU. For schedule 1, 2 and 3 the percentage of patients going to the ICU is determined per sub surgcial service, while this percentage is determined per surgical service for schedule 4. In total the different calculation methods should result in comparable occupation for *ORel* patients, but the small differences in occupation could be explained by the differences in calculation methods.

The OR schedules also influence the rejections of patients. Both for schedule 3 and 4 the average number of rejected *ORel* patients per year is significantly higher than for schedule 1 and 2. Schedule 3 has significantly the highest number of rejected *ORel* patients in comparison with schedule 1, 2 and 4. If we analyze schedule 4 in more detail, the flow of patients from the OR to the ICU is relatively smooth. In terms of the flow of patients, schedule 4 is more close to schedule 1 and 2 than to schedule 3. From this we can conclude that a more smooth flow of patients from the OR to the ICU results in a significantly lower average number of rejected *ORel* patients per year. However, there is no significant difference in performance if schedule 1 and 2 are compared. This result is counterintuitive, since schedule 2 results in a more smooth flow of patients from the OR to the ICU than schedule 1 and is thus expected to result in a better ICU performance.

For the other types of patients ($ORel, w$ and em) there are almost no significant differences in the average number of rejections per year. Only for patients from the ward the number of rejected patients is significantly lower in schedule 4 compared to schedule 1. Expected is, that the higher rejection of *ORel* patients influences the rejections of other types of patients. For schedule 4 this results in lower rejections of patients from the ward.

In general we can conclude that schedule 1 and 2 outperform the extreme schedule (schedule 3) and the random schedule (schedule 4) in terms of occupation by *ORel* patients and rejection of *ORel* patients. This was also the objective in constructing schedule 1 and 2. The results of this scenario thus show that the intended increase in performance is obtained.

5.3.3 Scenario 2 : Reservation scheme that matches a levelled ICU occupation

In subsection 5.2.3 two reservation schemes are described. Scenario 2 is the simulation of the ICU under the first reservation scheme. This scheme reserves a number of beds for *ORel* patients during the entire simulation. This way of reserving beds matches the levelled ICU occupation. Table 5.3 shows that the *ORel* patients occupy around 2.5 beds at the ICU. Since it is not possible to reserve a bed fractionally, the simulation model is analyzed with 3 reserved beds for *ORel* patients. The performance of the ICU can be found in Table 5.4 on page 53.

This reservation scheme results in general in a slightly lower usage of occupation than in the scenario without reservations. The scheme is advantageous for *ORel* patients, as was to expect. The rejection is much lower for this type of patients, but this results in higher rejections for the other types of patients.

The differences in occupation of the ICU are small. Schedule 4 has significantly the lowest occupation for *ORel* patients and the total occupation of the ICU for schedule 3 and 4 is significantly lower than for schedule 1 and 2. The differences in the average number of rejected patients per year are much larger. For *ORel* patients schedule 1 has significantly the lowest number of rejected patients per year. This is not suprising, since the reservation scheme is constructed to match the result of the levelled ICU occupation of this OR schedule. Also schedule 3 and 4 result in significantly higher rejections of *ORel* patients in comparison to schedule 1. Schedule 3 also has a significantly higher rejection of *ORel* patients than schedule 2. But the differences in rejection of *ORel* patients between schedule 2 and 4 are not significant.

Performance measure	**Schedule 1** mean	var	95% CI	**Schedule 2** mean	var	95% CI
Occupation						
ORel	2.6277	0.0564	[2.5619 , 2.6936]	2.6657	0.0515	[2.6028 , 2.7286]
ORem	8.2374	0.0994	[8.1500 , 8.3248]	8.2218	0.1311	[8.1214 , 8.3222]
w	14.8976	0.1710	[14.7829 , 15.0122]	14.8685	0.2295	[14.7357 , 15.0013]
em	11.1159	0.0946	[11.0306 , 11.2011]	11.1151	0.0511	[11.0524 , 11.1777]
total occupation	36.8786	0.1554	[36.7693 , 36.9878]	36.8710	0.2253	[36.7395 , 37.0026]
Capacity usage						
percentage	0.8171	0.0001	[0.8147 , 0.8195]	0.8170	0.0001	[0.8141 , 0.8199]
Rejections						
ORel	3.5400	0.8768	[3.2805 , 3.7995]	4.1422	1.1872	[3.8402 , 4.4442]
ORem	23.4689	11.3531	[22.5349 , 24.4028]	23.3000	13.4282	[22.2843 , 24.3157]
w	142.0956	308.0816	[137.2304 , 146.9607]	143.9556	507.6861	[137.7101 , 150.2010]
em	98.0000	135.2080	[94.7709 , 101.2291]	98.3311	244.5047	[93.9969 , 102.6653]
rejection probability	0.0196	$1.18 \cdot 10^{-5}$	[0.0186 , 0.0205]	0.0223	$2.58 \cdot 10^{-5}$	[0.0209 , 0.0237]
Performance measure	**Schedule 3** mean	var	95% CI	**Schedule 4** mean	var	95% CI
Occupation						
ORel	2.5681	0.0742	[2.4926 , 2.6436]	2.3840	0.0069	[2.3609 , 2.4071]
ORem	8.1719	0.0738	[8.0966 , 8.2472]	8.2313	0.1430	[8.1265 , 8.3361]
w	14.7984	0.1172	[14.7035 , 14.8933]	14.8339	0.1008	[14.7459 , 14.9219]
em	11.1354	0.0653	[11.0646 , 11.2062]	11.1149	0.0721	[11.0405 , 11.1893]
total occupation	36.6738	0.1252	[36.5757 , 36.7718]	36.5641	0.1366	[36.4617 , 36.6666]
Capacity usage						
percentage	0.8123	0.0001	[0.8101 , 0.8145]	0.8102	0.0001	[0.8079 , 0.8125]
Rejections						
ORel	5.2956	1.2515	[4.9855 , 5.6056]	4.4089	1.2842	[4.0948 , 4.7230]
ORem	21.9311	5.4053	[21.2867 , 22.5755]	21.8889	11.8191	[20.9360 , 22.8418]
w	137.2844	155.2195	[133.8311 , 140.7378]	135.4844	299.9107	[130.6842 , 140.2846]
em	95.122	78.5459	[92.6657 , 97.5788]	92.7733	149.7022	[89.3819 , 96.1647]
rejection probability	0.0152	$9.15 \cdot 10^{-6}$	[0.0143 , 0.0160]	0.0180	$7.32 \cdot 10^{-6}$	[0.0173 , 0.0188]

Table 5.4: Scenario 2 - the performance of the ICU under the four OR schedules.

In general schedule 3 and 4 result in higher rejection of $ORel$ patients than schedule 1 and 2. For the other types of patients, the results are opposite. Then the number of rejected patients is lower for schedule 3 and 4. This indicates that the rejection of one type of patients influences the rejection of other types of patients.

Schedule 1 and 2 are advantageous for $ORel$ patients and result in a lower average of rejections per year. Although these schedules peforms good, again the differences in performance are small. Also the performance measures of schedule 2 are very similar to those of schedule 4. This means that the schedule especially constructed to level the flow of patients from the OR to the ICU does not outperform a random schedule.

In general the results show that schedule 1 is the most advantageous for the $ORel$ patients and schedule 3 is the most disadvantageous. However, an advantage for one type of patients is disadvantageous for the other types of patients.

5.3.4 Scenario 3 : Reservation scheme that matches a levelled patient flow to the ICU

This subsection presents the results of the second reservation scheme. This scheme reserves a number of beds per day for arriving $ORel$ patients, which matches the levelled flow of patients from the OR to the ICU. On average 1 patient per day requires post-operative ICU care after an elective surgical operation. Therefore, this reservation scheme is simulated with reserving 1 bed per day for arriving $ORel$ patients. The results of the simulation can be found in Table 5.5 on page 55.

The results for this reservation scheme are comparable with the previous scenario. Again schedule 1 and 2 result in significantly lower rejections for the $ORel$ patients than schedule 3 and 4. Schedule 2 does not perform better than schedule 1, unexpectedly. The reservation scheme is constructed to match the schedule with the levelled flow, but the results do not show that match.

Schedule 4 has significantly the lowest occupation of $ORel$ patients. This also results in a significantly lower total occupation and capacity usage. In terms of rejection of patients, schedule 4 results in significantly less rejections for $ORel$ and $ORem$ patients in comparison with schedule 3.

In general the results of this reservation scheme show that schedule 1 and 2 result in less rejections of $ORel$ patients than schedule 3 and 4. For the other types of patients the rejections are higher. Schedule 3 is has the worst performance for $ORel$ patients. If we compare the OR schedules in terms of total occupation and capacity usage of the ICU the performance measures are comparable.

5.3.5 Scenario 4 : Increased percentage of ORel patients

The OR schedule only affects the arrival pattern of $ORel$ patients at the ICU. The percentage of this group of patients at the ICU of the Erasmus MC is quite small. The group accounts for less than 5% of all the ICU stays. The OR schedule thus affects only a small percentage of the ICU patients. This can be the reason that the different OR schedules result in small differences in ICU performance. This scenario analyzes the performance of the ICU in case of an increase in the percentage of the $ORel$ patients. It is possible that this gives more differences in performance between the different OR schedules. The arrival of $ORel$ patients is determined by the OR schedule. For the other groups of patients an arrival rate is given and they arrive according to a Poisson proces. For simplicity, the percentage of $ORel$ patients is increased by decreasing the percentage of the other patients ($ORem, w$ and em). The arrival rates of these groups of patients is decreased and multiplied with 0.1. The arrival rate of ORel patient is left unchanged. Define p_{ORel} as the percentage of patients at the ICU of type $ORel$. Table 5.1 on page 48 shows that $p_{ORel} = 4.38\%$. The total arrival rate of patients is thus multiplied with the factor $(0.1 * (1 - p_{ORel}) + p_{ORel})$. For a fair comparison on performance, the ICU capacity is multiplied with the same factor. The capacity of the ICU represents the number of available beds. This number can only take integer values. Therefore the capacity is rounded up, after multiplying with the given factor. The total arrival rate and the capacity are thus decreased with

Performance measure	Schedule 1 mean	var	95% CI	Schedule 2 mean	var	95% CI
Occupation						
ORel	2.6327	0.0521	[2.5694 , 2.6959]	2.6277	0.0337	[2.5768 , 2.6786]
ORem	8.2201	0.1023	[8.1314 , 8.3087]	8.2419	0.1118	[8.1493 , 8.3346]
w	14.8957	0.1349	[14.7939 , 14.9975]	14.8719	0.1608	[14.7608 , 14.9831]
em	11.1327	0.0647	[11.0622 , 11.2032]	11.1927	0.0994	[11.1053, 11.2801]
total occupation	36.8811	0.1875	[36.7611 , 37.0011]	36.9343	0.1491	[36.8272 , 37.0413]
Capacity usage						
percentage	0.8171	0.0001	[0.8145 , 0.8198]	0.8184	0.0001	[0.8160 , 0.8208]
Rejections						
ORel	2.3311	0.6846	[2.1018 , 2.5604]	2.5156	0.4715	[2.3252 , 2.7059]
ORem	21.8244	12.8199	[20.8320 , 22.8169]	22.6511	9.9063	[21.7787 , 23.5235]
w	134.7156	356.6143	[129.4812 , 139.9499]	137.4956	301.9764	[132.6789 , 142.3123]
em	92.4444	161.8619	[88.9180 , 95.9709]	94.4333	144.6733	[91.0994 , 97.7673]
rejection probability	0.0092	$2.86 \cdot 10^{-6}$	[0.0088 , 0.0097]	0.0099	$2.54 \cdot 10^{-6}$	[0.0095 , 0.0104]
Performance measure	**Schedule 3** mean	var	95% CI	**Schedule 4** mean	var	95% CI
Occupation						
ORel	2.5887	0.0424	[2.5316 , 2.6458]	2.3983	0.0079	[2.3736 , 2.4230]
ORem	8.2687	0.1055	[8.1787 , 8.3587]	8.2437	0.1080	[8.1526 , 8.3348]
w	14.9499	0.1236	[14.8524 , 15.0473]	14.9038	0.1252	[14.8058 , 15.0019]
em	11.1414	0.0755	[11.0652 , 11.2175]	11.0986	0.0909	[11.0150 , 11.1821]
total occupation	36.9486	0.1195	[36.8528 , 37.0444]	36.6443	0.2139	[36.5162 , 36.7725]
Capacity usage						
percentage	0.8185	0.0001	[0.8163 , 0.8206]	0.8120	0.0001	[0.8091 , 0.8148]
Rejections						
ORel	5.0422	1.0712	[4.7553 , 5.3291]	3.0911	0.9124	[2.8263 , 3.3559]
ORem	21.4178	4.8620	[20.8066 , 22.0290]	20.7000	14.1503	[19.6573 , 21.7427]
w	132.1022	228.4585	[127.9127 , 136.2918]	129.2689	382.3084	[123.8493 , 134.6885]
em	90.4867	110.2932	[87.5757 , 93.3976]	88.0267	189.4289	[84.2117 , 91.8416]
rejection probability	0.0093	$1.30 \cdot 10^{-6}$	[0.0090 , 0.0096]	0.0103	$3.42 \cdot 10^{-6}$	[0.0098 , 0.0108]

Table 5.5: Scenario 3 - the performance of the ICU under the four OR schedules.

the same percentage. The adjustments made to the input parameters for the simulation model are described in the following equations (5.7).

$$\begin{aligned}
&\lambda_{adj}^{ORem} = \lambda^{ORem} * 0.1 \\
&\lambda_{adj}^{w} = \lambda^{w} * 0.1 \\
&\lambda_{adj}^{em} = \lambda^{em} * 0.1 \\
&C_{(adj),j}^{ICU} = \lceil C_j^{ICU} * (0.1 * (1 - p_{ORel}) + p_{ORel}) \rceil \quad \forall j \in J
\end{aligned} \tag{5.7}$$

The adjustments described result in an ICU where the *ORel* patients account for about a third of all the patients. To analyze the influence of the OR schedules in more detail, the percentage of *ORel* patients is increased further and set equal to 100%. The adjustments needed are given in the equations (5.8).

$$\begin{aligned}
&\lambda_{adj}^{ORem} = 0 \\
&\lambda_{adj}^{w} = 0 \\
&\lambda_{adj}^{em} = 0 \\
&C_{(adj),j}^{ICU} = \lceil C_j^{ICU} * p_{ORel} \rceil \quad \forall j \in J
\end{aligned} \tag{5.8}$$

Again the performance of the ICU is compared under the different OR schedules. The results of the two versions of increasing the percentage of *ORel* patients can be found in Table 5.6 on page 57 and Table 5.7 on page 58.

The results show a difference in performance if the OR schedules are compared. The OR schedules especially influence patients from elective surgical operations (*ORel*). Schedule 1 and 2 give a significantly higher occupation of *ORel* patients if they are compared to schedule 3 and 4. This also leads to a significantly higher total occupation of the ICU and a higher capacity usage for schedule 1 and 2. This means that these two schedules, which are constructed while considering the ICU, indeed outperform the extreme case schedule and the random schedule. The differences in performance are larger than in the previous scenarios where *ORel* patients accounted for less than 5% of all the patients at the ICU.

In terms of rejection schedule 1 and 2 result in significantly less rejections of *ORel* patients compared to schedule 3 and 4. For the other types of patients schedule 3 and 4 have significantly lower rejections. Schedule 4 outperforms schedule 3 if we compare the rejection of *ORel* patients.

Schedule 1 and 2 do not differ significantly in performance in table 5.6. However, if the *ORel* patients account for 100% of all the patients at the ICU, there are some significant differences in performance. The total occupation of the ICU for schedule 2 is then significantly higher than in schedule 2, which also leads to a significantly higher percentual usage of the capacity. The number of rejected *ORel* patients for schedule 2 is significantly higher than for schedule 1, but the statement does not hold the other way around. We cannot say that the number of rejected *ORel* patients for schedule 1 is significantly lower than for schedule 2. If we analyze the rejection probability, this performance measure is significantly higher for schedule 2 than it is for schedule 1. In general we can conclude that schedule 1 is slightly better than schedule 2 for *ORel* patients, but the differences in performance are small.

Thus if the percentage of *ORel* patients is artificially increased, schedule 1 and 2 perform significantly better for *ORel* patients than the extreme schedule 3. The differences in performance are also bigger than in the previous scenarios. The schedules 1 and 2 perform significantly better than the random schedule (schedule 4) as well, but the differences in performance are smaller than in comparison with schedule 3. Schedule 1 and 2 result in lower rejections of *ORel* patients, which means less cancellations of elective surgical operations.

Compared to the normal simulation in scenario 1, the decrease of the capacity and of the patients of type $ORem, em$ and w result in a higher rejection probability. Although the capacity and arrival rate have decreased with the same percentage, the rejection increases. This is the result of the fact that the capacity becomes smaller and that the occupation is more influenced by a patient with a longer LOS. For comparison the Erlang B formula can be analyzed with different arrival rates and capacities. The service rate is kept

Performance measure	Schedule 1 mean	Schedule 1 var	Schedule 1 95% CI	Schedule 2 mean	Schedule 2 var	Schedule 2 95% CI
Occupation						
ORel	2.0808	0.0374	[2.0271 , 2.1344]	2.1092	0.0264	[2.0641 , 2.1543]
ORem	0.6849	0.0153	[0.6506 , 0.7191]	0.6569	0.0098	[0.6294 , 0.6843]
w	1.2161	0.0136	[1.1838 , 1.2484]	1.2065	0.0138	[1.1740 , 1.2391]
em	0.9078	0.0112	[0.8785 , 0.9372]	0.8921	0.0043	[0.8740 , 0.9101]
total occupation	4.8896	0.0188	[4.8516 , 4.9276]	4.8646	0.0145	[4.8313 , 4.8980]
Capacity usage						
percentage	0.7241	0.0004	[0.7185 , 0.7297]	0.7212	0.0003	[0.7163 , 0.7261]
Rejections						
ORel	48.1778	31.7894	[46.6150 , 49.7406]	47.9178	35.5393	[46.2654 , 49.5702]
ORem	8.9000	1.1107	[8.6079 , 9.1921]	8.8800	1.4008	[8.5519 , 9.2081]
w	55.7044	23.6620	[54.3560 , 57.0529]	55.8600	32.9145	[54.2689 , 57.4502]
em	38.5667	15.0558	[37.4912 , 39.6422]	38.0667	21.4628	[36.7825 , 39.3508]
rejection probability	0.2240	0.0005	[0.2176 , 0.2304]	0.2232	0.0005	[0.2172 , 0.2291]

Performance measure	Schedule 3 mean	Schedule 3 var	Schedule 3 95% CI	Schedule 4 mean	Schedule 4 var	Schedule 4 95% CI
Occupation						
ORel	1.9613	0.0334	[1.9107 , 2.0120]	1.9231	0.0057	[1,9021 , 1.9441]
ORem	0.6960	0.0060	[0.6745 , 0.7175]	0.7092	0.0090	[0,6829 , 0.7355]
w	1.2315	0.0083	[1.2062 , 1.2568]	1.2184	0.0112	[1,1891 , 1.2478]
em	0.9126	0.0052	[0.8927 , 0.9325]	0.9213	0.0065	[0,8989 , 0.9437]
total occupation	4.8015	0.0145	[4.7681 , 4.8349]	4.7720	0.0108	[4.7432 , 4.8007]
Capacity usage						
percentage	0.7089	0.0003	[0.7039 , 0.7138]	0.7075	0.0002	[0.7032 , 0.7117]
Rejections						
ORel	64.7689	40.6006	[63.0027 , 66.5350]	52.6822	36.1602	[51.1103 , 54.2541]
ORem	8.3622	1.7787	[7.9926 , 8.7319]	8.5311	1.6252	[8.1777 , 8.8845]
w	52.0644	25.1474	[50.6745 , 53.4544]	52.4267	30.1468	[50.9048 , 53.9486]
em	35.6200	12.0540	[34.6577 , 36.5823]	35.8844	10.7568	[34.9754 , 36.7935]
rejection probability	0.2088	0.0004	[0.2036 , 0.2141]	0.2107	0.0003	[0.2059 , 0.2155]

Table 5.6: Scenario 4 - the performance of the ICU under the four OR schedules.

Performance measure	**Schedule 1** mean	var	95% CI	**Schedule 2** mean	var	95% CI
Occupation						
ORel / total	1.7844	0.0068	[1.7616 , 1.8072]	1.8138	0.0107	[1.7851 , 1.8425]
Capacity usage						
percentage	0.6424	0.0009	[0.6343 , 0.6506]	0.6564	0.0013	[0.6463 , 0.6666]
Rejections						
ORel	73.5800	47.8606	[71.6624 , 75.4976]	75.8067	81.8240	[73.2997 , 78.3136]
rejection probability	0.3420	0.0008	[0.3343 , 0.3497]	0.3532	0.0014	[0.3429 , 0.3635]
Performance measure	**Schedule 3** mean	var	95% CI	**Schedule 4** mean	var	95% CI
Occupation						
ORel / total	1.6513	0.0166	[1.6155 , 1.6870]	1.6886	0.0022	[1.6757 , 1.7015]
Capacity usage						
percentage	0.5802	0.0022	[0.5672 , 0.5932]	0.6130	0.0003	[0.6084 , 0.6176]
Rejections						
ORel	96.7200	89.3541	[94.0999 , 99.3401]	79.9244	27.1133	[78.4812 , 81.3677]
rejection probability	0.2893	0.0018	[0.2775 , 0.3011]	0.3181	0.0003	[0.3137 , 0.3225]

Table 5.7: The performance of the ICU under the four OR schedules if only the *ORel* patients are analyzed.

constant. Then the results also show that a decrease with the same factor of the capacity and arrival rate also results in a higher rejection probability.

5.4 Further analysis of the results

In the previous section the performance of the ICU under different OR schedules is analyzed. Two OR schedules (schedule 1 and 2) are constructed to improve the interaction between the OR and the ICU. These schedules are compared with an extreme schedule with very high variance in the flow of patients from the OR to the ICU (schedule 3) and with a random OR schedule (schedule 4). The results show that schedule 1 and 2 outperform schedule 3 and 4. In the construction of schedule 1 and 2 it was expected that these schedules would improve the performance of the ICU. The results also show this.

Both schedule 1, 2 and 4 result in a more or less smooth arrival pattern of *ORel* patients at the ICU. This arrival pattern from schedule 3 is far more variable. The results show that schedule 1, 2 and 4 outperform schedule 3. This leads to the conclusion that a low variance in the arrival pattern of *ORel* patients at the ICU is preferred. However, schedule 2, which has the most smooth flow, does not result in the best performance of the ICU. In some cases the performance of schedule 1 and 2 does not differ significantly. In other cases schedule 1 even outperforms schedule 2. This result is counterintuitive. This section analyzes the performance of the ICU under an artificial optimal schedule with a completely smooth flow of patients from the OR to the ICU. This schedule is expected to be the best possible OR schedule. Analyzing the influence of this schedule on the performance of the ICU gives an indication for the room of improvement on the ICU performance.

The average flow of patients per day in schedule 1 and 2 is calculated by summing up the total flow over the week and dividing it over the 5 days. This resulted in an average of 0.8849 patients per day to the ICU after an elective surgical operation. An artificial OR schedule is constructed, which has exactly this average flow of patients per day to the ICU. This schedule is referred to as schedule 5. There is thus no variance in the arrival of *ORel* patients at the ICU from Monday to Friday. The actual arrival time of these patients is assumed to be randomly distributed over the general opening times of the OR department (from 08.00h to 15.30h).

The influence of schedule 5 on the performance of the ICU is analyzed and compared to schedule 1 and 2. These last two schedules are constructed with the sub surgical services and these sub surgical services also determine the parameters of the LOS. Schedule 5 is not constructed with the sub surgical services, but determines an artificial flow of patients from the OR to the ICU. To make a fair comparison between schedule 1 and 2 and schedule 5, the same distributions for the LOS must be used. Therefore, the patients who arrive at the ICU in schedule 5 are randomly assigned to a sub surgical service and the corresponding parameters for the LOS are used. The probability to belong to a sub surgical service is determined such that the distribution of the patients over the different sub surgical services in schedule 1, 2 and 5 is the same. The OR schedules are compared in subsection 5.4.1.

5.4.1 The performance of the ICU under a smooth arrival

The same four scenarios as in section 5.3 are used and schedule 1, 2 and 5 are compared. Schedule 5 is expected to give the best performance of the ICU and can thus be seen as an upper bound on the performance. The differences between the performance of schedule 1 and 2 and schedule 5 indicate the possibilities to improve on schedule 1 and 2. The results in the previous section show that schedule 1 and 2 give very similar performance measures, although schedule 1 sometimes performs better than schedule 2. Therefore only the performance measures of schedule 1 are presented in this section. The results can be found in Table 5.8, Table 5.9, Table 5.10, Table 5.11 and Table 5.12.

Performance measure	**Schedule 1** mean	var	95% CI	**Schedule 5** mean	var	95% CI
Occupation						
ORel	2.5360	0.0449	[2.4772 , 2.5947]	2.5916	0.1008	[2.5036 , 2.6796]
ORem	8.3599	0.1130	[8.2667 , 8.4531]	8.3035	0.0814	[8.2244 , 8.3826]
w	15.0918	0.1176	[14.9968 , 15.1869]	15.0267	0.1398	[14.9231 , 15.1303]
em	11.3128	0.1027	[11.2240 , 11.4016]	11.2819	0.0707	[11.2083 , 11.3556]
total occupation	37.3005	0.1820	[37.1822 , 37.4188]	37.2038	0.2637	[37.0614 , 37.3461]
Capacity usage						
percentage	0.8265	0.0001	[0.8238 , 0.8291]	0.8244	0.0001	[0.8212 , 0.8275]
Rejections						
ORel	8.0222	2.2817	[7.6035 , 8.4409]	8.2311	2.5900	[7.7850 , 8.6772]
ORem	18.5133	9.8770	[17.6422 , 19.3844]	17.6844	9.9987	[16.8080 , 18.5609]
w	114.0556	228.6406	[109.8643 , 118.2468]	111.0867	305.6187	[106.2410 , 115.9323]
em	78.1511	135.4073	[74.9257 , 81.3765]	76.0089	167.5278	[72.4213 , 79.5965]
rejection probability	0.0476	$4.45 \cdot 10^{-5}$	[0.0457 , 0.0494]	0.0470	0.0001	[0.0445 , 0.0495]

Table 5.8: Comparison of the performance of the ICU under schedule 1 and schedule 5 in scenario 1 (the normal simulation).

Performance measure	**Schedule 1** mean	var	95% CI	**Schedule 5** mean	var	95% CI
Occupation						
ORel	2.6277	0.0564	[2.5619 , 2.6936]	2.1050	0.0210	[2.0648 , 2.1453]
ORem	8.2374	0.0994	[8.1500 , 8.3248]	8.2511	0.1113	[8.1586 , 8.3436]
w	14.8976	0.1710	[14.7829 , 15.0122]	14.8936	0.1187	[14.7981 , 14.9891]
em	11.1159	0.0946	[11.0306 , 11.2011]	11.2661	0.0703	[11.1927 , 11.3396]
total occupation	36.8786	0.1554	[36.7693 , 36.9878]	36.5158	0.1954	[36.3933 , 36.6383]
Capacity usage						
percentage	0.8171	0.0001	[0.8147 , 0.8195]	0.8091	0.0001	[0.8064 , 0.8118]
Rejections						
ORel	3.5400	0.8768	[3.2805 , 3.7995]	3.1867	1.0106	[2.9080 , 3.4653]
ORem	23.4689	11.3531	[22.5349 , 24.4028]	20.6333	8.5680	[19.8220 , 21.4447]
w	142.0956	308.0816	[137.2304 , 146.9607]	125.8822	283.6087	[121.2143 , 130.5501]
em	98	135.7208	[94.7709 , 101.2291]	86.4133	146.4127	[83.0594 , 89.7673]
rejection probability	0.0196	$1.18 \cdot 10^{-5}$	[0.0186 , 0.0205]	0.0175	$1.07 \cdot 10^{-5}$	[0.0166 , 0.0184]

Table 5.9: Comparison of the performance of the ICU under schedule 1 and schedule 5 in scenario 2 (the first reservation scheme).

Performance measure	Schedule 1 mean	var	95% CI	Schedule 5 mean	var	95% CI
Occupation						
ORel	2.6327	0.0521	[2.5694 , 2.6959]	2.5553	0.0566	[2.4849 , 2.6213]
ORem	8.2201	0.1023	[8.1314 , 8.3087]	8.2925	0.1471	[8.1862 , 8.3988]
w	14.8957	0.1349	[14.7939 , 14.9975]	14.9062	0.2363	[14.7714 , 15.0409]
em	11.1327	0.0647	[11.0622 , 11.2032]	11.1911	0.0876	[11.1091 , 11.2731]
total occupation	36.8811	0.1875	[36.7611 , 37.0011]	36.9451	0.2876	[36.7964 , 37.0937]
Capacity usage						
percentage	0.8171	0.0001	[0.8145 , 0.8198]	0.8186	0.0001	[0.8153 , 0.8219]
Rejections						
ORel	2.3311	0.6846	[2.1018 , 2.5604]	2.5778	0.4747	[2.3868 , 2.7687]
ORem	21.8244	12.8199	[20.8320 , 22.8169]	22.6689	15.0413	[21.5939 , 23.7439]
w	134.7156	356.6143	[129.4812 , 139.9499]	140.1378	544.7788	[133.6682 , 146.6073]
em	92.4444	161.8619	[88.9180 , 95.9709]	96.6956	243.3317	[92.3718 , 101.0193]
rejection probability	0.0092	$2.86 \cdot 10^{-6}$	[0.0088 , 0.0097]	0.0102	$4.02 \cdot 10^{-6}$	[0.0096 , 0.0107]

Table 5.10: Comparison of the performance of the ICU under schedule 1 and schedule 5 in scenario 3 (the second reservation scheme).

Performance measure	Schedule 1 mean	var	95% CI	Schedule 5 mean	var	95% CI
Occupation						
ORel	2.0808	0.0374	[2.0271 , 2.1344]	2.0359	0.0220	[1.9948 , 2.0770]
ORem	0.6849	0.0153	[0.6506 , 0.7191]	0.6719	0.0091	[0.6454 , 0.6984]
w	1.2161	0.0136	[1.1838 , 1.2484]	1.2292	0.0184	[1.1915 , 1.2668]
em	0.9078	0.0112	[0.8785 , 0.9372]	0.9082	0.0076	[0.8841 , 0.9323]
total occupation	4.8896	0.0188	[4.8516 , 4.9276]	4.8452	0.0135	[4.8129 , 4.8774]
Capacity usage						
percentage	0.7241	0.0004	[0.7185 , 0.7297]	0.7178	0.0003	[0.7130 , 0.7226]
Rejections						
ORel	48.1778	31.7894	[46.6150 , 49.7406]	47.9677	17.3729	[46.8091 , 49.1198]
ORem	8.9000	1.1107	[8.6079 , 9.1921]	9.0533	1.7361	[8.6881 , 9.4185]
w	55.7044	23.6620	[54.3560 , 57.0529]	54.9378	36.7343	[53.2578 , 56.6177]
em	38.5667	15.0558	[37.4912 , 39.6422]	37.5156	14.5643	[36.4577 , 38.5734]
rejection probability	0.2240	0.0005	[0.2176 , 0.2304]	0.2176	0.0004	[0.2124 , 0.2229]

Table 5.11: Comparison of the performance of the ICU under schedule 1 and schedule 5 in scenario 4 (the increased percentage of *ORel* patients).

Performance measure	**Schedule 1** mean	var	95% CI	**Schedule 5** mean	var	95% CI
Occupation						
ORel / total	1.7844	0.0068	[1.7616 , 1.8072]	1.8201	0.0201	[1.7808 , 1.8594]
Capacity usage						
percentage	0.6424	0.0009	[0.6343 , 0.6506]	0.6558	0.0025	[0.6418 , 0.6697]
Rejections						
ORel	73.58	47.8606	[71.6624 , 75.4976]	77.0756	136.8871	[73.8326 , 80.3185]
rejection probability	0.342	0.0008	[0.3343 , 0.3497]	0.3534	0.0025	[0.3394 , 0.3674]

Table 5.12: Comparison of the performance of the ICU under schedule 1 and schedule 5 in scenario 4 (only *ORel* patients).

The results in this section compare schedule 5, which is expect to be optimal, to schedule 1. The performance of the ICU under both OR schedules is comparable in the simulation of scenario 1. There are no significant differences in performance. In scenario 2 schedule 5 results in significantly lower rejection levels than schedule 1. In that scenario the schedule with the completely smooth flow of patients thus outperforms schedule 1. However, the same cannot be said about scenario 3. Here schedule 2 results in significantly higher rejections for most types of patients.

The percentage of *ORel* patients is increased in scenario 4. The results show that this does not lead to significant differences in performance in terms of rejection. Only when the *ORel* patients account for 100% of the patients at the ICU, schedule 1 has significantly less rejections than schedule 5.

In general we can say that schedule 1 and 5 perform comparable. Sometimes the first schedule performs better, sometimes the other. This results was not expected, since schedule 5 was assumed to be an optimal schedule. The completely smooth flow of patients was expected to lead to an improvement in ICU performance. The results do not support this expectation.

Schedule 5 can be considered as an upper bound on the performance of the ICU. The results from section 5.3 showed that schedule 1 and 2 had a similar performance. Combining the results from this section and the previous section, we can say that schedule 5 does not perform better than schedule 1 and 2. There is thus no room for improving on schedule 1 and 2. A more smooth arrival of *ORel* patients at the ICU is preferred, since the extreme schedule (schedule 3) results in a worse performance. However, a completely levelled flow of patients does not result in a better ICU performance than a flow which is more or less levelled.

5.5 Conclusions and discussion

The constructed OR schedules in chapter 4 seem to be advantageous for the ICU. In addition to literature, the actual improvements for the ICU are analyzed by using a simulation model of the ICU. Only after analyzing the total ICU, statements can be made about the benefits of the OR schedules for the ICU. The simulation model of the ICU is constructed to analyze the performance of this department under different OR schedules. Two OR schedules were constructed with an OR scheduling model in chapter 4 and these schedules both tried to improve the interaction between the OR and the ICU. Two other schedules were constructed in this chapter for comparison. The third schedule is an extreme schedule, with a very unpreferable OR-ICU interaction. The fourth schedule is a completely random OR schedule, without the usage of the sub surgical services.

The results show that the constructed OR schedules of chapter 4 lead to a small increase in performance of the ICU under the normal simulation. The optimal OR schedules 1 and 2 perform slightly better than the extreme schedule and the random schedule. Schedule 1 and 2 are especially constructed to improve the performance of the ICU. The results show that these schedules indeed result in a better performance for patients at the ICU who had a surgical operation. For the other types of patients there are almost no significant differences in performance. With the simulation study we have thus proved that the constructed schedules actually result in an increase in performance of the ICU.

In practice the patients of *ORel* have a higher priority than other patients. To incorporate this in the simulation model, two reservation schemes are proposed. In literature usually priority queues are used if there are different types of patiens with different priorities. However, this thesis models the ICU without waiting capacity, such that there are no queues. Reserving beds for specific types of patienst gives them a higher priority. Two different scenarios are considered which try to model the ICU more realistically by reserving beds for the high priority *ORel* patients. These reservation schemes result in a better performance of the first two OR schedules compared to the extreme and random schedule. The number of rejected *ORel* patients is smaller, which again indicates that schedule 1 and 2 are advantageous for *ORel* patients. For these reservation schemes the improvement for one type of patients results in a worse performance for the other patients. Schedule 1 and 2 result in less rejections of *ORel* patients, but in more rejections for the other types of patients.

The ICU model in scenario 1 treats all different types of patients in the same way. Using an OR schedule especially constructed to improve the OR-ICU interaction (schedule 1 and 2) results in better performance. However, the differences are small. Also, between schedule 1 and 2 there are hardly any significant differences. Assumed is that this can be motivated by the fact that the OR schedule only influences a small percentage of the patients. Only less than 5% of the patients at the ICU comes from an elective surgical operation. To analyze this further the fourth scenario increases the percentage of *ORel* patients. This indeed results in a better performance of schedule 1 and 2 if they are compared to schedule 3. The differences in performance are larger. The number of rejected *ORel* patients is lower and there are on average more of these patients on the ICU. This scenario focuses on the *ORel* patients and these results show again that schedule 1 and 2 outperform schedule 3 and 4. This again leads to the conclusion that the schedules constructed in chapter 4 are advantageous for *ORel* patients.

The different OR schedules are compared in four scenarios. The results in the four scenarios are comparable. Schedule 1 and 2 give a similar performance on the ICU. Only in scenario 2 with the reservation scheme that matches the levelled occupation, schedule 1 outperforms schedule 2. It cannot be said that one of the schedules is obviously better than the other, although schedule 1 results in slightly less rejections of patients. We assume that the similar results are caused by the smooth flow of patients from the OR to the ICU.

Both schedule 1, 2 and 4 result in a more or less smooth arrival pattern of *ORel* patients at the ICU. This arrival pattern from schedule 3 is far from smooth. In general schedule 1, 2 and 4 outperform the extreme schedule 3. This leads to the conclusion that a more smooth arrival pattern of *ORel* patients at the ICU is advantageous for the performance of the ICU. This results is expected.

Unexpected is, that schedule 1 and 2 do not differ significantly in performance, although schedule 2 has a more smooth flow of patients from the OR to the ICU.

An artificial schedule is constructed with a completely smooth arrival pattern (schedule 5). The conclusion after comparing with schedule 3 was that a smooth arrival pattern is preferred. This would expectedly lead to the result that schedule 5 has the best performance on the ICU. However, the performance between schedule 1 and 2 is similar and schedule 5 does not perform better. This can be caused by different reasons.

The first reason is already investigated in the previous section in scenario 4 and analyzes the influence of an increase in percentage of *ORel* patients. The extreme schedule performs worse than the other schedules, but the differences are still small. Also the performance measures for schedule 1 and 2 are still comparable. This leads to the conclusion that the low percentage of *ORel* patients is not the main reason for the small differences in performance.

Another reason could be that the OR schedule is constructed on an aggregate level. The OR schedule assigns operation rooms to a surgical service, but does not construct the scheduling of the individual surgical operations. This thesis analyzes the influence of the aggregate OR schedule on the ICU. The level in between, which is the individual patient level on the OR, is not considered. It could be that this level has the most influence on the flow of patients from the OR to the ICU. Constructing a schedule on this level could perhaps improve the performance of the ICU. For the current OR schedules the assumption is made that the patients arrive randomly over the day during the time that elective surgical operations are performed. The actual arrival time of a patient at the ICU could be determined if the OR schedule would be made on the individual patient level. The results of this thesis show that a smooth arrival pattern is preferred. This means that a good OR schedule for individual patients must also result in a low variance in the flow of patients from the OR to the ICU. Schedule 1 and 2 in this thesis sent on average around 1 patient per day to the ICU. Scheduling the individual surgical operations would therefore make not that much difference in the actual arrival time at the ICU. The arrival time expectedly differs not more than a few hours. Patients stay on average around 3 days at the ICU. A few hours difference in arrival time is therefore not expected to result in a different performance of the ICU. Therefore, we conclude that it is not plausible that the aggregated level of the OR schedule is the reason of the small differences in performance between schedule 1 and 2. Constructing an OR schedule on the level of the individual patients is not assumed to lead to larger difference in performance.

Expected is that the small difference in performance are mainly caused by the distribution of the LOS. We already mentioned that patients stay on average 3 days at the ICU. The differences in arrival pattern between schedule 1 and 2 are small. This corresponds to differences in the arrival time at the ICU of only a few hours or at most a day. It is not surprising that a difference in arrival time of only a few hours does not result in a different performance of the ICU if the patient stays for a long time at the ICU after arrival. The LOS is assumed to follow a lognormal distribution with a large variation. This distribution is heavily tailed towards the right, which means that very long stays at the ICU can occur. The variance in the LOS is also large. The LOS can thus vary a lot and it is not rare that the LOS is a few hours longer or shorter than average. Then it is obvious that arriving a few hours earlier or later at the ICU does not make a difference.

In short, we can say that schedule 1 and 2 result in a similar smooth arrival pattern of *ORel* patients at the ICU. The differences in arrival times are expected to be not more than a few hours. Due to the long LOS and the large variance in LOS, these differences in arrival times are too small to result in differences in performance of the ICU. A flow of patients from the OR to the ICU with low variance over the week is preferred, but small changes in the variance do not result in differences in ICU performance. Expected is, that this is also the reason that the upper bound determined by schedule 5 is comparable to the performance measures of schedule 1 and 2.

The results sometimes show different relations between the performance measures of rejection and those of occupation. The relation between the rejection of patients and the occupation is twofold. First, a lower rejection is assumed to lead to a higher occupation. The total number of arriving patients is more or less the same for every OR schedule in a specific scenario. A lower number of rejections thus corresponds to a higher number of admitted patients. The distribution of the LOS is also independent of the OR schedule. A higher number of admitted patients is therefore expected to lead to a higher occupation. On the other hand a higher occupation will result in more rejections. A higher occupation means that the percentage of the time that all the capacity is used, is larger. Patients who arrive when all capacity is used, will be rejected.

Both relations can be found in the results. There is thus an interaction between rejection and occupation. To determine which OR schedule is preferred, a trade-off must be made between a high occupation and a low rejection. The actual decision then depends on the preferences of the hospital. Further research could analyze the relation between the occupation and the rejection in more detail. From a theoretical point of view this could be interesting and it could be helpful for decision making in the trade-off between rejection and occupation.

The results in this thesis also show that for some scenario's schedule 3 has the lowest rejection probability, although the average numbers of rejected patients are higher than for other schedules. This result is counterintuitive. Further research is needed to find out how the average number of rejected patients is related to the rejection probability.

This thesis analyzes the construction of an OR schedule to improve the performance of the ICU. Schedule 1 and 2 are the results of the OR scheduling problem. These schedules are compared with an extreme schedule and a random schedule to see the performance of the ICU. The results in comparison with the extreme schedule and the random schedule show that schedule 1 and 2 result in a better ICU performance for *ORel* patients. In short we can conclude that a more smooth flow of patients from the OR to the ICU is preferred. But small differences in smoothness do not result in differences in performance of the ICU. The other patients at the ICU and the long and variable LOS also contribute to the ICU performance. For the other types of patients the constructed OR schedules are not beneficial.

The analysis of the influence of different OR schedules on the performance of the ICU is a contribution to literature. In chapter 4 the constructed schedule 1 and 2 seemed to be advantageous for the ICU. Other studies in literature show the same results. However, the results in this chapter have actually shown that schedule 1 and 2 lead improvements in the performance of the ICU.

Chapter 6

Conclusion and reccommendations

6.1 Summary

This thesis has investigated the interaction between the OR and the ICU. One of the main objectives was to construct a cyclic OR schedule that incorporates the patients going from the OR to the ICU. In the current OR schedule the operation rooms are assigned to the surgical services in the hospital. To analyze the flow from the OR to the ICU in more detail, the surgcial services are split into groups. Surgical operations with a high percentage of patients going to the ICU are grouped together and operations of which the patients rarely need post-operative care at the ICU are grouped together. These groups of surgical operations are called sub surgical services. Every sub surgical service gets assigned one operation room per cycle in the OR schedule. This concept is a contribution to the methods of OR scheduling in literature.

The OR scheduling problem is formulated as a mathematical programming problem. Restrictions make sure that the capacity of the operation room department is not exceeded and that each surgical service gets assigned enough time in the schedule to operate their patients. The constructed schedules are cyclic schedules with a cycle time of one week. Two objectives are used in constructing the OR schedule, which focus on the influence of the OR schedule on the ICU. The first objective aims to level the occupation of patients at the ICU and is commonly used in literature. The second objective is presented in this thesis and tries to level the flow of patients from the OR to the ICU. In chapter 4 the OR scheduling model is described and the constructed OR schedules are given.

The OR schedule determines the amount of patients going to the ICU and the distribution of these patients over the cycle time of the schedule. The different OR schedules can thus be compared by analyzing the flow of patients from the OR to the ICU. However, only comparing the OR schedules does not provide enough information about the actual influence of the OR schedule on the ICU. Patients from the OR are not the only patients at the ICU, although they are the only group that is controlled by the OR schedule. In addition to the studies in literature, this thesis analyzes the influence of the OR schedules on the total ICU. The ICU is simulated as a queueing model in chapter 5. The OR schedule then determines the arrival at the ICU of patients from the OR. A simulation model is built to simulate the ICU as a queueing model. From the simulation results performance measures of the ICU can be obtained. The performance can be measured in terms of occupation of the ICU and rejections of patients. By comparing the simulation results, the performance of the ICU under the different OR schedules can be compared. In this way the actual influence of the OR schedule on the ICU can be determined and conclusions can be made about the advantages of the constructed OR schedules.

6.2 Conclusions

The first part of the research question asked for the ways to incorporate the OR-ICU interaction in the OR schedules. This thesis uses two ways to determine the influence of the OR schedule on the ICU. Both the occupation of patients from the OR at the ICU is determined and the flow of patients from the OR to the ICU. Two OR schedules are constructed with the objective to level this occupation and this flow respectively. The constructed OR schedules can be compared to the current situation. The results show that the constructed OR schedules have a lower variance in both occupation of the ICU and flow of patients to the ICU. This leads to the conclusion that the ICU can be considered in constructing the OR schedule and that this is advantageous for the ICU. The schedule for the OR must be adjusted and at first sight there is no advantage for this department. However, a positive influence on the ICU is indirectly beneficial for the OR as well. For some surgical operations, the patients require post-operative care at the ICU. These surgical operations must be cancelled if there is not enough ICU capacity available. If the OR schedule is advantageous for the ICU, it possibly results in less cancellations of surgical operations due to shortage of available ICU beds. However, to analyze the actual influence on the ICU, the simulation results must be considered.

The ICU is simulated under different OR schedules. The constructed schedules from the OR scheduling model are compared to a random schedule among others. The performance of the ICU can be compared and this performance indicates the actual influence of the OR schedule on the ICU. The results show that most OR schedules result in a similar performance of the ICU. For this thesis especially the group of patients from the OR is of interest, since these patients are influenced by the OR schedule. For these patients a difference in performance can be seen. The OR schedules especially constructed to improve the interaction between the OR and the ICU, result in lower rejections at the ICU for patients from the OR. This means that fewer surgical operations have to be cancelled because of lack of ICU capacity. The main difference in performance can be seen if the schedules with a more levelled flow of patients from the OR to the ICU are compared to an extreme schedule with a very variable flow. A more smooth flow is preferred and results in a slightly better ICU performance. This leads to the conclusion that it is advantageous for the ICU to spread the patients from the OR to the ICU smoothly over time. Two OR schedules which meet this requirement, but differ in other aspects, do not differ in performance of the ICU. Therefore we can conclude that the flow of patients from the OR to the ICU is the characteristic of the OR schedule that has the largest influence on the performance of the ICU.

If a more smooth arrival of patients at the ICU would be preferred, we would expect that the OR schedule with the most smooth arrival would lead to the best performance of the ICU. However, there is no difference in performance observable between OR schedules with small differences in the variance in flow of patients. To analyze this further and to analyze the actual possibilities for improvement on the ICU performance, an artificial OR schedule is constructed. This schedule has a completely smooth flow of patients from the OR to the ICU and can thus be considered as an optimal OR schedule. The performance of the ICU under this OR schedule can be seen as an upper bound on performance. This upper bound is compared to the performance of the ICU under the other schedules. This comparison shows that the upper bound on performance is comparable to the performance of the other schedules. This means that there is not much room for improving the ICU performance by adjusting the OR schedule. Assumed is that this is caused by the long duration and large variation of the Length of Stay (LOS) at ICU. Small differences in flow of patients from the OR to the ICU due to the OR schedule are then negligible compared to the LOS.

The second part of the research question asked for the actual influence of the constructed OR schedules on the ICU performance. The results of this thesis have shown that the constructed OR schedules are beneficial for patients who visit the ICU after an elective surgical operation. These patients will be accepted to the ICU more under the new OR schedules. However, for the other types of patients there is no difference in performance or the constructed OR schedules are disadvantageous. In general we can say that the OR schedules that incorporate the patients going from the OR to the ICU are beneficial only for these patients.

Finally, we can conclude that it is possible to construct OR schedules that incorporate the interaction between the OR and the ICU. At first sight these schedules seem to be advantageous for the ICU. These results correspond to the results of similar studies in literature. This thesis also analyzes the actual influence on the ICU with a simulation study. These results also show that the constructed OR schedules are advantageous for patients who go from the OR to the ICU. A more smooth flow of these patients from the OR to the ICU is preferred. However, small differences in the OR schedules do not result in differences in ICU performance. Also for the other types of patients the OR schedules do not result in a better performance. We can thus say that the constructed OR schedules are advantageous only for the patients from the OR at ICU, but that small differences in the OR schedules do not lead to an increase in performance on the total ICU.

6.3 Further research

The results and the conclusion show that a more smooth flow of patients from the OR to the ICU results in a better performance of the ICU compared to a very variable flow. However, small differences in the variance in this flow do not result in differences in performance. It is not clear where the actual border lies in terms of improvement. Further research could investigate which differences in the OR schedule do result in differences in the ICU performance and which do not.

The performance of the ICU is measured in terms of occupation and rejection among others. The relation between occupation and rejection is two-fold. More rejected patients will result in a lower occupation. A lower occupation on the other hand, allows more patients to be accepted and thus results in lower rejections. Both reactions can be seen in the simulation results if the results of rejection and occupation are compared. Further research could focus on the relation between these two performance measures. This could lead to a better understanding and could provide guidelines for the trade-off that has to be made between occupation of the ICU and rejection of patients.

6.4 Recommendations

The research performed in this thesis was commissioned by the Erasmus MC. Data of this hospital is used to construct the OR schedules and to simulate the ICU. In the Erasmus MC currently the OR schedule is constructed independently of the ICU. Assumed was that this leads to (unnecessary) cancellations of surgical operations. An OR schedule which takes the ICU into account is expected to reduce the number of cancellations.

To test this assumption OR schedules are constructed which take the ICU into account. To analyze the actual influence on the ICU, a simulation study is performed. This study shows that a levelled flow of patients from the OR to the ICU is preferred to a flow with a very high variance. The OR schedule is constructed with a cycle time of a week. In the Erasmus MC per week on average 5 patients go to the ICU after an elective surgical operation. For the ICU it is advantageous if these patients are evenly spread over the week. The recommendation to the OR planning coordinators of the Erasmus MC is therefore to level the flow of patients from the OR to the ICU.

A more levelled flow of patients can be obtained in several ways. The OR schedule in this thesis uses the concept of sub surgical services, which are groups of surgical operations from the same surgical service. The surgical service can then only perform specific types of surgical operations on specific days of the week. In this way surgical operations of which the patients require with a high probability post-operative care at the ICU are distinguished from surgical operations which rarely sent a patient to the ICU. Another way to level the flow of patients from the OR to the ICU is to assign specific times in a week to surgical services where they can operate patients who require post-operative ICU care. In this way the flow of patients from the OR to the ICU can be regulated more.

Levelling the flow of patients from the OR to the ICU is only benefical for these type of patients. For the other types of patients at the ICU there are no advantages or the schedules are even disadvantageous. The hospital has to make a trade-off between the benefits and the possible disadvantages for the different types of patients.

The results of this thesis thus provide support for the assumption that an OR schedule which takes the ICU into account will result in less cancellations of surgical operations. However, in general there is not much room for improvement on the performance of the ICU. Different OR schedules result in a comparable ICU performance. The arrival at the ICU of patients from the OR is preferred to have a low variance. But small differences in variance do not result in differences in ICU performance. This means that it is not necessary for the Erasmus MC to look for the best OR schedule with the lowest variance in flow of patients. Small reductions in the variance may be preferred by the ICU, but will not result in substantial improvements in performance.

Appendix A

The OR schedules of the Erasmus MC

The Erasmus MC constructs the OR schedule on two different levels. The planning coordinators of the Erasmus MC make the OR schedule on a high level. They assign the operation rooms to the surgical services. In Table A.1 an example of such a schedule is given. This is the OR schedule used in a week in August 2012. The number of operation rooms is below average, since August is in a holiday period. But the schedule is primarily presented to given an idea how the OR schedule looks like.

The operation rooms are thus assigned to a surgical service. The doctors of the surgical services then can decide themselves which patients are operated when. This results in the OR schedule on the level of the individual patients. A small example of this schedule is presented in Table A.2.

Room	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
OK1							
OK2	URO		URO				
OK3	NEC 08:00/17:30	NEC	NEC	NEC 08:00/17:30	NEC 08:00/17:30		
OK4			OOG		OOG		
OK5							
OK6		PLC					
OK7	KNO	KNO 08:00/20:00		KNO	KNO		
OK8	PLC	PLC	PLC 08:00/20:00	PLC			
OK9		KAA	PLC	KAA			
OK10	ORT 08:00/17:30	ORT	ORT	ORT	ORT		
OK11	ONG			ONG	ORT		
OK13		URO			GYN		
OK14							
OK15	GYN		GYN 08:00/17:30	GYN	URO		
OK16	CHI	CHI	CHI	CHI	CHI		
OK17	CHI	CHI 08:00/17:30	CHI	CHI 08:00/17:30	CHI 08:00/17:30		

Table A.1: The general OR schedule of the Erasmus MC of a week in august 2012.

Duration	Patient	Gender	PatientNumber	Age	Surgical Service
OK3		**time: 08:00 - 15:30**			
300	A	(M)	1111111	65	NEC
90	B	(F)	1111112	82	NEC
OK8		**time: 08:00 - 20:00**			
120	C	(M)	1111113	73	PLC
75	D	(F)	1111114	46	PLC
360	E	(F)	1111115	37	PLC
OK11		**time: 08:00 - 15:30**			
171	F	(M)	1111116	22	ORT
180	G	(M)	1111117	23	ORT
75	H	(M)	1111118	20	ORT
OK15		**time: 08:00 - 17:30**			
560	I	(F)	1111119	53	GYN

Table A.2: A small example of an OR schedule of the Erasmus MC on the level of the individual patients.

Appendix B

The different ICU departments

The Central Location of the Erasmus MC has five different ICU departments with the following codes: 16CD, 16TH, 3ZBE, AZIC and B3IC. Table B.1 shows the distribution of the patients over the different ICU departments. Almost 95% of the patients who go to the ICU after their surgical operation go to the departments of 3ZBE and AZIC. In Table B.2 these two departments are analyzed further. This table shows that the distribution of the patients over the surgical services is comparable for the ICU departments 3ZBE and AZIC.

This thesis considers the five ICU departments as one large ICU department. To determine the total capacity, the capacities of the individual departments are added together. The ICU departments can only be theoretically joined if the different departments have a comparable flow of patients arriving from the OR. The OR schedule tries to level the flow of patients from the OR to the ICU. If these patients are then unevenly distributed over the different ICU departments, the levelling at the OR department is undone at the ICU. However, the results in Table B.1 and Table B.2 show that almost all the patients go to two ICU departments. The distribution of the patients over the different surgical services for these two departments is also similar. The ICU departments 16CD and 16TH are especially for patients of the surgical services CAR and THC respectively. For these departments there is thus no even spread of patients over the different surgical services. However, the percentage of the patients going to the departments 16CD and 16TH is very small.

In conclusion we assume that we can consider the ICU as one large department. This assumption is justified by the comparable distribution of the patients over the surgical services in the departments 3ZBE and AZIC, which account for almost 95% of the patients going from the OR to the ICU.

Surgical service	**16CD**	**16TH**	**3ZBE**	**AZIC**	**B3IC**
ANE	0	0	0	0	0
CAR	14	1	0	2	0
CHI	0	2	153	136	0
DER	0	0	0	1	0
GER	0	0	0	0	0
GYN	0	1	5	4	0
HAE	0	0	5	0	0
INW	0	0	7	9	0
ISV	0	0	0	0	0
KAA	0	0	2	0	0
KGA	0	0	0	0	0
KNO	0	0	6	5	0
LON	0	0	2	1	0
MDL	0	0	8	13	0
NEC	0	2	68	61	0
NEU	0	0	23	26	0
ONC	0	0	2	1	1
OOG	0	0	0	0	0
ORT	0	0	8	6	0
PLC	0	0	2	3	0
REU	0	0	0	1	0
RTH	0	0	0	0	0
TBV	0	0	0	0	0
THC	0	11	0	0	0
URO	0	0	2	2	0
total	14	17	293	271	1
percentage	2.35	2.85	49.16	45.47	0.17

Table B.1: This table shows the distribution over the surgical services of the patients from the OR for the ICU departments of the Erasmus MC in 2011.

	ICU departments			
Surgical service	**3ZBE (total)**	**AZIC (total)**	**3ZBE (from OR)**	**AZIC (from OR)**
ANE	0	0	0	0
CAR	11	22	0	2
CHI	240	244	158	142
DER	1	1	0	1
GER	0	3	0	0
GYN	11	14	5	6
HAE	20	16	5	0
INW	74	64	7	9
ISV	2	2	0	0
KAA	3	0	2	0
KGA	0	0	0	0
KNO	15	10	6	7
LON	39	47	2	1
MDL	50	63	9	13
NEC	132	109	71	63
NEU	110	95	29	28
ONC	4	12	2	1
OOG	1	0	0	0
ORT	11	8	8	6
PLC	4	6	2	3
REU	0	1	0	1
RTH	0	0	0	0
TBV	21	23	0	0
THC	7	11	0	0
URO	6	6	2	3
total	762	757	308	286

Table B.2: This table shows the distribution over the surgical services of the total number of patients and the patients from the OR for the ICU departments 3ZBE and AZIC.

Appendix C

Calculating the number of surgical operations performed

The number of patients that can be operated per day in an operation room of type r by sub surgical service s is defined as $n_{s,r}$. The duration of a surgical operation of sub surgical service s is assumed to be lognormally distributed with parameters μ_s^D and σ_s^D. The equations (C.1) give the theoretical mean and mode of the duration of a surgical operation of sub surgical service s. The variable v_r indicates the time available per day in an operation room of type r. The number of patients that can be operated can be calculated by dividing the available time over the duration of a surgical operation. Since it is not possible to operate patients partially, the number of operated patients must be rounded in some way. In this section rounding or rounding down are used. Normal rounding would compensate for the fact that sometimes more and sometimes less surgical operations can be performed than determined. Rounding down simply assumes that surgical operations can only be performed if they completely fit in the available time. Rounding up is not considered, since it is not possible to continuously perform more surgical operations than actually fit in the available time.

$$\begin{aligned} mean_s &= exp\left(\mu_s^D + \left(\frac{(\sigma_s^D)^2}{2}\right)\right) \\ mode_s &= exp\left(\mu_s^D\right) \end{aligned} \tag{C.1}$$

The number of patients operated can now be calculated in different ways. Using the mean duration is assumed to overestimate the duration, since the lognormal distribution is heavily tailed and very long durations can occur. The number of patients that can be operated would then be underestimated. On the other hand, the modal duration does not reflect the spread of the different durations. In this Appendix six different methods are proposed and compared. The equations (C.2) and (C.3) calculate the total number of surgical opeations that can be performed in a year. A cyclic schedule is used with a cycle time of one week and the schedule is made for 49 weeks a year. Therefore the number of operations per week must be multiplied with 49 to obtain the number of operations per year.

$$\begin{aligned} n_{s,r}^1 &= \left\lfloor \frac{v_r}{mean_s} \right\rfloor * 49 \\ n_{s,r}^2 &= \left\lfloor \frac{v_r}{mode_s} \right\rfloor * 49 \\ n_{s,r}^3 &= \left\lfloor \frac{1}{2}\left(\frac{v_r}{mean_s} + \frac{v_r}{mode_s}\right) \right\rfloor * 49 \end{aligned} \tag{C.2}$$

$$n^4_{s,r} = round\left(\frac{v_r}{mean_s}\right) * 49$$

$$n^5_{s,r} = round\left(\frac{v_r}{mode_s}\right) * 49 \quad (C.3)$$

$$n^6_{s,r} = round\left(\frac{1}{2}\left(\frac{v_r}{mean_s} + \frac{v_r}{mode_s}\right)\right) * 49$$

The sub surgical services of General Surgery (CHI) are used to compare the different methods to calculate $n_{s,r}$. The calculated $n_{s,r}$ must correspond to the number of surgical operations in a sub surgical service s, which is given by n_s. The results can be found in Table C.1. The total difference between the calculated $n_{s,r}$ and n_s are presented in the table as well.

s	p	v_r	μ_s^D	μ_s^D	n_s	$n^1_{s,r}$	$n^2_{s,r}$	$n^3_{s,r}$	$n^4_{s,r}$	$n^5_{s,r}$	$n^6_{s,r}$
1	CHI	450	4.67	0.89	148	98	196	147	147	196	196
2	CHI	450	4.70	1.01	135	98	196	147	98	196	147
3	CHI	450	4.68	1.02	135	98	196	147	98	196	147
4	CHI	450	4.58	1.06	145	98	196	147	147	245	196
5	CHI	450	4.60	1.00	145	98	196	147	147	245	196
6	CHI	450	4.98	0.84	114	98	147	98	98	147	147
7	CHI	450	4.38	0.83	207	147	245	196	196	294	245
8	CHI	450	4.47	0.91	184	147	245	196	147	245	196
9	CHI	450	4.45	0.87	191	147	245	196	196	245	196
10	CHI	570	4.83	0.98	154	98	196	147	147	245	196
11	CHI	570	4.82	0.87	169	147	196	147	147	245	196
12	CHI	570	4.65	1.00	173	147	245	196	147	245	196
$\sum_s n_{s,r} - n_s$					0	-479	599	11	-185	844	354

Table C.1: Comparison of different ways to calculate the number of operated patients.

The results in Table C.1 indeed show that using the mean duration underestimates the number of patients that can be operated. The mode duration gives an over estimation, since the large variance in duration is neglected. Formula $n^3_{s,r}$ calculates $n_{s,r}$ with the average of the mean duration and mode duration and uses rounding down. This formula results in the lowest differences with the actual number of operated patients n_s. Therefore this thesis proposes to use the formula of $n^3_{s,r}$ to approximate $n_{s,r}$. The total formula for $n_{s,r}$ then can be found in equation (C.4).

$$n_{s,r} = \left\lfloor \frac{1}{2}\left(\frac{v_r}{exp\left(\mu_s^D + \left(\frac{(\sigma_s^D)^2}{2}\right)\right)} + \frac{v_r}{exp\left(\mu_s^D\right)}\right)\right\rfloor \quad (C.4)$$

Appendix D

OR schedules used in the ICU simulation

Four different OR schedules are used to analyze their influence on the ICU. The first two schedules are constructed with the OR scheduling model, described in chapter 4. In that chapter also more information is given about the (sub) surgical services, which are the codes and numbers in the schedules.

The OR schedule in Table D.1 is constructed to level the occupation of the ICU by patients from elective surgical operations. In Table D.2 a schedule is given which aims to level the flow of patients from the OR to the ICU. Schedule 3 in Table D.3 shows the extreme OR schedule. Finally, a random OR schedule is constructed without the use of the sub surgical services. This random schedule can be found in Table D.4.

In the OR scheduling model the occupation of the ICU and the flow of patients from the OR to the ICU are determined. The last characteristic, the flow to the ICU, can also be determined for the OR schedules 3 and 4. Table D.5 shows a comparison between the four OR schedules. Only schedule 1 and 2 are constructed with the OR scheduling model. Therefore only for these two schedules the occupation of the ICU is given, as this information can be obtained from the scheduling model.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
	CHI (5)	CHI (1)	CHI (2)	CHI (4)	CHI (6)		
	KNO (21)	CHI (8)	CHI (3)	CHI (9)	CHI (7)		
	NEC (25)	KAA (18)	GYN (15)	GYN (14)	DER (13)		
	NEC (29)	KNO (19)	GYN (16)	ONG (31)	GYN (17)		
	ONG (30)	ONG (32)	KNO (20)	OOG (35)	KNO (22)		
	ORT (37)	OOG (34)	NEC (24)	ORT (36)	NEC (26)		
	ORT (38)	PLC (42)	OOG (33)	PLC (43)	ORT (41)		
	PLC (47)	PLC (45)	PLC (44)	URO (51)	PLC (46)		
	URO (53)	URO (49)	URO (50)	NEC (28)	URO (52)		
	CHI (10)	NEC (27)	ORT (39)	KNO (23)	CHI (12)		
	CHI (11)	ORT (40)	PLC (48)				
total	11	11	11	10	10		
O_i^{ICU}	3.01	3.00	3.00	2.98	3.02	2.64	2.03
F_i^{ICU}	1.66	0.69	0.74	0.62	0.72	0	0

Table D.1: Schedule 1 - An OR schedule for the sub surgical services. The objective in this schedule is to level the occupation of the ICU.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
	CHI (6)	CHI (2)	CHI (1)	CHI (5)	GYN (17)		
	CHI (7)	CHI (3)	CHI (4)	KAA (18)	KNO (19)		
	GYN (15)	CHI (9)	CHI (8)	KNO (22)	NEC (25)		
	GYN (16)	NEC (29)	DER (13)	NEC (24)	ONG (31)		
	KNO (20)	OOG (33)	GYN (14)	NEC (26)	ORT (36)		
	ONG (30)	ORT (37)	KNO (21)	ONG (32)	PLC (42)		
	OOG (35)	PLC (43)	OOG (34)	ORT (41)	PLC (44)		
	PLC (45)	URO (49)	ORT (38)	PLC (46)	URO (53)		
	URO (51)	ORT (39)	URO (52)	PLC (47)	CHI (10)		
	NEC (28)	KNO (23)	NEC (27)	URO (50)	CHI (12)		
	ORT (40)		PLC (48)	CHI (11)			
total	11	10	11	11	10		
O_i^{ICU}	2.22	2.56	2.66	3.00	3.05	2.99	2.41
F_i^{ICU}	0.80	0.96	0.68	0.91	1.07	0	0

Table D.2: Schedule 2 - An OR schedule for the sub surgical services. The objective in this schedule is to level the flow of patients to the ICU.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
	CHI (2)	CHI (6)	CHI (1)	CHI (7)	CHI (9)		
	CHI (3)	CHI (10)	NEC (26)	CHI (8)	DER (13)		
	CHI (4)	CHI (11)	NEC (27)	GYN (16)	GYN (17)		
	CHI (5)	CHI (12)	ORT (40)	KAA (18)	KNO (22)		
	NEC (28)	NEC (29)	ORT (41)	KNO (21)	OOG (35)		
	ONG (30)	URO (49)	GYN (15)	ONG (31)	ORT (38)		
	GYN (14)	KNO (23)	ONG (32)	OOG (33)	PLC (44)		
	KNO (19)	NEC (25)	ORT (39)	PLC (43)	PLC (47)		
	KNO (20)	OOG (34)	PLC (45)	PLC (46)	URO (52)		
	NEC (24)	ORT (37)	PLC (48)	URO (51)	URO (53)		
	ORT (36)	PLC (47)	URO (50)				
total	11	11	11	10	10		
O_i^{ICU}							
F_i^{ICU}	2.1680	1.8362	0.4204	0	0	0	0

Table D.3: Schedule 3 - An OR schedule for the sub surgical services. This is an extreme schedule with only patients going to the ICU at the beginning of the week.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
	CHI	CHI	CHI	CHI	CHI		
	KNO	GYN	CHI	CHI	CHI		
	KNO		CHI	CHI	CHI		
	KNO	NEC	CHI	DER	GYN		
	NEC	ONG	NEC	GYN	GYN		
	ONG	ORT	NEC	NEC	KAA		
	OOG	PLC	NEC	ONG	KNO		
	PLC	PLC	OOG	OOG	KNO		
	PLC	URO	ORT	ORT	ORT		
	URO	URO	ORT	PLC	PLC		
		URO	ORT	URO	PLC		
total	10	10	11	11	11		
O_i^{ICU}							
F_i^{ICU}	0.5848	0.7771	1.5688	0.9807	0.8735	0	0

Table D.4: Schedule 4 - An random OR schedule for the surgical services.

	Occupation ICU		**Flow to ICU**	
OR schedule	mean	variance	mean	variance
Schedule 1	2.8124	0.1377	0.6321	0.3122
Schedule 2	2.6986	0.1048	0.6321	0.2018
Schedule 3			0.6321	0.9086
Schedule 4			0.6836	0.3102

Table D.5: Comparison between the different OR schedules.

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