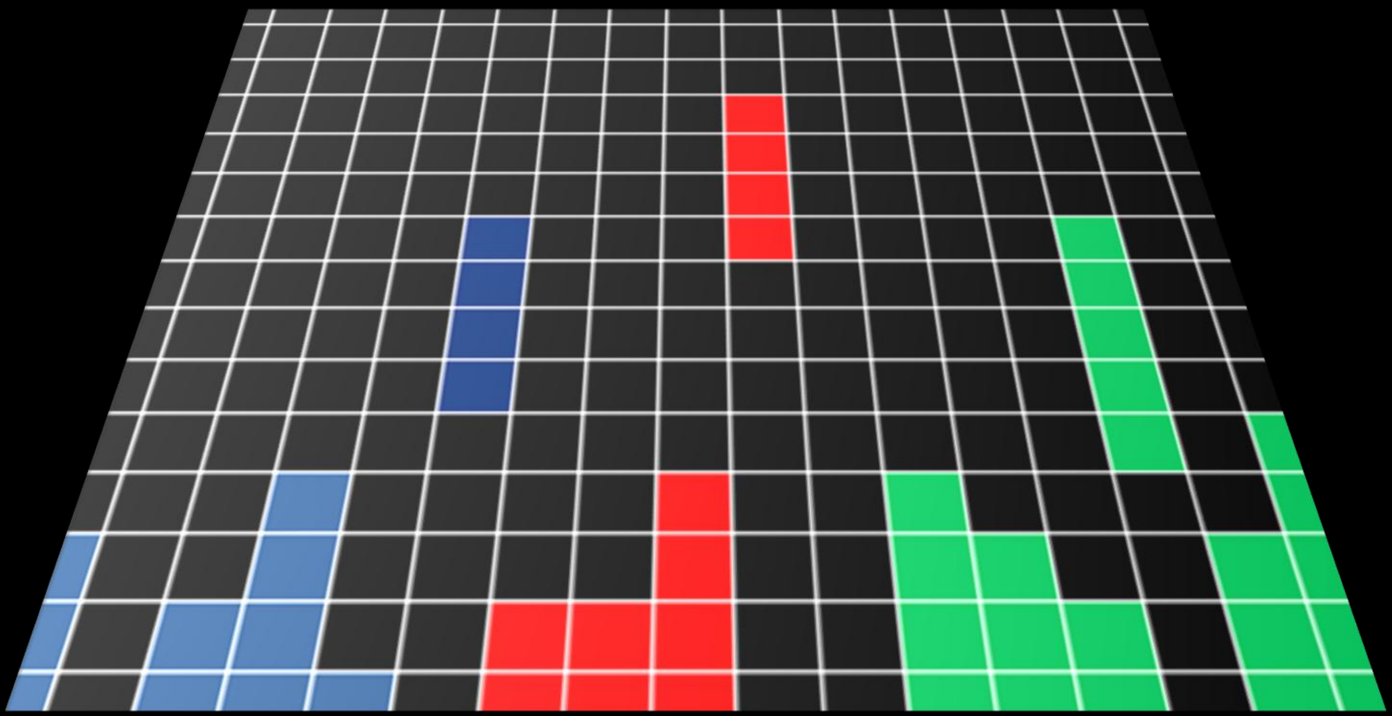
Designing a Master Surgical Schedule for Gelre Apeldoorn

Increasing the efficiency of the surgical nursing wards and leveling the workload for their nursing staff by regulating the patient flow that originates from the Operating Room department



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Preface

Before you lies my master's thesis on "Increasing the efficiency of the surgical nursing wards and leveling the workload for their nursing staff by regulating the patient flow that originates from the Operating Room department". It is the result of research conducted at the Gelre Apeldoorn hospital.

As I tried to think of a suitable cover for this report (my thanks go out to Jim Krokké for his aid in this matter), I realized that admissions planning for surgical nursing wards shows analogies with an ancient video game called "Tetris". The goal of said game was to efficiently arrange blocks of different shape and size in such a way that each horizontal line was completely filled. The order in which the blocks appeared on the screen was chosen randomly by the computer, and I still remember how blocks would appear that were impossible to fit neatly into the existing stack. How wonderful it would have been if I could determine what block appeared next...

Now, imagine that these blocks of different shape and size, are patients (no disrespect intended) that require post-surgery care at different wards and in a different quantity. In this case the goal is also to make sure that all patients fit neatly into the correct ward. How wonderful would it be if we could determine what type of patients appears each day... Well, in this case we can! The order in which patients appear is determined by the order in which patients are scheduled for surgery.

Currently, the effect the Operating Room schedule has on the surgical nursing wards is disregarded during the planning of surgeries. This leaves the staff in charge of admissions planning feeling like they are playing Tetris sometimes. In this report we show how we can transform admissions planning from a game of chance, to a logistic puzzle we can solve.

Conducting this research at Gelre Apeldoorn, in order to conclude my education in the subject of "Health Care Technology and Management" has been a gratifying experience. It was also a project with a healthy dose of setbacks and the occasional desperation. It has been an eye-opener to experience how challenging it is to structure a project of this magnitude. I can say that I have learned much, and for this I largely have my supervisors to thank.

I thank Marco Schutten for his constructive criticism and patience. Even though I was sometimes displeased with my own work, you still took the time to read it attentively. I feel you always judged my work with a high attention to detail, so that I would learn as much as possible.

I thank Erwin Hans for the many hours he freed up to help me with making adaptations to the simulation software. Next to your fast thinking and fast typing, which saved me a lot of time, I thank you for your enthusiasm. It was certainly contagious and gave me the energy to keep going each time I erroneously thought I was finished with adapting the software.

I thank Eelco Bredenhoff, for whom I performed this research, for confiding in me. Even though on occasion you did not agree with the choices I made, you still assisted me in any way you could. I enjoyed our discussions and learned much from them. I also enjoyed presenting parts of my research within the hospital on several occasions. I feel the opportunities and assistance you provided me with were not only in the interest of the research and the hospital, but also in the interest of my personal development. I appreciate all your efforts and hope that mine have made it worth your while. I also thank the other employees of Gelre Apeldoorn who I drank many a coffee with. Several people have made me feel welcome from the first day.

As I sit down and thank those that guided me throughout this final stage of my studies, it dawns on me that the coming month not only concludes my research, but a very important chapter in my life all together. I also realize that, as I conclude this chapter, I have a lot to be thankful for.

As a 17 year old, I moved to Enschede from a small village near Rotterdam. Although over the years the Netherlands seems to have gotten smaller, moving from the west all the way to the eastern border was a big step at the time. I still remember vividly how this felt like I was becoming a grown-up. The ensuing years however, proved I wasn't there by far…

Now, looking back at those years (and under the impression that I can finally call myself a man), I realize that the friends that have accompanied me in the struggle that is growing up, will doubtlessly be my friends for a lifetime. I also realize that they will never stop teasing me with their memories of that 17 year old boy I was when I met them. Nevertheless, I want to thank them for being there, through all the ups and downs this journey had in store for me.

I also want to thank my parents. It would be foolish to try and list all they have done that got me where I am today. Knowing my parents, I will just say to them that I am happy with who I have become and where I stand in life, knowing that to them, this is all the gratitude they would ever wish for.

To my brother Edwin I want to express my gratitude for the fact that he is always there for me. I know I don't call for my big brother's help as often as you think I should. But please know that the idea that someone is willing to help me with whatever ails me, is often enough. I'm proud to have you as my brother, and to have you at my back.

Of course I want to express my gratitude for the person I came home to after each long day. Kirsten: even though the past year has been especially hard on you, for multiple reasons, you still manage to produce a smile when I get home. A smile that, I can honestly say, time and time again made me forget what was troubling me. I can't express how glad I am to have had you by my side over the past years, and how excited I am to have you there during the years yet to come.

Guido Schol, July 2012

Management summary

Problem description

The amount of patients admitted to and discharged from surgical nursing wards, along with the amount of beds occupied at these wards, varies from day to day. These fluctuations are closely related to the workload of nursing staff, and are of a magnitude that they experience as unpleasant (interview with Brummelhuis, 2010, and Groters-Kremer, 2010). These fluctuations also cause inefficiency, since more fluctuation mean more beds and nursing staff are needed to cope with peaks in demand. The management believes that these fluctuations are mainly due to the current way of planning surgeries, which disregards its effect on the wards where patients recover.

Previous research in Gelre Apeldoorn (Vollebregt, 2011) showed that implementing a so called Master Surgical Schedule (MSS) can, for each specialty, level the flow of patients originating from the OR department. An MSS is a cyclical schedule, in which slots of OR-time are reserved for a specific set of surgeries, allowing surgeons to decide which patients to treat in these slots. Limiting the choice of surgeries to be performed in a slot to those with similar medical and logistical properties allows the (central) planner to design a recurring sequence of slots that optimizes the efficiency of the OR and the wards.

Vollebregt's research however, was exploratory in nature and did not take into account that wards are shared by specialties, and that some specialties use multiple wards.

Research goal

In the current research we redesign Vollebregt's method for creating an MSS and use a more realistic model to predict the impact it would have. The goal of this research is:

"Design a Master Surgical Schedule that levels the workload and increases the efficiency of the surgical nursing wards of Gelre Apeldoorn and does not deteriorate the OR department's efficiency"

In this research we model both the current ward configuration and the proposed alterations to this configuration (variant 1D, version 4.0, as determined on November 29, 2011).

Approach

We determine what surgeries make up the case-mix of Gelre Apeldoorn and what the expected surgery duration, length of stay (LOS), and annual frequency are for these surgeries, based on historical data of 2011. Surgeries that occur, on average, at least once every plan cycle of two weeks are eligible for a slot of OR-time on a specific OR on a specific day in that cycle.

To increase the percentage of the case-mix that is assigned such a slot, and to increase the MSS ability to cope with fluctuation in demand for a specific surgery, we first create sets of surgeries that use the same resources in a comparable quantity. Each set of surgeries defines a surgical case type and is assigned a number of slots corresponding to the expected demand.

We create case types from the historical data using a heuristic in which several parameters can be altered. By altering these parameters we can influence which surgeries are grouped together. We create multiple sets of case types to determine what settings are the best.

Each set of case types is used as input for Operating Room simulation and optimization software called "OR manager", currently under development by Dr. Ir. E.W. Hans of the University of Twente. Using this software we assign each case type a number of slots and optimize the sequence of these slots in a two week cycle using two variations of a heuristic (again to test which is the best). We compare the performance of the resulting Master Surgical Schedules to the current planning policy in a simulation study, also with "OR manager".

Results

It is apparent from the experiments we conduct that for both the current and proposed new ward configurations an MSS exists that levels the workload for nursing staff without deteriorating the OR performance compared to the current planning policy. It is also plausible that fewer beds would be needed in comparison to the current planning policy. However, we do not know the extent to which the capacities can be reduced.

The number of beds needed, resulting from our model, is higher than reality for two reasons (for both the current planning policy and the MSS). First, in our model, peaks in bed utilization sometimes occur that only last for a few minutes. In practice a patient would likely be discharged a few minutes earlier to prevent this peak. Second, our simulation model does not recognize what surgeries are schedule, but to what case type those surgeries belong. This artificially increases the uncertainty in length of stay. Since this affects both the current planning policy and the MSS, it does not disprove the benefits of the MSS. However, we cannot give an exact number of beds that can be saved by an MSS. The largest bed reduction in comparison to the current planning policy that results from our model is three beds in 2012 for both the current and new ward configuration.

Limitations

The most important limitation of our model is that it does not include restrictions that are imposed by the availability of surgical instruments. Whether or not an MSS can be infeasible in this respect and, if so, whether it can be made feasible without deteriorating the OR and ward performance, remains to be seen. We expect this is not a bottleneck since most surgical case types consist of a variety of surgeries. Therefore the same rules that are currently in place to assure feasibility of the schedule can be used under the MSS planning policy.

Conclusion

Our main goal was to *"Design a Master Surgical Schedule that levels the workload and increases the efficiency of the surgical nursing wards of Gelre Apeldoorn and does not deteriorate the OR department's efficiency".*

We conclude that we succeeded in this goal for both the scenario that Gelre Apeldoorn continues to use the current ward configuration and the scenario that they implement the current plans for a new ward configuration. However, there are a few important considerations.

The Master Surgical Schedules remain to be checked for feasibility judging by the available surgical instruments. Also, there are discrepancies between our model and reality. Because of this our results cannot quantify the efficiency increase and the workload leveling. However, since these discrepancies impact both our model of the current situation and our model of the MSS, we believe they do not disprove that implementing an MSS is preferable.

We investigated whether implementing an MSS makes the work of surgeons repetitive and conclude that this is not the case.

Recommendations

As a by-product of this research, the tools that enable Gelre Apeldoorn to predict the impact of an MSS also enable them to predict the impact of other organizational changes. Examples are changes in the allocation of OR-time to specialties, and the allocation of surgical beds to specialties. We suggest this is used to further perfect these allocations before a definitive MSS is created.

Also, in the final weeks of this research, plans were made to redistribute parts of the surgical case-mix between Gelre Apeldoorn, Gelre Zutphen, and the Deventer Hospital. These plans should be taken into account when creating the definitive MSS.

The outcome of the optimization step that we use to create an MSS is not constant. Because of this we believe that an even better MSS is possible than the ones we created. We recommend that multiple Master Surgical Schedules are created and compared in a simulation study each time an MSS is designed. With the tools we provide this should take no more than a day. The settings used to define surgical case types in the grouping heuristic should be maintained each time an MSS is created to minimize the changes in case type definitions. The best Master Surgical Schedules should then be assessed for possible problems with the available surgical instruments and adjusted accordingly

Management samenvatting

Probleem omschrijving

Het aantal opnamen en ontslagen dat het personeel van de chirurgische verpleegafdelingen af moet handelen varieert van dag tot dag, net als het aantal bezette bedden. Deze fluctuaties zijn sterk gerelateerd aan de werkdruk van verplegend personeel, en van een dusdanige aard dat ze als storend worden ervaren (interview met Brummelhuis, 2010, en Groters-Kremer, 2010). Deze fluctuaties zorgen ook voor inefficientie omdat er bij grotere fluctuaties meer bedden en verplegend personeel nodig zijn om deze op te vangen. Het management denkt dat deze fluctuaties vooral worden veroorzaakt door de huidige manier van operaties plannen, aangezien deze geen rekening houdt met de gevolgen voor het beddenhuis.

Voorgaand onderzoek in het Gelre Ziekenhuis (Vollebregt, 2011) toont aan dat een zogenaamd “Master Surgical Schedule” (MSS) per specialisme de stroom van patiënten die op de OK wordt gegenereerd kan afvlakken. Een MSS is een cyclisch rooster waarin operatietypen een vaste plek krijgen. Vervolgens kan de arts bepalen welke specifieke patient hij op deze plek wil behandelen. Door de keuze te beperken tot operatietypen die vergelijkbare logistieke eigenschappen hebben kan de volgorde waarin de operatietypen in de cyclus worden gepland zo worden gekozen dat deze de efficientie van het OK complex en de verpleegafdelingen optimaliseert.

Vollebregts onderzoek was echter exploratief van aard en hield geen rekening met de daadwerkelijke inrichting van het beddenhuis, waarbinnen specialismen vaak verpleegafdelingen delen, en somigge specialismen gebruik maken van meerdere verpleegafdelingen.

Doel van het onderzoek

In het huidige onderzoek herontwerpen we Vollebregts methode voor het creëren van een MSS en gebruiken we een meer realistisch model om de impact te voorspellen die het zou hebben. Het doel van het onderzoek is:

“Ontwerp een Master Surgical Schedule dat de werklast nivelleert en efficientie verhoogt voor de chirurgische verpleegafdelingen en geen afbreuk doet aan de efficientie van het OK complex”

In dit onderzoek modelleren we het huidige beddenhuis, alsmede de voorgestelde aanpassingen hierop (variant 1D, versie 4.0, zoals bepaald op 29 November 2011).

Aanpak

Op basis van de operaties die in 2011 zijn uitgevoerd bepalen we uit welke operatietypen de case-mix van Gelre Apeldoorn bestaat. Voor deze operatietypen berekenen we de verwachte operatieduur, ligduur, en jaarlijkse frequentie. De operatietypen die naar verwachting minimaal één keer per cyclus van twee weken voorkomen, komen in aanmerking voor een vaste plek in de cyclus.

Om het deel van de case-mix dat een vaste plek toegewezen krijgt te vergroten, en om het MSS minder afhankelijk te maken van de vraag naar een operatietype, creëren we eerst sets van operatietypen welke de zelfde middelen gebruiken in een vergelijkbare hoeveelheid. Elke set van operatietypen (ofwel operatiegroep) krijgt vervolgens een aantal plekken toegewezen dat overeenkomt met hun verwachte vraag.

Het creëren van operatietypen uit de historische dataset gebeurt met een heuristiek waarin verschillende parameters instelbaar zijn. Door deze parameters aan te passen beinvloeden we welke operatietypen worden gegroepeerd. We creëren verschillende sets van groepen om er achter te komen welke instellingen het beste werken.

Elke set van operatietypen dient als input voor de Operatie Kamer simulatie en optimalisatie software "OR manager", hetgeen wordt ontwikkeld door Dr. Ir. E.W. Hans van de Universiteit Twente. Deze software gebruiken we om aan elke operatie groep een aantal vaste plekken toe te wijzen in een tweewekelijkse cyclus, in een dusdanige volgorde dat het gebruik van de OK en het beddenhuis geoptimaliseerd wordt. Hiervoor gebruiken we twee varianten van een heuristiek (wederom om te bepalen wat het beste presteert). De prestaties van de resulterende MSS versies vergelijken we met de huidige manier van plannen in een simulatiestudie, tevens door gebruik te maken van "OR manager".

Resultaten

Uit de experimenten blijkt dat voor het huidige en nieuwe beddenhuis een MSS bestaat dat fluctuaties in de werklast voor verplegend personeel afvlakt zonder de OK prestaties te verminderen. Daarnaast is het aannemelijk dat het implementeren van een MSS in een beddenbesparing resulteert. We kunnen echter geen garanties geven over het exacte aantal.

Het benodigde aantal bedden dat we berkenen aan de hand van de uitkomsten van de experimenten is hoger dan in de realiteit het geval zou zijn (voor het MSS en voor het huidige beleid). Hiervoor zijn twee redenen aan te merken. Ten eerste komen er in het model soms pieken voor in de bedbezetting die slechts enkele minuten duren. In de praktijk zal er vaak een patient een paar minuten eerder worden ontslagen om deze piek te voorkomen. Ten tweede valt het totale aantal verpleegdagen hoger uit in ons model door het samennemen van operaties in operatietypen. In onze experimenten hebben beide effecten invloed op het model van de huidige situatie en het model van het MSS. Er is daarom geen rede om aan te nemen dat de voordelen van het MSS niet kloppen. Het betekent echter wel dat we geen exacte beddenbesparing kunnen geven.

In ons model was door gebruik van een MSS een beddenbesparing van drie bedden mogenlijk (bij het gebruik van het huidige beddenhuis en bij implementatie van het nieuwe). Dit verschil zou in realiteit kleiner of groter kunnen zijn.

We hebben de variatie in het werk van chirurgen onderzocht bij het gebruik van het MSS dat we creëerden voor 2012 met het nieuwe beddenhuis, om te controleren of dit repetetief zou worden. Dit blijkt niet het geval. We denken dat het invoeren van een MSS zoals wij dat creëren zou leiden tot betere werkomstandigheden voor verplegend personeel, zonder deze van de chirurgen te verslechteren. Daarnaast zijn er waarschijnlijk minder bedden nodig om het zelfde aantal patiënten te helpen.

Limitaties

De belangerijkste limitatie van ons model is dat er geen beperkingen zijn ingebouwd voor het aantal beschikbare instrumenten. Er moet dus nog worden bekeken of dit problemen kan geven bij het gebruik van een MSS. We verwachten niet dat dit een knelpunt zal zijn omdat er bij de invulling van de meeste slots keuze is uit meerdere operaties. Er kan dus alsnog worden gezorgd dat dezelfde operatie niet te vaak op de zelfde dag wordt gepland.

Conclusie

Ons hoofddoel was; *"Ontwerp een MSS dat de werklast voor verplegend personeel afvlakt en de efficientie van de verpleegafdelingen van de snijdende specialismen verhoogd, zonder de efficientie van het OK complex te schaden".*

We concluderen dat we in dit doel zijn geslaagd voor het scnenario waarin Gelre Apeldoorn de huidige beddenhuis indeling aanhoudt én het scenario waarin de plannen voor een nieuwe indeling worden geimplementeerd. Er zijn echter wel een aantal belangrijke kanttekeningen.

Er moet nog worden onderzocht of het instrumentarium problemen kan geven bij het gebruik van de MSS versies. Daarnaast kunnen we aan de hand van de resultaten van dit onderzoek nog niet nauwkeurig voorspellen hoeveel de werklast fluctuaties worden afgevlakt en hoeveel bedden er kunnen worden bespaart.

Aanbevelingen

De tools die Gelre Apeldoorn in staat stellen de impact van een MSS te voorspellen, kunnen ook worden gebruikt om de impact van andere organizationele veranderingen te voorspellen. Voorbeelden zijn het wijzigen van de verdeling van OK-tijd over specialismen, en de verdeling van bedden over specialismen. We adviseren Gelre Apeldoorn om deze allocaties eerst te optimaliseren alvorens een definitief MSS te maken.

Daarnaast worden er plannen gemaakt om delen van de case-mix uit te wissellen tussen Gelre Apeldoorn, Gelre Zutphen en het Deventer Ziekenhuis. Deze plannen zullen meegenomen moeten worden in het maken van een definitief MSS.

De optimalisatiestap die we gebruiken bij het creëren van een MSS levert niet constant een zelfde MSS op. We geloven daarom dat er MSS versies te maken zijn die beter zullen presteren dan degenen die we in dit onderzoek hebben gevonden. We adviseren Gelre Apeldoorn elke keer dat een nieuw MSS gemaakt dient te worden meerdere MSS versies op te stellen en hun prestaties te vergelijken in een simulatiestudie. De tools zijn nu aanwezig om op deze manier in een dag tot een nieuw MSS te komen. De parameters van de groeperingsheuristiek dienen elke keer het zelfde te worden toegepast zodat de "surgical case types" die worden gedefinieerd stabiel blijven. De beste MSS versie dient op haalbaarheid te worden beoordeeld met betrekking tot het instrumentarium en indien nodig te worden aangepast.

Contents

1. Introduction

In healthcare, customer service and efficiency are becoming more important than ever. Hospitals are faced with pressure to improve the quality of their services by decreasing the waiting lists and the in-process waiting times, political pressure to control national health care expenditures, and the need to control the workload of nursing staff and other personnel (Vissers & Beech, 2008). In meeting these challenges, hospitals have shown increasing interest in the application of Operations Management over the last decade (Hans et al., 2011).

Operations Management can be defined as *"the planning and control of the processes that transform inputs into outputs"* (Vissers & Beech, 2008). In manufacturing, this is widely applied and addresses *"decisions on the acquisition, utilization and allocation of production resources to satisfy customer requirements in the most efficient and effective way"* (Graves, 2002).

Operations Management in healthcare offers additional challenges in comparison to Operations Management in manufacturing. The "in- and outputs" are not resources and products, but the very customers whose demand must be satisfied. This patient flow through a hospital is subject to many forms of variability, such as response to treatment, and thus the amount of resources needed is hard to predict. This makes *"decisions on the acquisition, utilization and allocation of production resources"* all the more difficult, but also all the more important.

In this thesis, we address patient flow problems experienced at the "Gelre Apeldoorn" hospital from an Operations Management point of view. In this first chapter, we introduce Gelre Apeldoorn in Section 1.1; we introduce the problems they experience in Section 1.2; we explain where our focus lies in solving this problem in Section 1.3; we present the formal research goal of this thesis in Section 1.4, and we present the research questions along with the outline of the report in Section 1.5.

1.1 Gelre hospitals, Gelre Apeldoorn

The Gelre Hospitals (Dutch: "Gelre Ziekenhuizen") are amongst the largest hospitals in the Netherlands. They are a member of the association of tertiary medical teaching hospitals (Dutch: "STZ") in which 27 large teaching hospitals within the Netherlands are united. At these hospitals, both complex and more routine treatments are performed, whereas general hospitals focus on routine treatments and academic hospitals focus on highly complex treatments. The Gelre hospitals are located in Zutphen and Apeldoorn. Gelre Apeldoorn is the hospital where this research takes place. It is the larger of the two, with 10 inpatient Operating Rooms (ORs) and over 18,000 inpatient surgeries performed in 2011.

1.2 Problem description

The amount of patients admitted to and discharged from surgical nursing wards (from here on "wards"), along with the amount of beds occupied at these wards, varies from day to day. These fluctuations are closely related to the workload of nursing staff, and are of a magnitude that they experience as unpleasant (interview with Brummelhuis, 2010, and Groters-Kremer, 2010). These fluctuations also cause inefficiency, since more fluctuation means more beds and nursing staff are needed to cope with peaks in demand. The management believes that these fluctuations are mainly due to the current way of planning surgeries, which disregards the effects it has on the wards where patients recover.

The OR department is a major source of both income and expenditures within a hospital (Beliën et al., 2008) and as such it is often referred to as "the engine" of a hospital (Litvak & Long, 2000). Making sure that the OR department is utilized efficiently is therefore an important priority, especially given the increased pressure on hospitals to reduce operational costs. However, the activities of the OR department also have a large impact on many other parts of the hospital (Vissers & Beech, 2008). Because of the importance of filling the OR department schedule as efficiently as possible, the impact on departments such as wards often receives little attention.

Previous research at Gelre Apeldoorn by Vollebregt (2011) has demonstrated the potential to stabilize the patient flow originating from the OR department, by using a so called "Master Surgical Schedule" (MSS). We explain the properties of such a schedule in Chapter 2. Vollebregt's study was explorative in nature, aiming to determine what form of OR department planning is most promising in leveling fluctuation in the number of beds occupied (i.e. utilization) and fluctuation in admissions and discharges at wards, without deteriorating OR department performance.

Vollebregt created an MSS that is promising, but, inherent to the explorative nature of his study, his model lacks sufficient detail to accurately predict the consequences for the performance of the OR department and wards. The most important simplification is that in Vollebregt's model each specialty has its own ward. In practice, wards are shared by specialties and some specialties use beds at multiple wards. The management wants to know whether the advantages of an MSS calculated by Vollebregt hold in a model that accurately reflects reality.

Plans are currently being made at Gelre Apeldoorn to change the configuration of the wards. Therefore, the management also wants to know the performance of an MSS compared to the current planning policy upon implementation of the new ward configuration.

The management is also interested in what steps they need to take to implement an MSS and keep it up to date. The impact an MSS has on the work of surgeons (especially the impact on the diversity in surgeries they perform) is of particular interest.

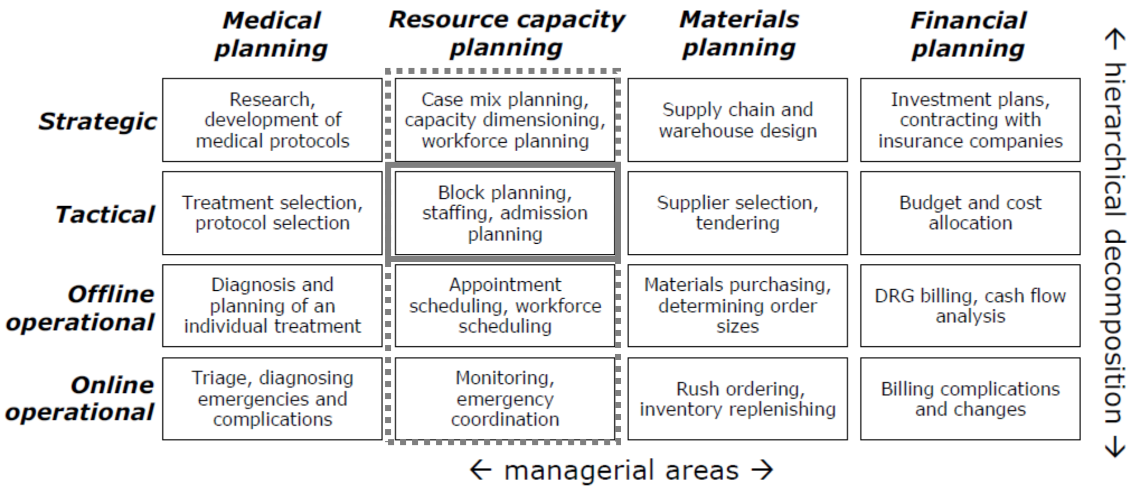
1.3 Research scope

As is apparent from the problem description, our research focuses on the performance of the wards. More specifically, our scope includes the current configuration of the wards, and the most recent plans for a new ward configuration.

Rather than focusing on workforce planning for the wards to cope with irregular patient flows, we focus on drafting a new way of planning and scheduling surgeries for the OR department to prevent irregular patient flows to the wards. We also include the performance of the OR department in our scope to ensure that it is not deteriorated by a new planning policy.

Within a hospital, there are many different planning and control functions. To clarify which functions we evaluate in this research, we use the framework presented by Hans et al. (2011) as depicted in Figure 1-1. This framework distincts between four managerial areas and four hierarchical levels. Note that the planning and control functions displayed in Figure 1-1 are examples and do not form a complete overview.

Figure 1-1 The framework for health care planning and control applied to a general hospital (Hans et al., 2011)



Planning and control functions that require clinical decision making belong to the managerial area of medical planning. The assignment of reusable resources to different tasks is the managerial area of resource capacity planning, whereas the ordering and using of consumable resources belong to the managerial area of materials planning. Managing costs and revenues belongs to the managerial area of financial planning.

Planning and control functions that regard long term decision making are said to be of the strategic level. They encompass determining the mission and long term goals of the organization. At the tactical level it is determined how the mission and goals can best be achieved, given demand predictions. Also, protocols and procedures are set, which planning and control functions at the operational levels adhere to. At the off-line operational level, short-term planning and control decisions are made based on known demand. At the on-line operational level ad hoc decisions are made to cope with circumstances that cannot be planned.

Following Vollebregt's research we aim to construct an MSS for Gelre Apeldoorn. Constructing an MSS is a resource capacity planning function at the tactical level. Although the tactical level is the main focus of proposed organizational changes, we also map the results of strategic planning since they provide restrictions for the tactical level, and we study the operational level since planning and control functions on these levels are affected by the tactical level. We treat the planning and control functions that are relevant to this research in more detail in Section 2.1.

1.4 Research goal

We summarize the problem description and research scope in the following research goal:

"Design a Master Surgical Schedule that levels the workload and increases the efficiency of the surgical nursing wards of Gelre Apeldoorn and does not deteriorate the OR department's efficiency"

In this goal, we view efficiency as how economically resources are utilized to produce a certain output. In that light, increased efficiency at the surgical nursing wards entails either treating more patients with the same amount of beds, or treating the same amount of patients while using fewer beds. Efficient use of the OR department entails a minimum of time that an OR is empty during regular working hours, along with a minimum of surgeries performed in overtime.

1.5 Research questions & outline of the report

In this section we discuss what knowledge we require to obtain our goal, according to what research questions we structure this search for knowledge, and where in this report we answer those research questions.

Q1. What are the basic principles of OR planning and what different forms of OR planning are known in the literature?

In Chapter 2, we review the literature on OR planning to gain a clear understanding of what it entails and what different approaches can be taken for this process.

Q2. What are the advantages of an MSS and which steps in constructing it are known in the literature?

Also in Chapter 2, we review the literature on Master Surgical Scheduling in particular to gain a clear understanding of what it entails, why it is a promising solution to the experienced problems, and how we can design an MSS that meets our demands as well as possible.

Q3. How can the performance of the OR department and wards be measured according to the literature?

Also in Chapter 2, we review the literature on performance measurement of wards and the OR department, to gain insight in how we can measure their performance upon using an MSS, compared to the current planning policy.

Q4. How is resource capacity planning currently done at Gelre Apeldoorn and what is the resulting performance?

In Chapter 3, we map how OR planning, and related planning and control functions, are currently done at Gelre Apeldoorn, along with the resulting performance of the OR department and the wards. We use this information to evaluate the performance of an MSS, and to understand what organizational changes are required upon implementation of an MSS.

Q5. How can we create a feasible MSS for Gelre Apeldoorn that decreases workload fluctuation and increases efficiency of the wards as much as possible?

In Chapter 4, we discuss our approach to design an MSS that decreases the problems at the wards as much as possible, and that is feasible to be implemented, given any restrictions that arise from the current situation.

Q6. How can we approach an optimal MSS and how can we predict the performance of a proposed MSS, compared to that of the current schedule?

In Chapter 5, we discuss how we conduct experiments to predict the performance of the OR department and wards under an MSS and compare it to their performance under the current planning policy. We also discuss how we structure our search for an MSS that performs as well as possible.

Q7. ***What are the benefits of implementing an MSS, compared to the current planning policy for the period of 2012-2013 with the current ward configuration and the new ward configuration?***

In Chapter 6, we show and discuss the predicted consequences of using an MSS, compared to the current planning policy for the period of 2012-2013. We investigate this period since it is the first period eligible for the implementation of an MSS. We investigate both the current and new ward configuration since it is yet to be decided which configuration will be used during that period.

In Chapter 7, we make concluding remarks on the benefits of this study along with recommendations for further research and/or actions.

2. Literature on OR planning

We define the goal of OR planning as the efficient use of resources to satisfy the demand for surgery. In this chapter we summarize the literature on how OR planning can achieve this goal, and how we can compare the OR department and ward performance of different OR planning policies.

In Section 2.1, we review the literature on OR planning as a process divided in four hierarchical levels. In Section 2.2, we review literature on tactical OR planning by means of an MSS. In Section 2.3, review the research of Vollebregt on the effects of an MSS for Gelre Apeldoorn. In Section 2.4, we review literature on performance measures for the OR department and wards.

2.1 OR planning as a multi-level problem

The literature states that OR planning is a multi-level process (Vissers & Beech, 2008; van Oostrum et al., 2009; Cardoen et al., 2010). However, there is no consensus on the number of levels that can be distinguished or to which level certain planning functions belong (Cardoen et al., 2010). In this report we use the framework of Hans et al. (2011) to structure the OR planning problem into four hierarchical levels.

According to the framework, OR planning considers the dimensioning of required resources (strategic), the allocation of resources (tactical), the forming of planning routines and rules (tactical), assigning patients to an OR on a specific date and the actual scheduling of surgeries (i.e. determining the time and sequence in which patients are treated within a day) (operational off-line), and making ad hoc changes to the schedule when needed such as the scheduling of emergency surgeries (operational on-line). In this section we discuss each of the four levels in more detail, with the emphasis on tactical OR planning as this is the main focus of this research.

2.1.1 Strategic OR planning

As mentioned earlier, strategic OR planning considers the dimensioning of required resources. According to the literature (Cardoen, Demeulemeester, & Beliën, 2010; Magerlein & Martin, 1978; van Oostrum et al., 2009), required resources for performing surgery on patients are: Operating rooms (inpatient, outpatient, or emergency), surgeons, anesthesiologists, surgical instruments, X-ray equipment, and nursing staff.

Blake and Carter (1997) address the need to include external resources in the capacity planning process, to ensure appropriate care for patients before and after surgery. External resources mentioned in the literature (Blake & Carter, 1997; van Houdenhoven, 2007; van Oostrum et al., 2009; Testi et al., 2007) are: the (surgical) nursing wards, nursing staff, intensive care unit, post anesthesia beds, outpatient departments, and central sterilization unit.

At the strategic level it is decided how much capacity is needed of these resources in order to efficiently satisfy the predicted demand for surgery.

2.1.2 Tactical OR planning

At the tactical level, boundaries are set for the scheduling of patients by allocating OR-time to specialties or surgeons. Surgeons can claim OR-time for treating a patient on a first come first served basis, which is called an open block planning approach (van Oostrum et al., 2009). Alternatively, a closed block planning approach can be used (van Oostrum et al., 2009). In such an approach, blocks of OR-time (a block typically being a morning session, afternoon session, or a full day) are assigned either to a specialty or a surgeon prior to the actual scheduling of patients (Beliën & Demeulemeester, 2007; Magerlein & Martin, 1978). An advantage of the closed block planning is a more efficient use of the ORs because surgeons can operate sequentially in the same OR (when surgeons operate in different ORs they may have to wait for another surgeon to finish in that OR before starting their own surgery). The closed block planning is the most common in Dutch hospitals (van Houdenhoven et al., 2007).

Capacity allocation at the tactical level is difficult because the demand is hard to predict. The number and type of patients that require treatment are not constant (flow variability) and the amount of resources needed to treat a patient is not constant because patients vary in degree of illness and response to treatment (clinical variability; Litvak & Long, 2000).

At the wards, the length of stay (LOS) needed for recovery varies per patient (clinical variability). Also, the arrival pattern varies (flow variability). However, at *surgical* wards this variability is not only influenced by the naturally occurring flow variability but also by OR planning. OR planning determines in what order patients from the waiting list undergo surgery, and thus, in what order patients arrive at the surgical wards. OR planning can therefore be used to level the natural occurring variability. When OR planning is done incorrectly, however, it can even add so-called artificial variability.

At the OR department the actual time a surgery takes also varies (clinical variability). When an OR is fully booked during regular working hours, there is a high probability that surgeries are finished in overtime or cancelled. To reduce this probability, slack is planned at the end of the schedule (van Houdenhoven et al., 2007). Additional slack can be planned in regular ORs for the arrival of patients in need of emergency surgery. Alternatively, an entire OR (or multiple ORs) can be reserved for emergency surgeries.

2.1.3 Operational OR planning (off-line and on-line)

At the off-line operational level, short-term decisions are made such as the date of surgery for a patient, and the sequence in which patients are received at the OR on a given day. Inherent to the short-term, more detailed demand information is available, but less flexibility in decision making exists. For instance: we can determine the amount of patients for next week much more exact than for the upcoming year, but we cannot decide to build an extra OR in a week. On the on-line operational level, ad hoc decisions are made such as the scheduling of emergency patients.

The assignment of patients to an OR on a specific date can either be done by a centralized planner or by the specialties themselves (decentralized). The centralized planner has a broader scope, which transcends that of an individual specialty and the OR department. This creates opportunities to assign OR-time more efficiently and integrate the planning of external resources such as wards. The autonomy of surgeons, however, is reduced by centralized planning (van Oostrum et al., 2009). There may be many reasons why a surgeon prefers to treat patients in a certain order, which are unknown to the central planner. If possible, the autonomy of surgeons should be maintained (van Oostrum et al., 2009). The tension between centralized and decentralized planning may be resolved by a so called “Master Surgical Schedule” as we explain in Section 2.2.

2.2 Tactical OR planning with an MSS

In this section we explain what OR planning with a Master Surgical Schedule entails (Section 2.2.1) and what approaches are known for creating an MSS in the literature (Section 2.2.2).

2.2.1 Master Surgical Scheduling: defining the concept

In a Master Surgical Schedule (MSS), slots of OR-time are reserved for a specific surgical case type (from here on “case type”) on the tactical level, allowing surgeons to decide which patient to treat in the slot. The difference between a block of OR-time and a slot of OR-time is that blocks are assigned to specialties or specialists and slots are assigned to a case type. Furthermore, the amount of OR-time assigned to a slot is linked to the expected surgery duration of the corresponding case type, while the length of a block is fixed. In the literature, a recurring sequence of blocks is sometimes referred to as an MSS (Beliën & Demeulemeester, 2007; Blake et al., 2002; Testi et al., 2007). We define an MSS as a slot planning in accordance to the definition given by van Oostrum et al. (2009).

Each case type has an expected annual demand, surgery duration, and LOS at a specific ward, based on a set of surgeries that belong to that case type. Surgeries that belong to the same case type should use the same resources in a comparable quantity. This allows the central planner to design a recurring schedule of slots (for case types) that optimizes the utilization of the OR and the wards. Since the specific surgery to plan in such a slot is not imposed by the MSS, the advantages of centralized and decentralized planning are combined (van Oostrum et al., 2009).

Increasing the choice of surgeries for a slot makes the MSS more robust against seasonal influences and less constrictive for planners. However, increasing the choice of surgeries makes the case types themselves less reliable, and therefore deteriorates the quality of the MSS. Therefore, the sets of surgeries that define case types should be as large as possible, yet have small internal variance for surgery duration and LOS.

Several methods for grouping (or clustering) surgeries into sets (case types) are found in the literature. However, some of these methods are limited to a single logistical parameter, grouping on either surgery duration or LOS at the wards (Bagirov & Churilov, 2003; El-Darzi et al., 2009). Other methods either do not make a clear trade-off between many small sets with small internal variance and a few larger sets with larger internal variance (Maruşter et al., 2002) or result in sets that are often not recognizable for planners (van Oostrum et al., 2009). Vollebregt (2011) designed a grouping heuristic that accounts for both logistical parameters.

Solution techniques for the optimal sequencing of slots mentioned in the literature are: mathematical programming, simulation, heuristics (constructive/improvement), and analytical procedures (Cardoen et al., 2010).

2.2.2 Known methods for creating an MSS

Two step-wise methods for constructing an MSS are mentioned in the literature (Testi et al., 2007; van Oostrum et al., 2009). One of these however, the three-step approach of Testi et al., considers an MSS to be identical to a block planning. Van Oostrum et al. provide an elaborate seven-step approach to create an MSS that recognizes that the desired scope for the MSS, and the desired solution techniques to apply, differ on a case-by case basis. We use this approach as a guideline to creating an MSS. The 7 steps mentioned by van Oostrum et al. to create an MSS are:

Step 1: scope of the MSS

In this step it is defined which resources and departments should be included in the MSS. The inclusion of a resource or department should result in an improved patient flow. If this is not the case it complicates the creation of an MSS without benefits.

Step 2: data gathering

In this step at least a year of (recent) historical data is gathered on all processes and resources within the scope to account for seasonal influences. The quality of the MSS relies on accurate data. This step also includes finding a way to deal with missing and polluted data. Ideally, the hospital should implement reliable ways of collecting necessary data for creating and updating the MSS.

Step 3: capacity planning

In this step it is decided how much resources are needed to treat the expected patient volume (i.e. the dimensioning of resources) and how these resources should be allocated to the specialties, for each resource within the scope of the MSS, based on the historical data.

Step 4: defining a set of recurrent standard case types

In this step it is defined what surgeries belong to the same case type. Thus, the set of all performed surgeries is disaggregated into sub-sets, each subset forming a case type. Ideally, the patient volume of each case type is large enough to assume demand for it occurs at least once each MSS cycle. The expected demand for a case type each cycle determines the amount of slots assigned to a case type.

Step 5: construction of the Master Surgical Schedule

In this step it is determined how many slots each case type is appointed per cycle, and on what OR-day these slots should be planned within the cycle.

Step 6: execute the Master Surgical Schedule

In this step the operational scheduling rules for surgeries are determined. The goal should be to schedule each patient within an appropriate slot for optimal resource utilization, yet also within an appropriate time interval, depending on the medical priority.

Step 7: update a Master Surgical Schedule

In this step it is determined how the MSS should be kept up-to-date. An MSS may become infeasible or sub-optimal through changes in resource availability or changes in the case mix. It must be determined how to adapt the MSS to such changes and how often.

2.3 Preceding research at Gelre Apeldoorn

In this section we discuss the choices made by Vollebregt in creating an MSS, structured by the steps mentioned by van Oostrum et al. (Section 2.3.1). We also discuss the results of his research (Section 2.3.2).

2.3.1 Creation of the Master Surgical Schedule

Vollebregt determined that OR planning by means of an MSS is a promising way of leveling the fluctuation in resource demand experienced at the wards. He tested this by creating different Master Surgical Schedules and comparing their performance to the current planning policy in a simulation study. His work corresponds to the execution of steps 1 through 5 of van Oostrum et al.

Step 1: scope of the MSS

Vollebregt limited the scope of the MSS to the OR department. He did measure the amount of beds required per specialty as an output of the MSS, but did not take the actual configuration of the wards into account (i.e. he disregarded that specialties use multiple wards and sometimes share wards). Therefore, the effects of an MSS on the wards are still unknown.

Step 2: data gathering

Vollebregt gathered historical data on the performed case mix in 2008. He used this data to validate his simulation model and to predict the case mix and resource demand of this case mix for 2011.

Step 3: capacity planning

Vollebregt's research focused on the tactical level of resource capacity planning. As this step concerns capacity planning on a strategic level, Vollebregt used the dimensioning and allocation of capacity as determined by the management instead of calculating it himself.

Step 4: defining a set of recurrent standard case types

Vollebregt concluded that methods for grouping case types mentioned in the literature were not able to create a set of groups from which an MSS could be constructed that improves performance of wards without damaging the performance of the OR department.

Vollebregt then created a heuristic that starts out with a historical set of surgeries, disaggregates this set into sub-sets of surgeries that use the same resources, and, within those sub-sets, evaluates which surgeries should together form a set that defines a case type, based on the quantity of resource usage.

For creating the sets which define case types he uses a greedy approach to repeatedly aggregate sets of surgeries whose expected surgery duration is most comparable, until no sets exist for which these expected durations differ less than 30%. When multiple combinations can be made that are equally comparable in expected surgery time, the heuristic favors the combination of surgeries that are most comparable in terms of expected LOS.

Contrary to other approaches mentioned in the literature, Vollebregt's approach takes into account both the use of OR time, and LOS at the wards. It also has a method of safeguarding that groups do not become too large and unrecognizable for planners.

Step 5: construction of the Master Surgical Schedule

Vollebregt found that in determining the amount of slots to assign to a case type, the performance of the MSS is hardly affected by the decision to round the calculated amount of slots up, down, or to the nearest integer.

In determining the optimal sequence of slots, Vollebregt used a constructive heuristic that randomly places slots in a feasible location within the cycle, followed by an improvement heuristic that randomly swaps and moves slots between different days of the cycle. This improvement heuristic accepts the swap if it is feasible and if the optimization criterion is not deteriorated.

Vollebregt used three different optimization criteria: the standard deviation of OR utilization, the standard deviation of ward utilization, and the standard deviation of admissions and discharges. He concluded that using the standard deviation of ward utilization as optimization criterion resulted in the best performing MSS. It reduced fluctuations in ward utilization and admissions and discharges the most, while resulting in an OR performance almost identical to the OR performance under the current planning policy.

Vollebregt did not study the final two steps mentioned by van Oostrum et al., which are needed to implement an MSS.

2.3.2 Results of Vollebregt's research

Compared to the simulation of the current planning policy, the best performing MSS showed a 5% decrease in the fluctuation of the daily amount of admissions and discharges to handle (measured by the coefficient of variation). The MSS showed the same average daily peak utilization of the wards. The day to day fluctuation of the peak utilization (measured by the coefficient of variation) decreased by approximately 10%. Vollebregt used the mean peak height and the fluctuation thereof to calculate the number of beds needed to accommodate the daily peak demand on 98% of the days. The number of beds needed was 226 for the current planning policy and 213 for the MSS.

We believe that the estimation that 13 beds can be saved by using an MSS is too optimistic. It is unrealistic to aim for demand satisfaction on 98% of the days, and such a high percentage magnifies the difference between the current planning policy and the MSS. The difference between 226 and 213 beds needed is irrelevant since in practice there are less than 200 surgical beds available. Using a more realistic goal, such as demand satisfaction on 90% of the days, results in a difference of 8 beds.

Furthermore, Vollebregt uses the standard deviation of the daily peak utilization that results from his model, along with the average peak height measured in the realization. We believe this is not justified since the average peak height is influenced by the quality of the planning policy. Recalculating the savings using the average daily peak utilization that results from the model results in a predicted saving of 7 beds.

2.4 Performance measurement

In this section we discuss how we define performance from a resource capacity planning point of view (Section 2.4.1). We also present what Performance Indicators (PIs) are mentioned in the literature for judging the merits of an OR planning policy for the OR department and wards (Section 2.4.2).

2.4.1 Resource capacity planning and performance

To assess the efficiency of OR planning, we use three types of criteria as mentioned by Vissers & Beech (2008):

1. Level of resource use
2. Fluctuation in resource use
3. Violations of resource restrictions

When the level of resource use is low, resources are often idle. In this case, theoretically, a higher production can be realized with these resources. A high level of resource use is thus most efficient.

A higher level of resource use can be attained by either increasing production (if there is enough demand) or realizing the same production with fewer resources. Because there is always fluctuation in resources use, a resource use of 100% can never be attained in practice. These fluctuations can be driven by natural and artificial demand variability (see Section 2.1.2) and need to be kept to a minimum to attain maximum efficiency.

Attaining a higher level of resource use may be undesirable if this leads to violations of resource restrictions (i.e. situations where demand exceeds the capacity). Especially in healthcare, for instance in cases where there is a high medical priority, these situations need to be avoided.

2.4.2 Performance indicators for OR planning

In this section we first present the performance indicators found in the literature, and that are relevant from the resource capacity planning perspective, structured according to the three criteria of Vissers & Beech. We then present how we measure the performance of the OR department and the wards.

Table 2-1 shows performance indicators for the OR department found in the literature (van As et al., 2011[a]; Beliën & Demeulemeester, 2007[b]; Cardoen & Demeulemeester, 2007[c]; van der Bij & Vissers, 1999[d]; Cardoen et al., 2010[e]; Joustra et al., 2011[f]; van Oostrum et al., 2009[g]) along with PIs used by Vollebregt (2011)[v].

Table 2-1 Performance indicators for OR department performance found in the literature, structured according to the three performance criteria for resource capacity planning mentioned by Vissers & Beech (2008)

Criteria	Performance indicators
Level of resource use	Utilization of OR time[b,d,e,f,g,v] Underutilization of OR time[e]
Fluctuation in resource use	Deviation from surgery start time[a,c] Waiting time for emergency patients[a] Fluctuation in OR finish time[e,v]
Violations of resource restrictions	Cancellations/rescheduled surgeries due to Insufficient OR-time remaining[a,c,e,f,v] Cancellations/rescheduled surgeries due to no postoperative beds available[a,c,e,v] Surgeries started in overtime[c] Overtime[e,f,v] Percentage of (semi-)urgent patients treated within target period[f]

Table 2-2 shows performance indicators for the wards found in the literature (van As et al., 2011[a]; Beliën & Demeulemeester, 2007[b]; Cardoen & Demeulemeester, 2007[c]; Cardoen et al., 2010[e]; van Houdenhoven, 2007[h]; Ma & Demeulemeester, 2010[i]) along with PIs used by Vollebregt (2011)[v].

Table 2-2 Performance indicators for ward performance found in the literature, structured according to the three performance criteria for resource capacity planning mentioned by Vissers & Beech (2008)

Criteria	Performance indicators
Level of resource use	Utilization of beds[d,e,v] Underutilization of beds[e]
Fluctuation in resource use	Fluctuation in ward utilization[b,c,e,v] Fluctuation in admissions and discharges[v]
Violations of resource restrictions	Volume of patients misplaced[i] Patient misplaced bed days[i]

We select and adapt PIs from the literature and PIs used by Vollebregt that together cover all three criteria for measuring resource capacity planning performance mentioned by Vissers & Beech. We believe the following indicators provide enough information to judge the performance of OR planning policies by (the equations are shown in Appendix A):

OR department performance indicators

Level of resource use

Utilization of OR time - We define utilization as the total amount of time patients are in the OR during regular working hours divided by the total amount of regular working hours. We exclude emergency patients from this calculation.

Fluctuation in resource use

Fluctuation in OR finish time - We measure how much the use of ORs fluctuates by the standard deviation of the time between the last patient leaving the OR and the time the OR is scheduled to close.

Violations of resource restrictions

Cancellations due to insufficient theatre time - When the expected time needed for the surgeries scheduled in an OR exceeds regular working hours, surgeries are sometimes cancelled. We measure this indicator through the number of cancelled patients as a percentage of the total patient volume.

Overtime - We define overtime as the total amount of surgery time for elective and urgent surgeries that fell outside of regular hours as a percentage of the total amount of regular capacity available.

Ward performance indicators

Level of resource use

Average peak utilization of ward - We average, for each ward, the daily peak number of beds divided by the capacity (excluding weekends).

Fluctuation in resource use

Fluctuation in peak utilization of ward - We measure this, for each ward separately, through the standard deviation of the daily peak utilization (excluding weekends).

Fluctuation in admissions and discharges - We measure these through the coefficient of variation of the daily sum of admissions and discharges handled, separately for each ward (excluding weekends).

Violations of resource restrictions

Ward overflow - When there is no bed available for a patient at his designated ward after surgery, this is seen as a violation of resource restrictions. This indicator is the average number of patients that do not fit into the ward where they should recover (for each ward; excluding weekends).

2.5 Chapter conclusion

OR planning considers the dimensioning of required resources (strategic), the allocation of resources (tactical), the forming of planning routines and rules (tactical), assigning patients to an OR on a specific date and the actual scheduling of surgeries (i.e. determining the time and sequence in which patients are treated within a day) (operational off-line), and making ad hoc changes to the schedule when needed such as the scheduling of emergency surgeries (operational on-line) Hans et al. (2011).

In a Master Surgical Schedule (MSS), slots of OR-time are reserved for a specific case type on the tactical level, allowing surgeons to decide which patient to treat in the slot. Each case type has an expected annual demand, surgery duration, and length of stay at a specific ward, based on a set of surgeries that use the same resources in a comparable quantity. This allows the central planner to design a recurring schedule of slots (for case types) that optimizes the utilization of the OR and the wards.

Vollebregt created a heuristic that starts out with a historical set of surgeries, disaggregates this set into sub-sets of surgeries that use the same resources, and, within those sub-sets, evaluates which surgeries should together form a set that defines a case type, based on the quantity of resource usage. In determining the optimal sequence of slots, Vollebregt used a constructive heuristic that randomly places slots in a feasible location within the cycle, followed by an improvement heuristic that randomly swaps and moves slots between different days of the cycle. This improvement heuristic accepts the swap if it is feasible and if the optimization criterion is not deteriorated. Vollebregt used three different optimization criteria, and concluded that using the standard deviation of ward utilization as optimization criterion resulted in the best performing MSS.

Compared to the current planning policy, the best performing MSS showed a 5% decrease in the fluctuation of the daily amount of admissions and discharges to handle (measured by the coefficient of variation). The MSS showed the same average daily peak utilization of the wards. The day to day fluctuation of the peak utilization (measured by the coefficient of variation) decreased by approximately 10%. Vollebregt used the mean peak height and the fluctuation thereof to calculate the number of beds needed to accommodate the daily peak demand on 98% of the days. The number of beds needed was 226 for the current planning policy and 213 for the MSS. However, we believe a predicted savings of 7 beds is more realistic based on his results.

3. Current situation

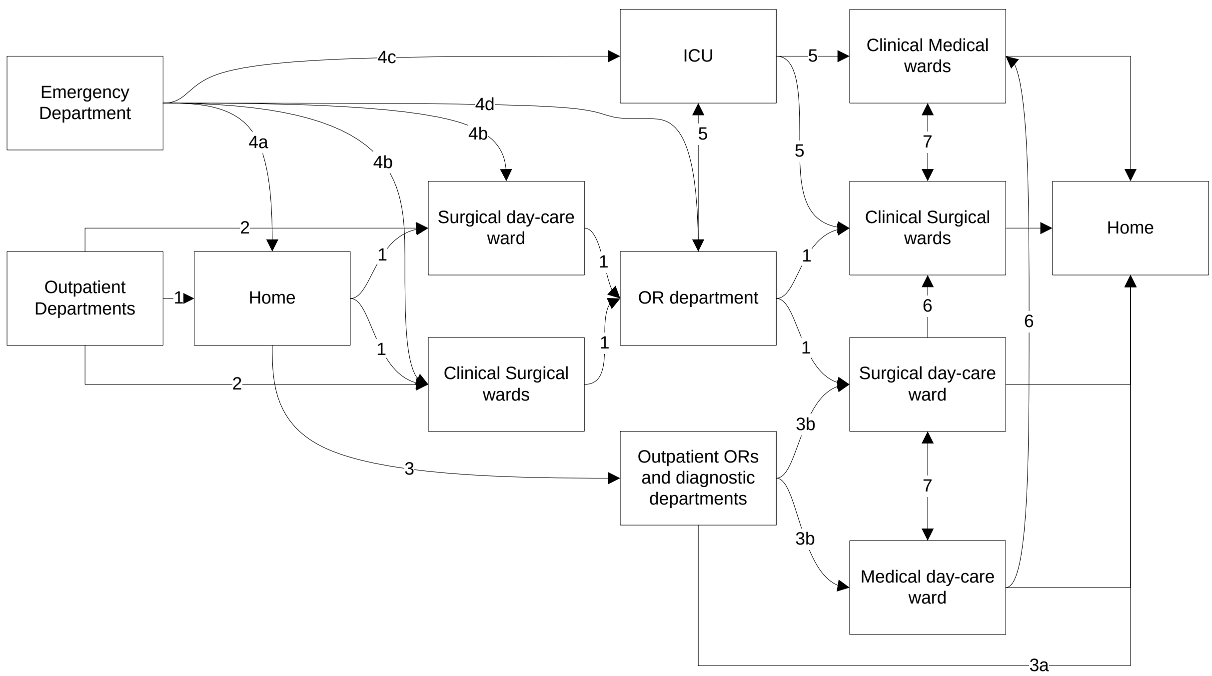
In this chapter we describe how the flow of surgical patients through the hospital is currently regulated. In Section 3.1 we describe what departments the patients visit and in what order. In Sections 3.2 through 3.5 we describe how OR planning is currently done at Gelre Apeldoorn to manage those patient flows. We structure these sections according to the 4 hierarchical levels of planning and control as mentioned by Hans et al. (2011).

3.1 Process description

Gelre Apeldoorn divides surgical cases into three categories based on their medical priority. Each priority has a different planning horizon. For elective cases, planners aim to schedule the surgery within 7 weeks from the time the patient is placed on the waiting list. It is the patient's prerogative to undergo surgery on a later date. For urgent cases, this planning horizon is two weeks. For emergency cases, this planning horizon is 24 hours. Emergency cases also include rare, immediately life threatening cases, for which an ongoing surgery is cancelled if no OR is available.

We depict the various departments surgical patients visit in Figure 3-1, along with the order in which patients visit these departments. Patient flows are represented by numbered arrows that we explain further after the figure.

Figure 3-1 Patient flows through departments influencing bed occupancy of the surgical wards



1) Usually a patient has an appointment at the outpatient department and, if surgery is deemed necessary, the patient is placed on a waiting list and returns home. Patients are planned for admission to the appropriate ward once they reach the top of the waiting list. Before admission, patients have visited the hospital for pre-surgery screening, to assess whether the patient is fit enough for surgery. After admission, the patient is brought to the OR department to undergo surgery, and afterwards, brought back to the ward for recovery. The standard procedure is that patients are admitted to a ward on the day the surgery is scheduled and brought to the OR department an hour in advance.

2) Should examination at the outpatient department reveal the necessity for the patient to be operated within 24 hours, the patient is sent directly to the ward to await surgery.

3) Some surgeries do not require patients to recover at a ward. These surgeries are performed at one of the outpatient ORs after which they can return home (3a). Note however, that some patients that undergo surgery at an outpatient OR do make use of a bed at a day-care ward. For some solely diagnostic purposes, patients are also required to stay at a day-care ward (3b).

4) Patients entering through the emergency department are either treated and sent home (4a), sent to a ward to await surgery if there is need for surgery within 24 hours (4b), sent to the Intensive Care unit (ICU) (4c), or sent directly to the OR department if the surgery has to be performed instantaneously (4d).

5) Patients that are admitted to the Intensive Care Unit sometimes also require surgery. In that case patients are sent to the OR department for surgery and back to the ICU. As soon as the need for intensive monitoring of the patients is over, the patient is sent to an appropriate clinical ward. Patients admitted to a “normal” ward can also enter the ICU if complications arise during surgery, which create a necessity for intensive monitoring of the patient after surgery.

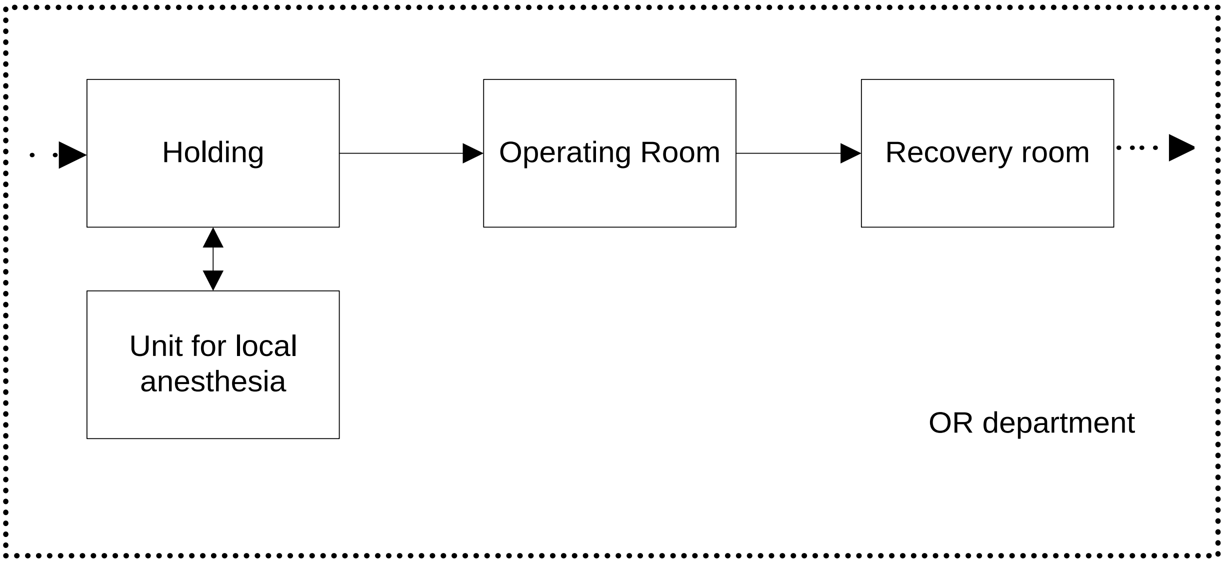
6) If a patient recovering at a day-care ward cannot be discharged at the end of the day, the patient is transferred to a clinical ward for overnight stay.

7) Sometimes medical wards harbor surgical patients, and vice versa, if one has a shortage of capacity and the other has capacity to spare.

The routing possibilities for patients inside the OR department are depicted in Figure 3-2. Patients are received at the holding, in their hospital bed, to await surgery. When the OR is prepared, the patient is brought to the OR and transferred from the hospital bed onto the operating table. After surgery the patients are transferred back into their hospital bed and brought to the recovery room while anesthesia wears off. Anesthesia is administered either in the Operating Room or, for local anesthesia such as an epidural, in advance at the unit for local anesthesia.

As an exception to this situation, patients that are sent to either the OR dedicated to Ophthalmology or the OR dedicated to Anesthesiology, visit only the Operating Room.

Figure 3-2 Patient flow through the Operating Room department



3.2 Strategic OR planning

Case mix planning is done by the board of directors in deliberation with insurance companies.

The capacity dimensioning of resources that are used to treat surgical patients is done by the board of directors and the CEOs of the 4 main business units. Business unit Apeldoorn (Resultaat Verantwoordelijke Eenheid in Dutch), Business unit Zutphen, Shared service center for medical support services, and Shared service center for general support services.

Case mix planning

As a rule, the management anticipates a 3% growth of the elective and urgent surgery volume each year. This growth is assumed to be equal for all segments of the case mix unless information is available that suggests otherwise.

Dimensioning of OR department resources

Gelre Apeldoorn has an OR-department with 10 inpatient ORs and no dedicated emergency ORs. Outside the OR complex there are 3 outpatient ORs. The standard working hours for the inpatient ORs are Monday to Friday from 8 AM to 4 PM.

Time to use an inpatient OR (OR-time) is allocated to ten different specialties (see Table 3-1), of which 1 (General surgery) consists of four sub-specialties. Important resources of the OR department that need to be shared by these specialties (apart from the OR-time) are the 3 mobile X-ray machines.

Table 3-1 List of specialties that make use of inpatient ORs

Specialties
Anesthesiology
Ear - Nose - Throat (ENT)
General surgery - Gastroenterological surgery - Oncology - Trauma surgery - Vascular surgery
Gynecology & obstetrics
Ophthalmology
Oral surgery
Orthopedics
Pediatrics
Plastic surgery
Urology

Dimensioning of ward resources

There are 343 clinical beds and 54 beds for day-care. These beds are divided over 16 wards. 8 of these wards are dedicated to medical specialties, 4 are dedicated to surgical specialties, and 4 are dedicated to both (see Table 3-2). The wards derive their names from their location in the hospital (wing & floor). We will call beds assigned to surgical and medical specialties surgical beds and medical beds respectively.

Table 3-2 Current dimensioning of ward resources ("beddenplan" 2010)

<table>
<tr><th>Ward</th><th>Surgical beds</th><th>Medical beds</th></tr>
<tr><td>A4</td><td></td><td>33</td></tr>
<tr><td>A5</td><td></td><td>33</td></tr>
<tr><td>B5</td><td></td><td>33</td></tr>
<tr><td>B6</td><td></td><td>33</td></tr>
<tr><td>A6</td><td>33</td><td></td></tr>
<tr><td>A7</td><td>33</td><td></td></tr>
<tr><td>B7</td><td>33</td><td></td></tr>
<tr><td>A8</td><td></td><td>18</td></tr>
<tr><td>B8</td><td>17</td><td>16</td></tr>
<tr><td>Geriatrics ward</td><td></td><td>10</td></tr>
<tr><td>C2 (day-care)</td><td></td><td>20</td></tr>
<tr><td>D2 (day-care)</td><td>34[1]</td><td></td></tr>
<tr><td>Child/Youth ward</td><td colspan="2">28[2]</td></tr>
<tr><td>Woman/Child ward</td><td colspan="2">15</td></tr>
<tr><td>A2 (ICU)</td><td colspan="2">12</td></tr>
<tr><td>B4 (CCU)</td><td></td><td>17</td></tr>
</table>

[1] including 5 chairs used for ophthalmology patients

[2] 18 clinical & 10 day-care

3.3 Tactical OR planning

Given the capacity dimensioning on the strategic level, the available capacity is allocated to the specialties on the tactical level.

Allocation of OR department capacity

The division of OR department capacity is currently done through a closed block-planning approach. As explained in Section 2.1, this entails that blocks of OR-time (a block being a morning session, afternoon session, or a full day) are assigned either to a specialty or a surgeon prior to the actual scheduling of patients. At Gelre Apeldoorn the block planning on the specialty level is done centrally. The division of OR-time amongst surgeons is decided upon by the specialties themselves.

The division of OR blocks amongst specialties is standardized in a recurring cycle of two weeks. In a monthly meeting of the committee “planning group OR capacity” (Dutch: planningsgroep OK capaciteit), it is decided whether changes in this division of OR blocks are needed. In practice the division is quite stable. This group consists of the manager of patients logistics, the head of admissions and OR planning, the OR board, the head of the OR, and the manager of surgical specialties. We adhere to the current block planning to limit the amount of organizational changes needed upon implementing an MSS.

When less than 75% of an OR block is filled 14 days in advance, this block is returned to the head of admissions and OR planning. Such an OR-block is assigned to a specialty that has a long waiting list, and is able to free up a surgeon to operate during that block. The head of admissions and OR planning is also authorized to reclaim a block of OR-time if it remains unfilled and a specialty neglects return it. In practice however, this authority is hardly ever exercised.

3.4 Operational off-line OR planning

After the capacity dimensioning and allocation, the actual scheduling of patients for surgery is done on the operational off-line level.

When specialties have decided which surgeons use which OR-blocks, this allocation is sent to the centralized department for admission- and OR planning. This department schedules patients from the waiting list of the various surgeons into the corresponding OR blocks on a first-come first-served basis.

Surgeries for some specialties are planned by the specialties themselves (decentralized). These specialties are: Anesthesiology, Ear- Nose- Throat, Ophthalmology, Oral surgery, Orthopedics, and Plastic surgery.

Each working day the draft of the surgical schedule for that day two weeks later, is presented to the schedule-coordinator of the OR department. As a rule, 15 minutes of slack is reserved in each OR schedule at the end of the day as a buffer against overtime. On each day, a total of 200 minutes of slack is reserved for emergencies that arrive during the day or the night before. This emergency slack is divided over the schedules of Orthopedics and/or General surgery. 300 minutes of slack time is reserved for patients with an urgent demand for surgery during the two weeks leading up to an OR schedule.

The presented schedule is reviewed by the schedule coordinator on feasibility. When the schedule-coordinator approves the schedule, the department of admission- and OR planning calls the scheduled patients to inform them about their surgery date and date of admission, which is usually on the day of surgery (sometimes a day earlier, depending on the condition of the patient and the type of surgery and anesthesia). Rules are in place that limit the number of admissions to each ward.

During the deliberation with the schedule coordinator the urgent cases to plan are also discussed. When surgeries in approved schedules are cancelled by the patient, or have to be cancelled by the hospital, this is also discussed. When time reserved for urgent patients is not filled two days in advance, this time is used for elective patients. On the other hand, when there is no room for an urgent patient within the two week planning horizon, elective surgery is cancelled to free up OR time.

3.5 Operational on-line OR planning

Apart from the schedule-coordinator, who is consulted for the surgical schedules from the next day until 14 days from the current day, there is also a schedule coordinator responsible for the ongoing schedule of the current day. For clarity we refer to this person as the day-coordinator.

Ad hoc changes to the surgery schedule are sometimes needed to prevent resource conflict or overtime, or when an emergency patient enters the hospital. These planning and control functions are performed at the OR department by the schedule-coordinator, for the schedule of the next day, and by the day-coordinator, for the schedule of the present day. The scheduling of emergency surgeries is done by the day-coordinator in coordination with the anesthesiologist on duty. Cancelling scheduled surgeries for the present day is also the responsibility of the day-coordinator.

Each working day (at half past 11) the ward managers and the manager of patients logistics discuss where beds are available for emergency admissions, should they arise.

3.6 Current performance

In this section we present the performance of the OR department and wards, resulting from the current OR planning policy, according to the performance indicators that we defined in Section 2.4. We present only the performance of those wards that harbor mainly surgical patients, as their performance is the result of the OR policy.

We calculate the utilization of OR time as the total amount of surgery (including emergencies) during regular hours, as a percentage of the available regular capacity. Data on cancelled surgeries due to insufficient OR-time is unavailable since those surgeries are removed from the information system. The overtime is calculated by the amount of surgery time performed after the regular hours, of surgeries that started inside regular hours (also including emergencies). Note that this differs from our “overtime” performance indicator, but this was the only overtime measure available. Data on the opening hours of the ORs was incomplete and therefore we cannot measure the performance indicator “fluctuation in OR finish time”.

The hospital information system uses so called "admission movements" to register the admission of a patient to a ward. Such a movement is activated upon admission of the patient, and deactivated upon discharging of the patient. We map the number of beds occupied at each ward, throughout 2011 (excluding weekends), by taking a sample of the number of admission movements that are active every 10 minutes. The "average peak utilization of ward" is for each ward, the average of the highest value we measure at each day. The "fluctuation in peak utilization of ward" is for each ward, the standard deviation of the highest value we measure each day. We determine the number of admissions and discharges each day by sampling each 10 minutes, how many admission movements are active that were not active in the previous sample, and how many are no longer active that were active during the previous sample. We use the daily sums of these samples to calculate the performance indicator "fluctuation in admissions and discharges". We could not measure the ward overflow because it is not registered whether a patient recovers at the correct ward. Table 3-3 shows the performance data we were able to determine.

Table 3-3 Current performance

Performance Indicators	Realization of 2011
Utilization of OR time (including emergencies)	76,4%
Cancellations due to insufficient theatre time	Data unavailable
Overtime (including emergencies)	4,5%
Fluctuation in OR finish time	Data unavailable
Average peak utilization of ward:	
- **A6**	74,8%
- **A7**	85,9%
- **B7**	82,6%
- **B8**	74,8%
- **D2**	96,1%
Fluctuation in peak utilization of ward (standard deviation):	
- **A6**	7,7%
- **A7**	13,1%
- **B7**	11,6%
- **B8**	20,1%
- **D2**	20,3%
Fluctuation in admissions and discharges of ward (coefficient of variation):	
- **A6**	40,0%
- **A7**	26,4%
- **B7**	25,0%
- **B8**	35,6%
- **D2**	27,3%
Ward overflow	Data unavailable

3.7 Chapter conclusion

In this section we recap the most important aspects of the current situation at Gelre Apeldoorn.

Gelre Apeldoorn divides surgical cases into three categories based on their medical priority. Each priority has a different planning horizon. For elective cases, urgent cases, and emergencies the planning horizons are 7 weeks, 2 weeks, and 24 hours respecitively.

Gelre Apeldoorn has an OR-department with 10 inpatient ORs and no dedicated emergency ORs. Time to use an inpatient OR (OR-time) is allocated to ten different specialties, of which 1 (General surgery) consists of four sub-specialties. Important resources of the OR department that need to be shared by these specialties are the 3 mobile X-ray machines.

The division of OR department capacity is currently done through a closed block-planning approach. The division of OR blocks amongst specialties is standardized in a recurring cycle of two weeks.

The centralized department for admission- and OR planning schedules patients from the waiting list of the various surgeons into the corresponding OR blocks first-come first-served (for surgeries with identical medical priorities). Some specialties schedule surgeries themselves (decentralized).

Each working day the draft of the surgical schedule for two weeks later, is presented to the schedule-coordinator of the OR department. As a rule, 15 minutes of slack is reserved in each OR schedule at the end of the day as a buffer against overtime. On each day, a total of 200 minutes of slack is reserved for emergencies that arrive during the day or the night before. 300 minutes of slack time is reserved for patients with an urgent demand for surgery during the two weeks leading up to an OR schedule.

The presented schedule is reviewed by the schedule coordinator on feasibility. When the schedule-coordinator approves the schedule, the department of admission- and OR planning calls the scheduled patients to let them know their surgery date and date of admission, which is usually on the day of surgery. Rules are in place that limit the number of admissions to each ward. The centralized department for admission- and OR planning and the schedule coordinator also discuss when to plan urgent cases, and how to deal with patient cancellations. When time reserved for urgent patients is not filled two days in advance, this time is used for elective patients. On the other hand, when there is no room for an urgent patient within the two week planning horizon, elective surgery is cancelled to free up OR time.

Ad hoc changes to the surgery schedule are sometimes needed to prevent resource conflict or overtime, or when an emergency patient enters the hospital. These planning and control functions are performed at the OR department by the schedule-coordinator, for the schedule of the next day, and by the day-coordinator, for the schedule of the present day. The scheduling of emergency surgeries is done by the day-coordinator in coordination with the anesthesiologist on duty. The cancelling of scheduled surgeries for the present day is also the responsibility of the day-coordinator.

4. Creation of the Master Surgical Schedule

In this chapter we describe how we create multiple Master Surgical Schedules, in order to find the one that shows the most improvement compared to the current planning policy. We structure this chapter according to the first five steps for creating an MSS by van Oostrum et al. (2009). We consider the final two steps to be managerial implications, which we treat in Chapter 6.

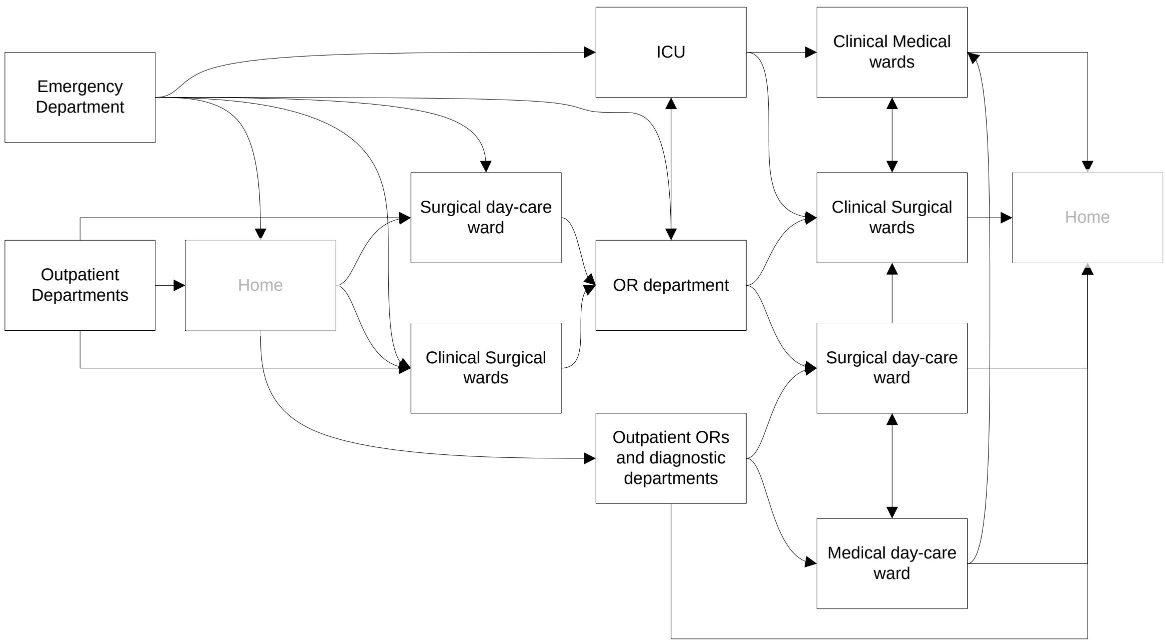
4.1 Scope of the MSS (step 1)

In this section we define the scope of the MSS. Including a resource or organizational unit in the scope of the MSS is only beneficial if it results in an improved patient flow (van Oostrum et al., 2009). In Section 4.1.1, we discuss the organizational units we include in the scope. In Section 4.1.2, we discuss the additional resources that are essential for performing surgery, that we include in the scope.

4.1.1 Organizational units within the scope of the MSS

Figure 4-1 shows the organizational units that are involved in the surgical patient flow (see Chapter 3 for an extensive description). For each organizational unit we discuss whether we add it to the scope.

Figure 4-1 Organizational units involved in the surgical patient flow



Operating Room Department

The OR department consists of the holding area, unit for local anaesthesia, recovery room, and 10 operating rooms. The capacities of the holding, recovery room, and unit for local anaesthesia are more than sufficient to fulfil the demand generated by any OR schedule, because patients remain in their own beds. We therefore exclude these from the MSS scope.

One OR is dedicated to Ophthalmology and one is dedicated to Anaesthesiology. The case-mix for these specialties is homogeneous in terms of surgery duration and LOS. Changing the surgery schedule for these specialties is of little consequence to the OR department and wards. Therefore, we include only the 8 general inpatient ORs in the MSS scope.

Wards

We divide the wards we introduced in Chapter 3 into five different types: Clinical surgical wards (A6, A7, B7), a surgical day-care ward (D2), clinical medical wards (A4, A5, A8, B4, B5, B6, F8), a medical day-care ward (C2) , and mixed wards (ICU, B8, G2, H2) at which patients of both medical and surgical specialties are treated.

The surgical wards (clinical and day-care) are all included in the scope, since it is their patient flows we aim to optimize. The surgical day-care in practice also harbours some medical patients. There is no formal allocation of beds to surgical and medical specialties. However, the number of beds available to surgical patients is stable and determined to be 20 by the head of D2 (S. Groters-Kremer, personal communication, February 29th 2012).

We do not include the medical wards (clinical and day-care) in the scope because it does not improve surgical patient flows.

At mixed wards, only the beds dedicated to surgical specialties are considered. The Child/Youth ward (G2) and the Woman/Child ward (H2), do not have a clear distinction between surgical and medical beds (see Chapter 3). Thus, for these wards we cannot exclude the medical beds. As a consequence we cannot calculate the utilisation of surgical beds at these wards. However, we can measure the fluctuation in surgical patient flow to these wards. Therefore we include G2 and H2 in the scope. A separate part of G2 is dedicated to a part of the ENT specialty case-mix. This part of G2 is excluded from the scope since those surgeries are either performed at an outpatient OR, or in dedicated time slot at the OR complex (which we also exclude from our scope).

We exclude the ICU from the MSS scope. The Intensive Care Unit has a heavy influx of patients who do not visit the OR department. Optimizing the flow from the OR department to the ICU therefore has only marginal results for fluctuation in bed utilization of this department. Furthermore, part of the surgical patient flow to the ICU cannot be optimized through an MSS because the ICU stay is not related to the performed surgery. In 2011 there were 5 surgical procedures that more often than not resulted in admission to the ICU. The 29 surgeries that contained one of these surgical procedures lead to a total of 223 nursing days at the ICU. This equals about 1 patient on average staying at the ICU, which we could perhaps regulate through an MSS.

The wards included in the scope are thus: A6, A7, B7, B8, D2, G2, and H2. Apart from the current configuration of these wards, we also create an MSS based on plans that are made to revise the current configuration of wards (variant 1D, version 4.0, as determined on November 29th 2011). In that configuration ward B8 is no longer a surgical ward and the RGC is added as a surgical ward, as we show in Section 4.3.

Outpatient ORs and diagnostic departments

Since we excluded beds that are used by patients that do not visit the OR department, we also exclude outpatient ORs and diagnostic departments from the MSS scope.

Emergency- and Outpatient departments

The goal of this research is to improve the performance of nursing wards through OR planning. Although the planning at the emergency- and outpatient departments influences the emergency surgery load and the waiting lists, it is not a part of this research and we exclude it from the MSS scope.

4.1.2 Resources within the scope of the MSS

In this section we discuss the inclusion or exclusion of resources that are essential for the treatment of surgical patients, and that are not organizational units.

The availability of surgical equipment is critical for the feasibility of an OR schedule. However, there is currently no data available on what surgical instruments are used for what surgeries. Therefore, we exclude surgical instruments from the MSS scope during the creation of the MSS. It is important to assess the feasibility of an MSS before implementation using expert knowledge.

The use of X-ray equipment is registered and therefore included in the MSS scope during its creation.

The availability of staff at the OR department and nursing wards is also critical to the feasibility of an OR schedule. We exclude staffing at the nursing wards from the scope of this research (see Section 1.3). Since we use the current block plan as a basis for the MSS, staffing at the OR is not altered and therefore excluded from the scope.

4.2 Data gathering (step 2)

To design a suitable MSS, we need data on all processes and resources within the scope of the MSS, i.e. data on the case mix, the OR department, and wards. In order to account for seasonal influences, we need data from at least one full year. We use the most recent data available, from the year 2011. We use no more than a year of data because the data of 2010 is less reliable (in 2010 Gelre Apeldoorn switched to another IT system for scheduling and registering surgeries). We exclude data from so called "reduction periods". During these periods, the capacity of the OR departments and wards is reduced (for instance during the summer holiday), meaning that an MSS we create is not feasible during these periods. In Chapter 6 we describe how surgeries should be planned during these reduction periods.

As mentioned in Section 2.1, surgeries that form a case type use the same resources. The resources in our scope are 8 general inpatient ORs, 6 wards, and the X-ray equipment. Therefore, of each surgery performed in 2011 we need to know the properties that determine: in which OR that surgery can be scheduled, at which ward the patient recovers, and whether X-ray equipment is needed for that surgery.

In which **OR** (and on which day) a surgery can be scheduled depends on how the OR-time is allocated to the (sub-)specialty that performs the surgery. Thus, of each surgery we need to know the performing sub-specialty. Also, we need to know the medical priority of each surgery, because this determines how soon a surgery should be scheduled in an OR. The patient's age is also relevant, because surgeries on children are preferable done early in the morning. Thus, the medical priority and the patient's age determine what **planning rules** apply.

At which **ward** a patient recovers depends on the patient's age (non-adults recover at the child/youth ward), whether the patient requires overnight stay (the child/youth ward has a separate section for day-care patients and for adults there is the day-care ward (D2)), and the performing sub-specialty (see Chapter 3 for the allocation of wards to specialties). The surgical procedures that are performed during the surgery are also important because ward H2 is dedicated to a specific set of surgical procedures. In Appendix N we show the order of importance for these properties in the decision at which ward a patient recovers.

Table 4-2 summarizes what logistical properties of the patient/surgery determine which resources are needed and what planning rules apply. These properties are the data we have to gather of each surgery performed in 2011.

Table 4-2 Logistical properties linked to patient/surgery characteristics

Logistical property of patient/surgery	Determines
Operating (sub-)specialty	**OR-block**
Patients age (adult yes/no) **Clinical status (day-care/ overnight stay required)** **Operating (sub-)specialty** **Surgical procedure**	**Ward**
X-ray usage (yes/no)	**X-ray usage (yes/no)**
Medical urgency (elective/urgent/emergency) **Patients age (adult yes/no)**	**Planning rules**

For surgeries to be interchangeable within an MSS slot, they must use these resources in a comparable quantity. Therefore we also need to know the surgery duration and LOS of each surgery. We describe the process of gathering and validating data on surgeries in Appendix B.

4.3 Capacity planning (step 3)

This step entails all resource capacity planning functions that precede the creation of an MSS (i.e. relevant parts of strategic and tactical planning).

Case mix

The portion of the 2011 case mix that falls within our MSS scope consists of 9274 surgeries. This excludes surgeries on patients that were already admitted to ward (for another surgery), since these surgeries do not influence ward utilization and admissions/discharges at the wards. Of these surgeries, 1645 are emergencies, 1385 are urgent, and 6144 are elective. See Appendix B for extensive case-mix information.

We assume that the elective and urgent case-mix increases annually by 3% (See Chapter 3). We define the 2012-2013 period as the period that starts after the summer holiday reduction of 2012 and ends at the start of the summer holiday reduction of 2013. This is the first period eligible for the implementation of an MSS. We therefore estimate their patient volume for the 2012-2013 period to be around 7870 ($½ * ((1385+6144) * 1,03) + ½ * ((1385+6144)*1,03^2)$). From here on we call this period 2012 for short.

According to the manager of patients logistics there is no indication that the emergency surgery volume increases annually.

Operating Room Department

Table 4-3 shows the amount of OR capacity assigned to each specialty in the current block plan. We show the division of ORs over specialties on each day of the two-week cycle in Appendix C. We show the exact amount of schedules assigned to each specialty, along with the duration of those schedules, in Appendix D. In this research we do not change the allocation of resources to specialties. Therefore, the cycle length of the MSS we create is also two weeks.

Table 4-4 Allocated OR-time to each specialty within the 2-week cycle

Specialties	OR-time (min.)	*Percentage of available capacity*
Ear-Nose-Throat (ENT)	*3240*	*9,6%*
General surgery	*12020*	*35,6%*
Gynecology & Obstetrics	*2640*	*7,8%*
Oral surgery	*960*	*2,8%*
Orthopedics	*8540*	*25,3%*
Pediatrics	*210*	*0,6%*
Plastic surgery	*3300*	*9,8%*
Urology	*2880*	*8,5%*
Total	*33790*	*100%*

Wards

The current ward configuration is under revision. Therefore we present both the current and proposed allocation.

Table 4-5 Current allocation of beds to specialties. The gray blocks indicate to which specialties the number of beds is assigned.[3]

<table>
<tr><th rowspan="2">Specialties</th><th colspan="7">Wards</th></tr>
<tr><th>A6</th><th>A7</th><th>B7</th><th>B8</th><th>G2 (Clinical)</th><th>G2 (Day-care)</th><th>D2</th></tr>
<tr><td>Ear- Nose – Throat</td><td></td><td>6</td><td></td><td></td><td rowspan="12">18</td><td></td><td rowspan="11">20</td></tr>
<tr><td>Gastroenterological surgery</td><td rowspan="2">19</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Oncology</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Trauma surgery</td><td></td><td></td><td>16</td><td></td><td></td></tr>
<tr><td>Vascular surgery</td><td>14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>General surgery (short stay)</td><td></td><td></td><td>13</td><td></td><td></td></tr>
<tr><td>Gynecology</td><td></td><td></td><td></td><td>6</td><td></td></tr>
<tr><td>Oral Surgery</td><td></td><td>1</td><td></td><td></td><td></td></tr>
<tr><td>Orthopedics</td><td></td><td>26</td><td></td><td></td><td></td></tr>
<tr><td>Plastic Surgery</td><td></td><td></td><td>3</td><td></td><td></td></tr>
<tr><td>Urology</td><td></td><td></td><td></td><td>11</td><td></td></tr>
<tr><td>Pediatrics</td><td></td><td></td><td></td><td></td><td>10</td><td></td></tr>
<tr><td>Total beds</td><td>33</td><td>33</td><td>33</td><td>17</td><td>18</td><td>10</td><td>20</td></tr>
</table>

[3]Any patient treated by a General surgeon (regardless of the sub-specialty) with an expected hospitalization up to 4 overnight stays, is regarded a "short-stay" patient

In the proposed new situation (Table 4-6), Orthopedics is harbored in the Regional Health Centre (Regionaal Gezondheidscentrum in Dutch), adjacent to the hospital. Other important changes are the combination of ENT with short-stay surgery, the combination of Vascular- and Trauma surgery, and the combination of short-stay with Urology and Gynecology.

Table 4-6 Proposed allocation of beds to specialties (version November 29th 2011). The gray blocks indicate to which specialties the number of beds is assigned.

	Wards						
Specialties	**A6**	**A7**	**B7**	**RGC**	**G2 (Clinical)**	**G2 (Day-care)**	**D2**
Ear- Nose – Throat		6					
Gastroenterological surgery	19						
Oncology							
Trauma surgery			16				
Vascular surgery			14				
General surgery (short stay)		13			18		20
Gynecology		5					
Oral Surgery		1					
Orthopedics				28			
Plastic Surgery			3				
Urology		11					
Pediatrics						10	
Total beds	**19**	**33**	**33**	**28**	**18**	**10**	**20**

4.4 Defining a set of recurrent standard case types (step 4)

In this section we describe how we determine whether the surgery duration and LOS of surgeries, that use the same resources, are similar, and thus, define a case type.

We use a grouping heuristic, based on Vollebregt (2011), which creates a set of case types as input for the MSS creation in 4 steps. We use a year of historical data on performed surgeries. To clarify the heuristic we briefly describe the 4 steps, which we also depict in Figure 4-7. We then describe each of them in more detail, explaining how each step is executed.

Step 1: Create sub-sets of identical surgeries

In this step, we disaggregate the historical set of performed surgeries into disjunctive sub-sets of surgeries that are medically homogeneous, use the same resources, and abide by the same planning rules. Each sub-set has an expected surgery duration, LOS, and annual frequency, based on the surgeries contained within the sub-set

Step 2: Verify the created sub-sets using expert knowledge

In this step, we verify the sub-sets using expert knowledge. Missing or polluted data can cause the creation of multiple sub-sets that in practice are medically and logistically identical. Therefore, in this step, we re-aggregate sub-sets that have wrongfully been separated.

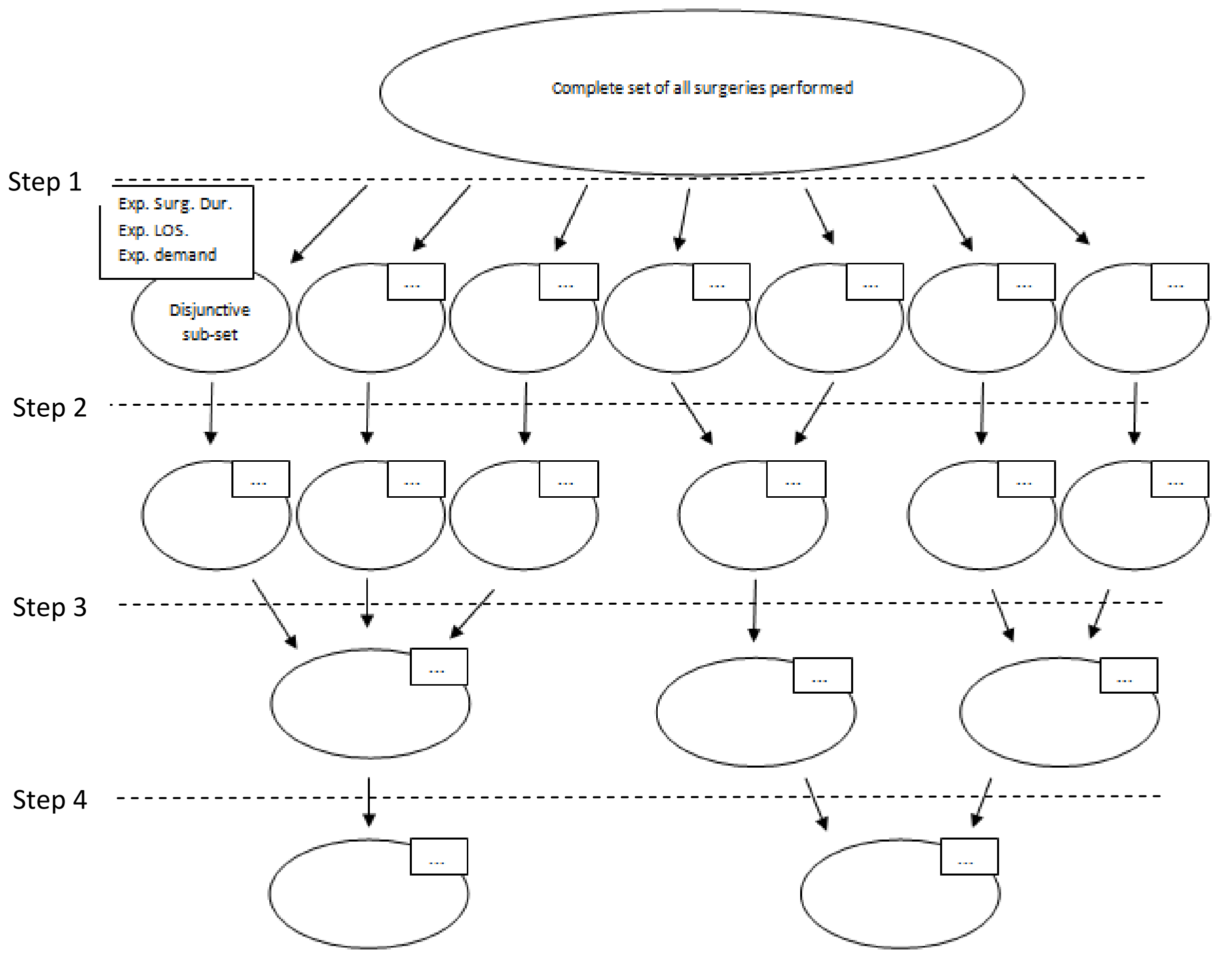
Step 3: Aggregate sub-sets that use the same resources in a comparable quantity

In this step, we compare the expected surgery duration and LOS of the sub-sets that use the same resources and abide by the same planning rules and aggregate the sub-sets that are similar, based on a threshold value.

Step 4: Create minimum sized sub-sets

In this step, we aggregate each sub-set that is too small to occur every MSS cycle, with the sub-set that is the most similar to it based on surgery duration an LOS. This step is optional. The heuristic results in a set of surgical case types that form the input for the creation of the MSS.

Figure 4-7 Schematic of the 4-step heuristic we use to define a set of case types.



We now describe each step in more detail.

Step 1: Create sub-sets of identical surgeries

The input for the heuristic consists of a historical set of performed surgeries. During a *surgery*, a set of *surgical procedures* is performed on a patient. Surgeries that consist of the same set of surgical procedures are considered *medically identical*. We disaggregate this set into disjunctive sub-sets of surgeries that are medically identical, use the same resources, and abide by the same planning rules. In Section 4.2 we explained on what patient/surgery characteristics we determine what resources are needed and what planning rules apply.[1] Each sub-set defines a case type, which has an expected surgery duration, LOS, and annual frequency, based on the surgeries contained within the sub-set.

In accordance to Strum et al. (2000), we model the expected surgery duration and LOS with a lognormal distribution. Therefore, we calculate their expected values as shown in Figure 4-1.

Figure 4-1 Equations used for calculating expected LOS or surgery duration E(x). n is the number of surgeries in a sub-set, x represents either surgery duration or LOS.

$$E(x) = e^{\alpha + 0.5\,\sigma^2}$$

$$\alpha = \frac{\sum_{i=1}^{n} ln(x_i)}{n}\ ,\ \sigma^2 = \frac{\sum_{i=1}^{n} ln(x_i - \mu)^2}{n}$$

Missing values in surgery duration or LOS are omitted. However, we do add these surgeries to the expected annual frequency of a case type.

Step 2: Check the created sub-sets using expert knowledge

We verify whether the created case types, which in this stage contain only surgeries that are medically identical, are recognizable for planners and make adjustments accordingly. Case types can for instance be unrecognizable because the surgeries within them contain a combination of surgical procedures that is in practice never planned within one surgery.

[1] In addition to Vollebregt we incorporate the medical urgency and whether a patient is an adult in this decision

Table 4-8 shows how missing or polluted data on the surgery level can lead to unrecognizable case types.

Table 4-8 Problems caused by missing or polluted data

Encountered problems in the data set	Ensuing problems at the case type level
X-ray usage for a surgery is not registered but is used in practice or vice versa.	A separate case type is created erroneously that is not scheduled in practice. The frequency of the correct case type is lower than in practice.
Registration of surgical procedures after surgery (for instance: the treatment of an unexpected bleeding during surgery).	A separate case type is created that is not scheduled in practice. The frequency of the correct case type is lower than in practice.
The performing surgeon is not registered and therefore the performing sub-specialty is unknown.	Sub-sets are created that consist of surgeries of which the performing sub-specialty is unknown. The correct sub-set is smaller and thus, the case type it defines has a frequency that is lower than in practice.
The surgery duration or LOS of a surgery is polluted.	The expected surgery duration or LOS of the case type becomes less reliable.

We treat surgery duration and LOS values that are equal to, or smaller than 0 (resulting from polluted data) as missing values. Values that are exceptionally large are likely to be the result of multiple complications or co-morbidities. Nevertheless we consider such registrations data pollution, since they are unrelated to the case type, but to patient characteristics. We define values that are larger than the sub-set average + 5 times the standard deviation as outliers. We replace these values by the largest value registered in the sub-set that is not an outlier.

All other potential problems mentioned in

Table 4-8 result in additional case types that are not used in practice. We used the expert knowledge of planners to identify and solve these problems.

Another potential problem, not related to data quality, is that some surgical procedure descriptions are not specific enough. This can lead to case types with large internal variance. Manually splitting these case types into several smaller ones might increase the quality of the case types, but was impossible with the current data set.

If after this step calculating either surgery duration or LOS is impossible for a sub-set (no surgeries with registered values), this sub-set is omitted from the data set.

Step 3: Aggregate sub-sets that use the same resources in a comparable quantity

As we explained in Section 2.2, the sets of surgeries should be as large as possible, yet have small internal variance for surgery duration and LOS. The case types we define do not have to contain surgeries that are medically identical. Even more so, we aim to define case types that are medically heterogeneous, to increase the robustness of the MSS and to increase the flexibility of the MSS for decentral planners. Surgeries that define a case type should however use the same resources (in a comparable quantity) and abide by the same planning rules.

In this step we aggregate sub-sets, that use the same resources, abide by the same planning rules, and have an expected surgery duration and LOS that is similar (based on a threshold), using a Greedy algorithm.

We start with N sub-sets that contain surgeries that use the same resources and abide by the same planning rules. We then calculate how much the expected surgery duration and LOS differ between each of the sub-sets, and aggregate the sub-sets with the smallest difference. This process is repeated for the new set of N-1 sub-sets and so forth until the smallest difference exceeds a threshold. Then we continue with the next N sub-sets that use the same resources and abide by the same planning rules.

We calculate the difference between two sub-sets (which we define as the cost of a combination) by combining the relative difference in surgery duration and relative difference in LOS into a single measure. We do so by adding the relative differences after multiplying each with a weight. These weights determine the relative importance of similarity in surgery duration versus LOS[2]. Figure 4-2 shows the equation we use.

Figure 4-2 Calculation of the difference between sub-sets "1" and "2"

$$C = \beta * \frac{\max\ (E(LOS_1), E(LOS_2))}{\min\ (E(LOS_1), E(LOS_2))} + \gamma * \frac{\max(E(surgery\ duration_1), E(surgery\ duration_2))}{\min(E(surgery\ duration_1), E(surgery\ duration_2))}$$

$$\beta + \gamma = 1$$

The optimal value for the cost “C” is thus equal to 1. Both the weight and threshold can be chosen freely[3]. This allows for the creation of different sets of case types (i.e. different sets of sub-sets). For an example of the execution of this step, see Info box 1.

[2] In Vollebregt’s heuristic, comparability in LOS was only taken into account when multiple combinations tied in terms of surgery duration comparability. In our heuristic ties hardly ever occur. When a tie does occur, the choice of which sub-sets to aggregate is considered arbitrary, and the heuristic combines the groups of which the costs were calculated first.

[3] Vollebregt used a single threshold value.

Info box 1 Example of step 3 of the grouping heuristic

We show the execution of step 3 for a set of sub-sets that contain surgeries that use the same resources, abide by the same planning rules, and are at this point medically homogeneous. We depict the numbered sets that serve as input for the example in Table 4-9.

Table 4-9 Initial set of sub-sets that are candidates for aggregation (example)

Sub-set	Patient volume	Expected surgery duration (h:mm)	Expected LOS (days)	Surgical procedures (coded)		
521	19	2:12	3,84	37111		
545	39	1:30	1,19	36915	37618	
559	39	2:53	2,34	37113		
561	14	1:08	2,38	37263	34505	32654
563	6	1:39	3,50	36916		
575	5	2:10	2,34	37265		
586	4	1:18	1,38	37052	37890	
596	4	1:54	1,27	35588		
606	9	1:13	1,97	37268		
610	9	2:01	3,27	37269		
612	61	1:38	2,58	37385		

For each combination of sub-sets we calculate the cost, and determine what combination results in the smallest cost (see Table 4-10).

Table 4-10 Cost-factors (C values) of all potential sub-set aggregations, the smallest cost-factor is marked

	521	545	559	561	563	575	586	596	606	610	612
521											
545	2,34										
559	1,47	1,94									
561	1,77	1,66	1,77								
563	1,21	2,01	1,61	1,46							
575	1,33	1,70	1,16	1,46	1,40						
586	2,23	1,15	1,95	1,44	1,90	1,68					
596	2,09	1,16	1,68	1,78	1,95	1,49	1,27				
606	1,88	1,45	1,78	1,14	1,57	1,48	1,25	1,56			
610	1,13	2,04	1,41	1,57	1,14	1,24	1,96	1,82	1,66		
612	1,42	1,62	1,43	1,26	1,19	1,22	1,56	1,60	1,32	1,25	

Info box 1 Example of step 3 of the grouping heuristic (continued)

We now execute the combination with the smallest cost-factor, and for the new set of N-1 sub-sets, again determine the smallest cost-factor upon aggregating two sub-sets, as depicted in Table 4-11.

Table 4-11 Best aggregation of sub-sets is executed and cost-factors recalculated, smallest cost is marked

	545	559	561	563	575	586	596	606	610 / 521	612
545										
559	1,94									
561	1,66	1,77								
563	2,01	1,61	1,46							
575	1,70	1,16	1,46	1,40						
586	1,15	1,95	1,44	1,90	1,68					
596	1,16	1,68	1,78	1,95	1,49	1,27				
606	1,45	1,78	1,14	1,57	1,48	1,25	1,56			
610 / 521	2,24	1,45	1,71	1,17	1,29	2,14	2,00	1,81		
612	1,62	1,43	1,26	1,19	1,22	1,56	1,60	1,32	1,36	

This process continues until no combination exists with a cost-factor smaller than the threshold. In this example the threshold is 1,20, so the aggregating of sub-sets stops in the situation depicted in Table 4-12.

Table 4-12 Threshold has been reached, smallest cost-factor is marked

	575 / 559	596 / 586 / 545	606 / 561	610 / 521 / 563	612
575 / 559					
596 / 586 / 545	1,89				
606 / 561	1,73	1,56			
610 / 521 / 563	1,46	2,17	1,69		
612	1,41	1,60	1,28	1,33	

The result is a set of five sub-sets as shown in Table 4-13.

Table 4-13Resulting sub-sets and their contents

Re-numbered sub-sets	Original sub-sets (contents)	Annual frequency	Expected surgery duration (h:mm)	Expected LOS (days)
1		**23**	**1:10**	**2,22**
	606	9	1:13	1,97
	561	14	1:08	2,38
2		**34**	**2:03**	**3,62**
	610	9	2:01	3,27
	521	19	2:12	3,84
	563	6	1:39	3,50
3		**44**	**2:49**	**2,34**
	575	5	2:10	2,34
	559	39	2:53	2,34
4		**47**	**1:31**	**1,21**
	596	4	1:54	1,27
	586	4	1:18	1,38
	545	39	1:30	1,19
5		**61**	**1:38**	**2,58**
	612	61	1:38	2,58

Step 4: Create minimum sized sub-sets (optional)

When the frequency of a sub-set is lower than the amount of MSS cycles in a year, the case type it defines is not entitled to even a single slot in the MSS, and therefore excluded from the MSS. To increase the portion of the case-mix that is included in the MSS, we combine those sub-sets with the sub-set that is most compatible. This is done analogous to step 4, but the threshold is dropped. Instead, the process stops when all sub-sets are of a minimum size.

Without the threshold that ensures a level of similarity in surgery duration and LOS the quality of the MSS may deteriorate. Since we do not yet know when it is more harmful to plan surgeries outside of the MSS, or to accept deterioration of the quality of the MSS itself, this step is optional.

4.5 Construction of the Master Surgical Schedule (step 5)

In this section we explain how we form an MSS from a set of case types, that "*levels the workload and increases the efficiency of the surgical nursing wards … and does not deteriorate the OR department's efficiency*". First, we explain how we determine the number of MSS slots to assign to each case type. Second, we explain how we determine the order in which to plan these slots throughout the MSS cycle. Third, we explain how we create different Master Surgical Schedules.

4.5.1 Number of slots

The number of slots assigned to a case type has to be an integer number, and reflect the demand for that case type. Therefore, we determine the number of slots by dividing the expected annual number of surgeries for this case type by the number of cycles, and then rounding that number. The block plan that we conform ourselves to is a two week cycle. Therefore, our MSS also has a cycle length of two weeks.

It is unclear from the literature whether it is preferable to round the number of slots up, down, or to the nearest integer. When rounding up, many surgeries are contained within the MSS and thus, their influence on OR department and ward efficiency is controlled. Slots will however regularly remain empty making the MSS less robust. Rounding down results in an MSS that is robust and reliable, but with many surgeries planned outside of the MSS. Rounding to the nearest integer results in a shortage of slots for some case types and a surplus of slots for other case types.

Vollebregt (2011) shows that rounding slots up, down, or to the nearest integer does not affect the performance of the MSS. Apparently the negative effects caused by rounding up and rounding down are of the same magnitude in the Master Surgical Schedules he created. In deliberation with the manager of patients logistics, we choose between rounding up and rounding down, since rounding to the nearest integer results in a situation that can be confusing for planners (sometimes there are too few slots, and sometimes too many). We experimented with both and found that rounding up sometimes resulted in more slots than fit in the available OR capacity, creating Master Surgical Schedules that were infeasible. Therefore we round the number of slots down.

4.5.2 Slot sequence

With the amount of slots for each case type now known, we determine the sequence of these slots in the MSS cycle. Sequencing the slots concerns assigning each slot to an OR on a day in the cycle.

For determining the best sequence for these slots we use heuristics available in a software package under development by E.W. Hans of the University of Twente called “Operating Room Manager”. This Operating Room simulation and optimization software package uses a constructive heuristic to create an initial MSS that is feasible in terms of OR utilization, but disregards the effects it has on ward utilization. After this heuristic, an improvement heuristic is used to alter the initial MSS in a way that optimizes ward utilization.

Constructive heuristic

The constructive heuristic places the slots into a 2-week cycle one by one. First, the slots are sorted, then each slot is assigned to an OR-day in this predetermined order.

In the software, the slots can either be sorted according to their expected duration or according to their duration variance (in ascending or descending order), or in a random order. They can then be placed in the 2-week cycle in the first location that fits, the location that results in the most leveled OR utilization, a random location, or the location where it fills an OR the most.

We aim to create an initial MSS that has as much room as possible for moving and swapping slots during the improvement phase. Therefore, we place each slot in such a way that the OR utilization is as leveled as possible (aiming at evenly distributed free space in the MSS). The best way to achieve this is to sort the slots by expected duration in descending order. This way we place the large slots first, while there is still a lot of room in the cycle, and place the smallest slots last, to fill in the gaps.

Where an MSS slot can be placed in the 2-week cycle (i.e. where a case type can be planned) is subject to the current block plan, i.e. we do not change the current division of OR-time to specialties. However, this should also depend on the performing sub-specialty. Therefore, in the case of General Surgery, the current block plan is made more specific, including the division of OR-time to sub-specialties. We further explain how we decide upon the division of OR-time amongst sub-specialties in Appendix E.

Improvement heuristic

During the improvement heuristic we either move 1 slot or swap two slots between different OR-days in the cycle. Only swaps between OR-days that are allocated to the same sub-specialty are allowed. After each move or swap, we calculate whether the solution has improved (i.e. we calculate the optimization criterion). In accordance with Vollebregt (2011) moves are done in 70% of the iterations and swaps in 30% of the iterations. Moves are done more often because they generally have more impact on the utilization resulting from the MSS. However, sometimes swaps are needed because there is no room to move a slot.

If the performance criterion does not deteriorate, the swap/move is accepted. As Vollebregt suggests we perform a maximum of 1.000.000 iterations of the heuristic. However, if the optimization criterion does not improve during 1000 consecutive iterations, the heuristic terminates.

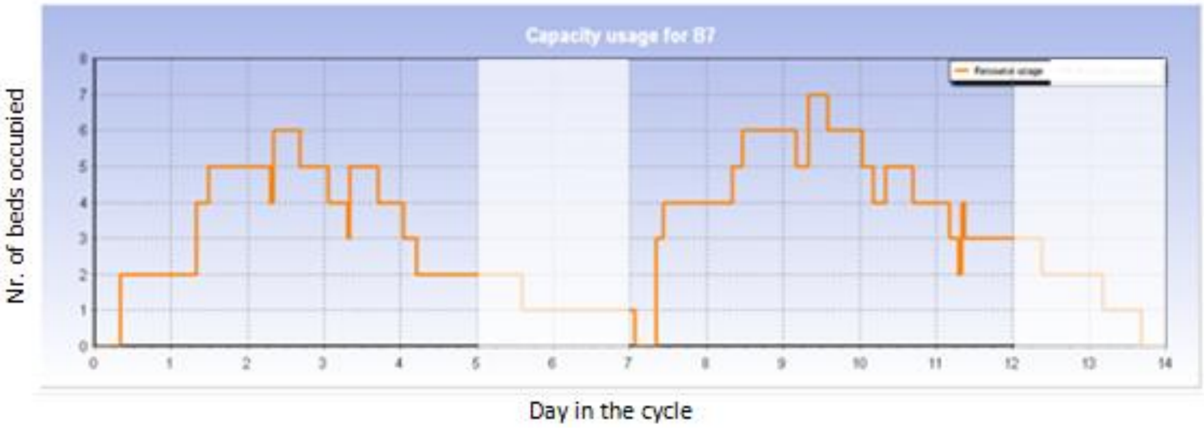
Two optimization criteria can be used in “OR manager” to determine the quality of the solution: the standard deviation the daily peak of ward utilization, or the standard deviation in the daily number of admissions and discharges. Vollebregt (2011) found that optimizing the MSS using the first option performs best. We therefore also employ that optimization criterion. We also test the performance of the heuristic using a new criterion that we add to “OR manager”: the sum of squares of the largest utilization values registered during the MSS cycle. From here on we refer to these optimization criteria as respectively the “daily peak” and “cycle peaks” optimization criterion.

We introduce this new optimization criterion because it specifically targets the peaks during the cycle that are most harmful to both the efficiency of the wards (amount of beds needed) and the workload. With the “daily peak” optimization criterion swaps are possible that do not influence these bottlenecks, yet are considered an improvement. Therefore, we expect the “daily peak” optimization criterion is more likely to “get stuck” in a local optimum instead of a global optimum. We clarify the optimization criteria through an example in Info box 2.

Infobox 2 Clarification of optimization criteria

We first show an example of how each optimization criterion is calculated. We then show why we believe the "cycle peaks" criterion is more promising. In Figure 4-3 we show the predicted number of beds used at ward B7 throughout the two week cycle (excluding weekends), resulting from an initial MSS.

Figure 4-3 Predicted number of beds occupied throughout the MSS cycle on ward B7, resulting from an initial MSS (before execution of the improvement heuristic)



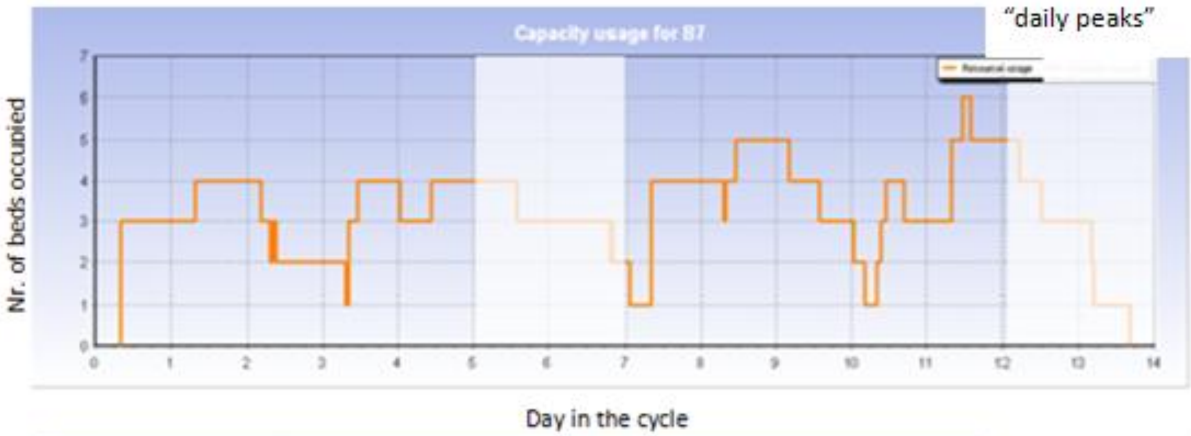
For the value of the "daily peak" optimization criterion we take the daily peak values and calculate the standard deviation of these values. In this example the daily peak values are {2,5,6,5,4,4,6,7,5,4}. The standard deviation of these values is 1,4.

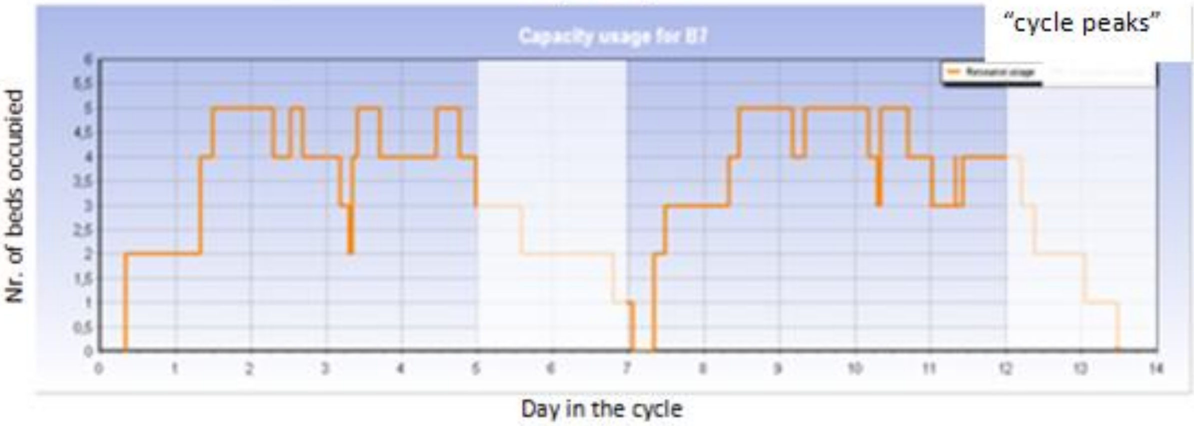
For the value of the "cycle peaks" optimization criterion we disregard the fact that the cycle consists of different days. Instead, each time the number of beds occupied changes, we add the number of beds occupied to an array. In this case this results in an array with 30 values: {0,2,4,5,4,6,5,4,…}. Of this array we take the sum of the squared largest values. We only consider the 15,9% largest values to be relevant (i.e. we assume a normal distribution and aim to prevent all peaks that are larger than the average + 1 standard deviation). In this case we consider the 5 largest values (15,9% of 30, rounded to the nearest integer) which are {7,6,6,6,5}. The value of the optimization criterion thus becomes 182. We square the largest values because we want the criterion to reflect that one very high peak is less desirable than multiple lower peaks.

Infobox 2 Clarification of optimization criteria (continued)

In Figure 4-4 we show an MSS that has been optimized using the “daily peak” optimization criterion. And an MSS that has been optimized using the “cycle peaks” criterion. Note that the y-axis is not identical in the graphs because in the software the scale is adapted to the highest peak.

Figure 4-4 Predicted number of beds occupied throughout the MSS cycle on ward B7, resulting from an optimized MSS (1000 iterations with the “daily peaks” and “cycle peaks” optimization criterion respectively)





As expected, the MSS optimized on the “daily peaks” is the best performing based on the “daily peaks” criterion, and the MSS optimized on the “cycle peaks” is the best performing based on the “cycle peaks” criterion. The optimization criterion value for the MSS optimized on “daily peaks” is 0,8 according to the “daily peaks” and 111 according to the “cycle peaks” (judged by the 4 highest values squared). The optimization criterion value for the MSS optimized on “cycle peaks” is 1,1 according to the “daily peaks” and 100 according to the “cycle peaks” (judged by the 4 highest values squared).

We believe that the MSS optimized on the “cycle peaks” criterion is favourable because it never uses more than 5 beds, whereas the MSS optimized on the “daily peaks” criterion would have a shortage of beds on day 11 with a capacity of 5 beds.

4.5.3 Master Surgical Schedules

As we explained, there are various ways to create an MSS from a set of surgery groups. Also, different sets of surgeries can be defined out of the same dataset. Ergo, we can make different Master Surgical Schedules. In this section, we present how we create different Master Surgical Schedules.

First we recap what options we have to create different Master Surgical Schedules. The grouping heuristic uses:

- A threshold value for how much expected OR time and LOS may differ in order to be grouped together
- A weighing factor indicating the importance of OR time in relation to LOS in that comparison
- An option to create minimum sized groups, with its own weighing factor for the importance of OR time in relation to LOS

From the sets of case types we create an MSS through a constructive heuristic and an improvement heuristic, using either the "daily peak" or the "cycle peaks" optimization criterion.

Ideally we would try a lot of different values for the options available in the grouping heuristic, as not to miss the optimal solution. However, by increasing the number of values we try, we increase the number of different sets of surgical groups polynomially. Therefore, we restrict the amount of values we employ. To still create Master Surgical Schedules that are dissimilar we use values that are far apart. Table 4-13 shows the values we attempt.

Vollebregt (2011) used a threshold of 30% in his grouping heuristic. He also created groups with a minimum size of 40 (a frequency of two per period). We found that with our data set, the groups created with this threshold had too much internal variance to be recognizable for planners, as did the groups created with this minimum size (as shown in Appendix F). Therefore, we search for the best threshold value in a lower range and create minimum sized groups with a lower frequency. Because of the large internal variations that can occur in this step, and because OR time is expensive, we use a high value for the weight of surgery duration if minimum sized groups are made (0,9).

Table 4-13 Parameter values we use to create different Master Surgical Schedules

GROUPING HEURISTIC			
Parameter	**Values**		
Threshold for grouping	5%	10%	20%
Weight of surg. dur. for grouping	0,50	0,66	0,80
Minimum group size	20	1	
IMPROVEMENT HEURISTIC FOR SLOT SEQUENCE			
Parameter	**Values**		
Optimization criterion	Daily peak	Cycle peaks	

With this approach we create 18 sets of case types and 36 Master Surgical Schedules of which we evaluate the performance.

4.6 Chapter conclusion

In this chapter we explained how we executed the first five steps for making an MSS. In step 1 (scope of the MSS) we confine the scope of our MSS to the surgical specialties (excluding ophthalmology and anesthesiology) and the operating rooms and wards that are assigned to these specialties. For wards that also have a specific number of beds dedicated to medical specialties, the amount of beds available for surgical patients is adjusted accordingly. Including surgical instruments in our scope is preferable to ensure feasibility of the created MSS. However, the data needed for this is not available, and we are only able to include the use of X-ray equipment in the scope.

In step 2 (data gathering) we explained that we use data on all surgeries performed in the year 2011, excluding, so called “reduction periods”. We also explain that of these surgeries we need to know the operating (sub-)specialty, whether the patient was an adult, whether the patient required overnight stay, whether X-ray was used during surgery, what the medical priority was for the surgery, and the surgery duration and LOS.

In step 3 (capacity planning) we showed how the capacity of resources within our scope is currently allocated to the specialties (an allocation which we adhere to in this research).

In step 4 (defining a set of recurrent standard case types) we explain that we use a 4-step heuristic, based on a greedy algorithm, to define sub-sets of surgeries within the data set (obtained in step 2), which use the same resources in a comparable quantity, and abide by the same planning rules. Each sub-set defines a surgical case type.

In step 5 (construction of the Master surgical Schedule) we explain how we use a constructive and an improvement heuristic to create an MSS from a set of case types that results from step 4. We also explain how we use different settings for this improvement heuristic and for the grouping heuristic of step 4 to create 36 different Master Surgical Schedules of which we evaluate the performance.

5. Design of the experiments

In this chapter we describe how we prospectively assess the consequences of implementing an MSS. Experimenting with the actual system is expensive, disruptive, and in this case dangerous as lives are at stake during surgery. A (mathematical) model of the real-world system is therefore the only viable option. We use a simulation model because it is a safe way to produce accurate and convincing predictions (Law, 2006). For running the simulations, we use the same software package as we use for creating an MSS from a set of case types.

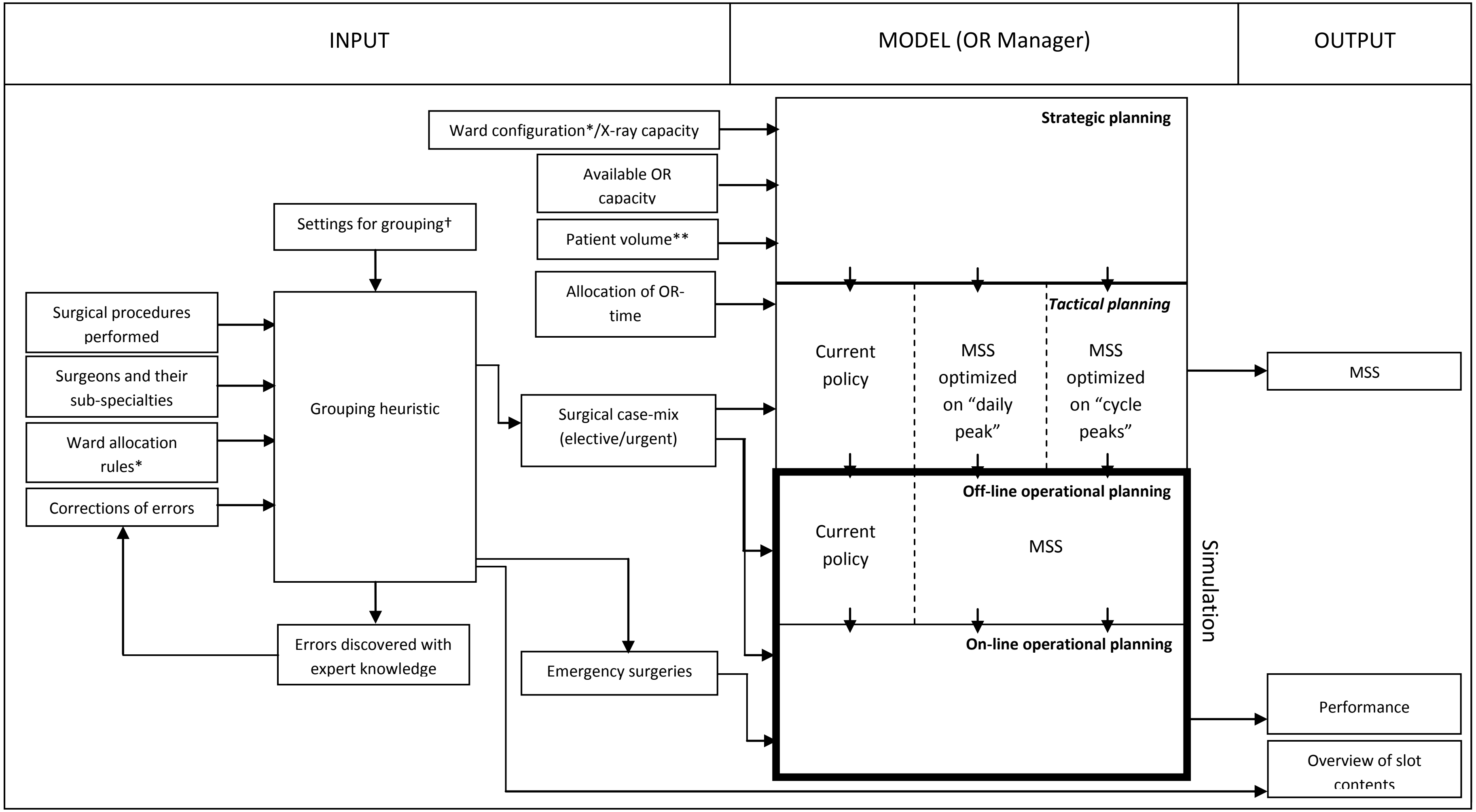
In Section 5.1 we describe the simulation model. In Section 5.2 we validate the simulation model (current planning policy) with the realization. In Section 5.3 we explain the design of the experiments.

5.1 Simulation model

Figure 5-3 shows a schematic of the simulation model, along with its inputs and outputs. Note that the model also consists of the 4 hierarchical levels of OR planning. The results of strategic planning are offered to the software as input, along with the allocation of OR-time to sub-specialties (tactical planning), and the case-mix. Within the software these inputs are used to create an MSS (or not, when we simulate the current planning policy; tactical planning). At the off-line operational level patients are generated based on the case-mix (flow variability is simulated), and planned into an OR-day. At the on-line operational level, emergency arrivals are generated (flow variability), along with clinical variability for all patients, and on-line planning rules are executed. In Chapter 4 we described how we obtain all the inputs.

The schematic also shows how we model different Master Surgical Schedules and different scenarios. In Section 5.3 we explain how we use the outputs of these scenario's to compare performance of the current planning policy to that resulting from an MSS.

Figure 5-3 Schematic of the experimental design and simulation model. The box marked with ** contains the expected number of patients, and is varied to create the 2011 and 2012 scenarios. The boxes marked with * are altered to create the current and new ward configuration (for 2012 only). The boxes marked with † are altered to create different Master Surgical Schedules (see Chapter 4).



We describe the model according to each of the hierarchical levels. At each level we discuss how we model OR-planning as it is done at Gelre Apeldoorn. At the tactical and off-line operational level we also discuss how we model the MSS planning policy. At the off-line and on-line operational level we also discuss how we simulate naturally occurring (flow and clinical) variabilities. At the on-line operational level we also discuss the simulation settings and their underlying assumptions.

When there is a discrepancy between our model and reality, we explain why this discrepancy exists and how it affects the quality of our model

5.1.1 Strategic level

On the strategic level the dimensioning of resource capacity is decided. As we show in Figure 5-3 we offer ward configuration, X-ray capacity, and OR capacity to the simulation software as input. The simulation software then uses this input as restrictions for the tactical level. In Chapter 4 we discussed the dimensioning of these resources.

The patient volume is also offered to the software as input, but the volume is higher than we presented in Chapter 4. We increase the patient volumes to compensate for surgeries that are cancelled during on-line operational planning, as we further explain in Section 5.2.4. We use an elective/urgent patient volume of 7600 for 2011 and 7950 for 2012 in our model.

5.1.2 Tactical level

On the tactical level, boundaries are set for the scheduling of patients by allocating OR-time to specialties. Also the forming of planning rules is done at this level. For both we discuss how we model this and whether this is consistent with reality.

Allocation of OR-time

We offer the current allocation to the simulation model as input. When we model the current planning policy, this allocation directly provides restrictions for the operational levels. When we model the use of an MSS, this allocation provides restrictions for the creation of an MSS.

The allocation of emergency slack is also included. In our model, once every two weeks on Monday, 1 General surgery schedule has 100 minutes of slack reserved and 1 Orthopedics schedule has 100 minutes of slack reserved. In practice this occurs once each month on both Monday and Tuesday. The adaptation is necessary because our MSS is a two week cycle. This has no effect on the ward performance since the recovery ward for emergency surgeries is not affected by the surgeon who performs the surgery.

When we create an MSS (allocate OR-time to case types), we use the surgical case-mix (i.e. the set of case types) as input. Within the software we then determine the amount of slots for each case type and optimize the slot sequence as we explained in Chapter 4.

Planning rules

In our model, the planning horizon for elective/urgent surgeries is 4 weeks. In practice the planning horizon is 7 weeks for elective and two weeks for urgent surgeries, but the software does not allow for separate planning horizons for these medical priorities and the planning horizon must be a multiple of the cycle length (two weeks). We choose 4 weeks because it is closest to the average of 7 and two weeks. If a surgery cannot take place within the horizon without overtime, it is schedules on the day where the least overtime is created. Compared to reality, it is easier to schedule urgent surgeries without creating overtime and harder to schedule elective surgeries without creating overtime. Also, more urgent surgeries are planned in an MSS slot, and less elective surgeries are planned in an MSS slot, compared to reality. Since there are more elective surgeries, we believe our model will result in more overtime and more fluctuation in ward utilization than would be the case in reality.

In our model, a surgery is only planned on an OR-day is the resulting schedule for that day has an overtime probability smaller than or equal to 40%. In practice planners do not calculate the overtime probability, but reserve 15 minutes of slack against overtime. This option was not yet included in the software package and we do not add it since the manager of patients logistics deems it more desirable to let the amount of slack depend on the amount of uncertainty in the OR schedule for that day (the method that is currently used in the software). The 40% rule results in slack amounts around 15 minutes. We believe the effect this has on the quality of the model is negligible.

5.1.3 Off-line operational level

On the off-line operational level, short-term decisions are made such as the date of surgery for a patient, and the sequence in which patients are received at the OR on a given day. In this section we discuss how we model these off-line planning rules for the current planning policy, and for the MSS. We also discuss how we simulate flow variability (see Chapter 2).

Planning rules (current policy)

In our model, patients are randomly selected and planned on a random OR-day within the planning horizon where they fit (where the total expected OR duration of all planned surgeries, the slack for emergency surgeries, and the slack against overtime fit within regular working hours), or if no such OR-day exists, on a random OR-day. In reality, patients are placed on a waiting list each day, and planned in the first OR-day where they fit, on a first-come first-served basis. In our model waiting lists are generated for two weeks at a time. Therefore, planning patients on the first OR-day where they fit results in empty ORs at the end of each two week period. We plan the patients on a random OR-day where they fit within their planning horizon, to prevent such a concentration. We believe that planning the patients at a random location is comparable to putting patients on a waiting list at a random day.

The sequence in which surgeries are performed during an OR-day is decided by the order in which they were assigned to that OR-day. Emergency surgeries are scheduled at the end of the schedule on a first-come first served basis. In practice, elective/urgent surgeries are often postponed in order to schedule an emergency surgery. Also, the age or condition of a patient may make an early surgery important (for instance for diabetics). This means the performance resulting from our model differs from reality when the order in which surgeries are performed influences performance. We treat this matter in Chapter 6.

Planning rules (MSS)

The planning of surgeries under the MSS is done the same as for the current planning policy, with a few additional rules. Under the MSS, all surgeries that are of a case type that has MSS slots assigned to it, are planned first. When for each of those-case types either all the surgeries have been planned, or all slots are filled, the slots that remain empty are removed and the planning of the remaining surgeries commences.

The sequence in which surgeries are performed during an OR-day is decided by the order in which they were assigned to that OR-day. Thus, surgeries with an MSS slot are performed first, then the other elective and urgent surgeries, and finally the emergency surgeries.

Flow variability

We use the surgical case-mix (elective/urgent) to simulate for each two week period, what surgeries are added to the waiting list. The patients on each waiting list all share the same due date, which is the Friday of the next period (planning horizon of 4 weeks). In practice, new patients are added to the waiting list every day. Under “planning rules” we explained how we attempt to mimic this effect.

Within each period the waiting lists are generated per specialty. The number of patients that are placed on a waiting list is equal to the expected number of patients. For each specialty, the amount of patients for each surgical-case type is randomized with an expected frequency corresponding to its share in the case-mix.

5.1.4 On-line operational level

On the on-line operational level, ad hoc decisions are made such as the scheduling of emergency patients. In this section we explain the rules our model employs for these ad hoc decisions. We also discuss how we simulate flow variability, and clinical variability at this level. We also present the settings we employ during the simulation of the on-line operational level and the underlying assumptions.

Planning rules

In our model, emergency surgeries are scheduled into the OR with dedicated slack for emergencies, which has the least expected workload remaining when the emergency surgery arrives. In practice there is also a small volume of emergency patients for specialties other than General surgery and Orthopedics that are treated in the designated OR time of those specialties. This assumption leads to a small shift in emergencies performed from regular hours, to outside of regular hours.

In our model, surgeries are never cancelled due to overtime. In practice the schedule-coordinator deliberates with the anesthesiologist and performing surgeon if a surgery should be cancelled when it is expected to start in overtime. However, the actual cancellation of a surgery is very rare (A. Burghart, A. Nijborgh, schedule coordinators, personal communication). Therefore we believe the influence on the quality of our model is negligible. This also means that we drop the amount of cancellations as a performance indicator.

Flow variability

The flow variability at the on-line operational level consists of emergency surgeries and scheduled elective/urgent surgeries that are cancelled at the last moment because a patient is not present or not ready for surgery.

We assume that the arrival of emergency surgeries follows a Poisson process. Thus, we consider the time between two consecutive emergency surgeries of a single case type exponentially distributed with the expected arrival frequency as the parameter. At the start of the simulation an arrival moment is generated for each emergency case type. During the simulation, when an emergency surgery arrives, a new emergency surgery arrival moment is generated for that case type according to the exponential distribution for inter-arrival times.

We determine a surgery duration and LOS for each emergency surgery in the same fashion as for elective/urgent surgeries.

As we mentioned in Chapter 3, in certain immediately life-threatening cases, an ongoing surgery is be aborted to free up an OR. However, such surgeries are extremely rare and we do not to include them in the emergency case-mix.

For each surgery we model a 1% probability of cancellation, due to factors uncontrollable by the hospital. For instance: patients that failed to adhere to the sobriety rule, or patients that have a fever on the day of surgery. There is no reliable data on the amount of surgeries that are cancelled for these reasons. The head of admissions and OR planning estimated that this occurs in less than 1% of the cases.

Clinical variability

At the on-line operational level we replace the expected value for surgery duration and LOS for each patient by an actual value, based on the probability distributions of their case type.

Simulation settings and assumptions

We now present all relevant simulation settings and underlying assumptions.

- A bed is reserved for a patient at the same time the surgery starts - *In practice patients are admitted to the ward before their surgery is scheduled (see Chapter 3). Therefore, the bed utilization pattern our model shows is correct, but shifted in time, compared to reality.*
- Elective and urgent surgeries may start before their planned time - *We assume that patients are always admitted to the ward and ready for surgery, even when their surgery goes on before its planned time.*
- Surgery duration cannot be more than 600 minutes - *Because the surgery durations in the simulation are drawn from a lognormal distribution, they can take on values that are much larger than any of the historical surgery durations that the distribution is based on. To prevent this we define a maximum duration equal to the largest surgery duration we encounter in the historical data set.*

- Surgeries cannot last into the next day (are stopped at midnight) - *Surgeries that last past midnight pose a problem for the simulation software. When a surgery's duration causes it to end after midnight, this duration is adapted so that it ends at midnight. This is of no consequence to the ward performance and of little consequence to the OR performance because it rarely occurs (about twice a year for the 2012 scenario with the current planning policy and even less in other scenarios).*
- The changeover time between surgeries (the time between one patient exiting the OR and the next patient entering) is 8 minutes (see Appendix G).
- Day-care patients never require an overnight stay - *In practice day-care patients are sometimes transferred to a clinical ward for overnight stay. In our model those patients are admitted directly to a clinical ward.*
- The number of beds occupied after a period with reduced OR capacity is identical to the number of beds occupied before this period - *In reality some wards are closed during reduction and others have more beds occupied because they took over patients from these closed wards.*
- Specialties are always able to provide a surgeon to operate in an assigned block of OR time
- Surgeons are able to perform all surgeries of their sub-specialty
- If a patient is discharged his bed is immediately available for the next admission (i.e. there is always a clean bed in storage to replace a used bed)
- When a surgery requires an additional surgeon, the planning of the outpatient department can be adjusted to free up this extra surgeon.

5.2 Model validation

We simulated a recent period of 1 year (January 1st 2011 to December 31st 2011) – excluding weeks with reduced capacity – e.g. 40 regular weeks – under the current planning policy to validate the model. The 40 weeks are preceded by 4 weeks of simulation, which we discard before calculating the outcome of the simulation (so called warm-up period; see Appendix H). This prevents that the wards are empty at the start of the simulation. To account for the clinical- and flow variability, we simulate each scenario 20 times and average the outcome measures, to achieve a relative error smaller than 2,5%. We determined that 20 "runs" are needed using a sequential procedure from Law (2007; See Appendix H).

Table 5-1 shows the performance measures we obtain from the simulation, and the realized performance of 2011. The registration of when each OR-day schedule is finished was no longer correct after an alteration we made to the model (a necessary alteration to allow some surgeries to be performed by each of the sub-specialties of general surgery). We correct the calculation of the total OR utilization accordingly, but drop the "fluctuation in OR finish time" indicator, since this indicator is the least important.

Table 5-1 Validation of the simulation model

Performance Indicators	Realization of 2011	Simulation of 2011	Difference
Number of elective/urgent surgeries performed	7529	7517	0%
Number of emergency surgeries performed	1635	1645	1%
hours spent on elective/urgent surgeries	8514	8676	2%
hours spent on emergency surgeries	1683	1927	14%
OR utilization (including emergencies)	76,4%	79,4%	3%
Overtime	4,5%	2,7%	-2%
Ward utilization			
A6	74,8%	77,9%	3%
A7	85,9%	93,4%	8%
B7	82,6%	82,1%	-1%
B8	74,8%	68,8%	-6%
D2	96,1%	88,0%	-8%
Fluctuation in ward utilization			
A6	7,7%	13,7%	6%
A7	13,1%	15,8%	3%
B7	11,6%	12,6%	1%
B8	20,1%	13,0%	-7%
D2	20,3%	19,12%	-1%
Fluctuation in admissions and discharges			
A6	40,0%	43,5%	4%
A7	26,4%	24,2%	-2%
B7	25,0%	28,0%	3%
B8	35,6%	38,3%	3%
D2	27,3%	23,2%	-4%

5.2.1 Validation of OR department performance

The number of surgeries performed in the simulation corresponds to the number of surgeries in the data set for 2011. The actual surgery time in minutes is higher in the simulation. The reason for this is that we remove respectively 2% of elective and urgent surgeries and 14% of emergency surgeries from the dataset that lack or duration and/or LOS registration in the dataset. In our model we compensate for this loss of data.

The time spent on surgery in the simulation matches what we expect it to be based on the dataset. However, we keep in mind that the registrations in the dataset itself are not an exact representation of reality (see Appendix B).

In our model there is less overtime than in the realization, which suggests a more efficient surgical schedule. However, we cannot attach much value to this comparison since the realized overtime is calculated different from our performance indicator. Our performance indicator measures all elective and urgent surgery minutes outside of regular hours. The realization measure takes into account the overtime of elective, urgent, and emergency surgeries, but only if they started inside regular hours.

In our model there is also a higher OR utilization, which is measured in the same way as the realization. This confirms that the surgical schedule is more efficient in our model. We believe this is due to the changeover times, which are consistently 8 minutes in the simulation, whereas in practice it can occur that either the patient or the staff runs late.

The ward performance of 2011 is not based on the dataset we use to determine the 2011 case-mix. Instead it is based on samples taken directly from the hospital information system (see Section 3.6). This causes the utilization for wards B8 and D2 to be higher in the realization. Surgical specialties sometimes admit patients to ward D2 for examinations that do not require surgery. These are measured in the realization but excluded from our model. The same holds for Gynecology and ward B8.

Discrepancies between the measures of the realization and the simulation are also the result of the data set we used to determine the 2011 case-mix, which contained missing and polluted data (see Appendix B). Finally, the registration of admissions and discharges is not always done real-time, polluting both the realization measures and the data set.

We believe the values of the realization and the simulation are similar, in spite of the disturbing factors we mentioned, and that the model is valid for our purposes.

5.3 Design of the experiments

In this section we describe what experiments we conduct to predict the performance of the OR department and wards under an MSS and compare it to their performance under the current planning policy. We also discuss how we structure our search for an MSS that performs as well as possible

We simulate the OR department and surgical nursing wards for 40 weeks (i.e. a full year, minus the reduction periods) under the current planning policy and under different Master Surgical Schedules (see Chapter 4) in three scenarios. These scenarios are: 2011 with the current ward configuration, 2012 with the current ward configuration, and 2012 with the new ward configuration (see Chapter 3).

We use the 2011 scenario to determine what combination of parameter values that we use in the MSS creation (see Chapter 4) results in the best performing MSS. First, we determine for each parameter, whether employing different values also leads to differences in the performance of the resulting Master Surgical Schedules. Second, we determine what combination of values for these relevant parameters results in the best performing Master Surgical Schedules

For each parameter we employ two or three values in the creation of the 36 Master Surgical Schedules. To judge if employing different values for a parameter has an effect on the overtime generated by the resulting Master Surgical Schedules, we divide the 36 Master Surgical Schedules into two or three clusters, according to the values that we used for that parameter in the MSS creation. We then perform one-tailed two-sample t-tests to determine if the clusters show a different performance with statistical significance at the confidence level $\alpha = 0,05$. We do this for all four parameters, and for all PIs

We then divide the 36 Master Surgical Schedules into clusters according to the values we employ for all parameters that turn out relevant. We compare the performance of these clusters to the performance of the current planning policy using one-tailed two-sample t-tests to determine if the clusters show a different performance with statistical significance at the confidence level $\alpha = 0,05$. We do this for each PI. We then assess what combination of parameter values produces the best performing Master Schedule (or schedules if no single combination can be appointed the best).

In creating Master Surgical Schedules for 2012 we use only the parameter values that we decide produce the best performing Master Surgical Schedules.

For both 2012 scenarios (current ward configuration and new ward configuration. We discard the Master surgical Schedules that show deterioration in OR performance, compared to the performance of the current planning policy. We prospectively assess the consequences of implementing an MSS for the 2012 period because we aim to design an implementable MSS for this period. Therefore, we present the results for this period in more detail and focus on each ward separately.

In addition to presenting the outcomes on each PI (again with t-tests), we calculate the probability that there is a shortage of beds for each of the planning policies given the current capacities. We also calculate what capacity is needed to have sufficient beds on at least 90% of the days. This serves as an indication of the operational significance of improvements/deteriorations caused by the MSS

5.4 Chapter conclusion

In this chapter we presented our model of the 4 hierarchical levels of OR planning and discussed where it differs from the actual state of affairs at Gelre Apeldoorn. We also validated the model by simulating a recent period of 1 year (January 1st 2011 to December 31st 2011) – excluding weeks with reduced capacity under the current planning policy.

We described how we predict the consequences of implementing an MSS with a simulation model. For running the simulations we use the same software package as we use for creating an MSS from a set of case types.

We create different scenarios, for which we simulate the OR department and surgical nursing wards for 40 weeks (i.e. a full year, minus the reduction periods).

To determine the best settings for the grouping heuristic and improvement heuristic for the slot sequence, we apply 36 Master Surgical Schedules (see Chapter 4) to the year 2011, along with the current planning policy.

We use the settings for the grouping heuristic and the optimization method that create the best performing MSS for the year 2011, to create an MSS for 2012. This is the first period eligible for the implementation of an MSS.

We compare the performance of Master Surgical Schedules we create using the best performing combinations of parameter values to the current planning policy for the scenario that Gelre Apeldoorn continues to use the current ward configuration, and the scenario that Gelre Apeldoorn implements the plans for a new ward configuration.

In addition to presenting the outcomes on each PI, we calculate the probability that there is a shortage of beds for each of the planning policies given the current capacities. We also calculate what capacity is needed to have sufficient beds on at least 90% of the days. This serves as an indication of the operational significance of improvements/deteriorations caused by the MSS

6. Results

In this chapter we discuss the results of the experiments we describe in Chapter 5, along with supplementary experiments. We also discuss the managerial implications of implementing an MSS.

In Section 6.1 we discuss the results of the experiments we perform for the 2011 scenario. We use these experiments to determine what combination of parameter values that we use in the MSS creation results in the best performing MSS.

In Section 6.2 we discuss the results of the experiments we perform for the 2012 scenarios (current ward configuration and new ward configuration). For the 2012 experiments we limit ourselves to creating Master Surgical Schedules with the parameter values that we select in Section 6.1. We use the 2012 experiments to determine which of those Master Surgical Schedules are feasible solutions based on their OR performance (no deterioration). For those Master Surgical Schedules we evaluate their ward performance in comparison to the current planning policy.

In Section 6.3 we discuss questions that arise from the results of the experiments, and discuss the results of supplementary experiments. In Section 6.4 we discuss the managerial implications of using an MSS.

6.1 Experiments for 2011

In this section we discuss the results of the experiments we perform for the 2011 scenario. In Section 6.1.1, we determine which of the parameters that we alter in the MSS creation have a statistically significant impact on the overtime generated by the resulting Master Surgical Schedules. Also, we determine for these parameters, which combination of parameter values results in Master Surgical Schedules that produce the least overtime. In Section 6.1.2, we do the same for the ward PIs. In Section 6.1.3, we discuss to which parameter values we limit ourselves for the creation of Master Surgical Schedules for the 2012 scenarios. In Table 6-1 we show the parameter values we use to create different Master Surgical Schedules (first presented in Chapter 4).

Table 6-1 Parameter values we use to create different Master Surgical Schedules

GROUPING HEURISTIC			
Parameter	**Values**		
Threshold for grouping	5%	10%	20%
Weight of surg. dur. for grouping	0,50	0,66	0,80
Minimum group size	20	1	
IMPROVEMENT HEURISTIC FOR SLOT SEQUENCE			
Parameter	**Values**		
Optimization criterion	Daily peak	Cycle peaks	

6.1.1 OR performance

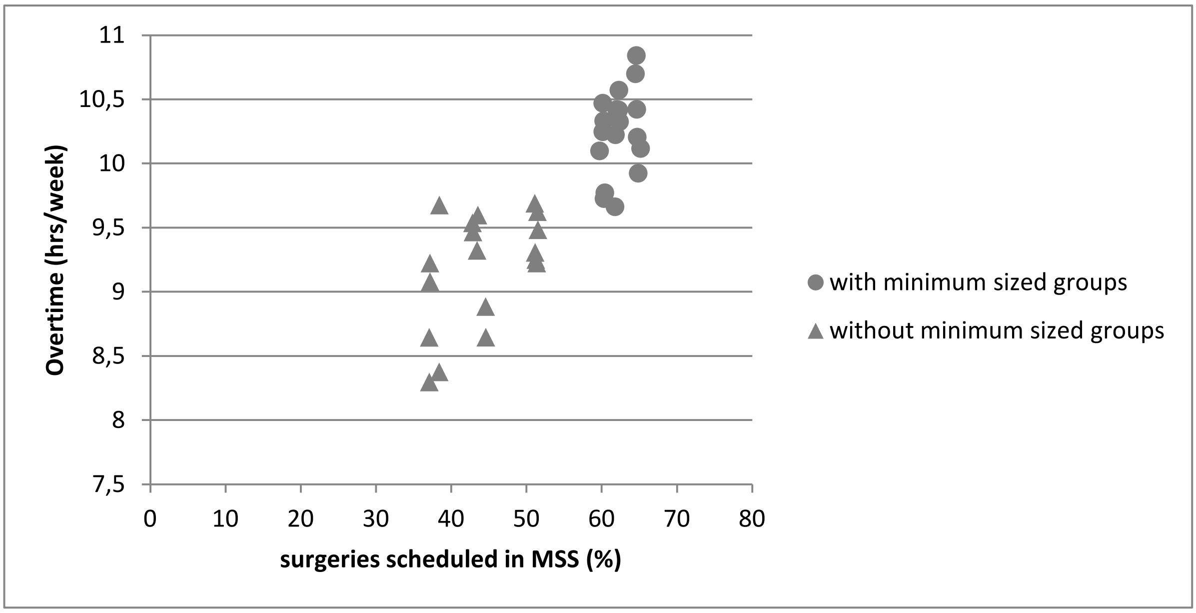
In this section we show for which of the parameters, that we alter in the MSS creation, employing different values leads to a statistically significant difference in the overtime generated by the resulting Master Surgical Schedules. "Overtime" is the only remaining PI for OR performance.

By employing different parameter values in the creation of Master Surgical Schedules we aim to create larger case types, which increases the percentage of surgeries scheduled in the MSS. This increases the part of the case-mix we regulate with the MSS and increases the robustness of the MSS. However, the reliability of the utilization predicted by the MSS decreases because the reliability of the case-types decreases. Therefore, the graphs in this chapter show the percentage of surgeries scheduled in the MSS versus the PI we evaluate (in this case "overtime").

The effect of different values for "threshold" on overtime was unconvincing (see Appendix I for the t-tests). The effect of different values for "weight" on overtime was absent. For both "minimum group size" and "optimization criterion", employing different values has a significant impact on the overtime. Therefore, we limit ourselves to showing the effects of "minimum group size" and "optimization criterion" in this section.

In Figure 6-1 we show the overtime resulting from the 36 Master Surgical Schedules, clustered according to the creation of minimum sized groups. Note that for "overtime" (and all other PIs that we use in this research) a lower value is better.

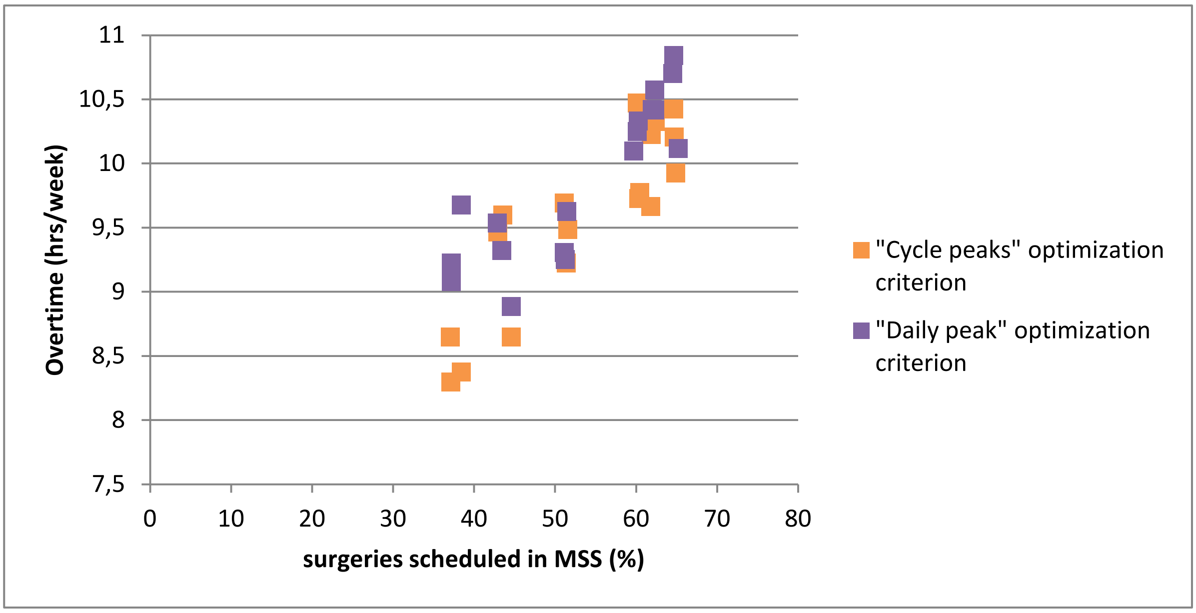
Figure 6-1 Percentage of surgeries scheduled in the Master Surgical Schedules and overtime generated by the Master Surgical Schedules, clustered according to the "minimum group size" parameter.



The creation of minimum sized groups increases the percentage of surgeries that is scheduled within the MSS. However, creating minimum sized groups results in more overtime (on average an hour more each week).

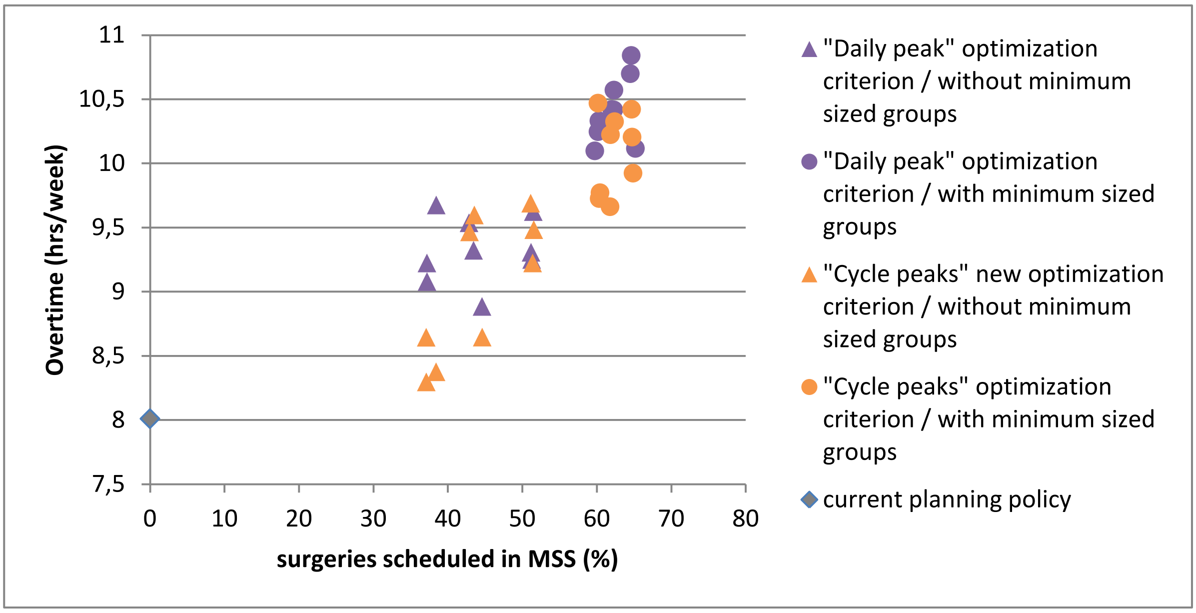
In Figure 6-2 we show the overtime resulting from the Master Surgical Schedules, clustered according to the optimization criterion used. Using the “daily peak” optimization criterion results in more overtime (on average 35 minutes more each week).

Figure 6-2 Percentage of surgeries scheduled in the Master Surgical Schedules and overtime generated by the Master Surgical Schedules, clustered according to the “optimization criterion” parameter.



We now divide the Master Surgical Schedules into clusters according to both the optimization criterion and the creation of minimum sized groups to determine which combination of values performs best (see Figure 6-3).

Figure 6-3 Percentage of surgeries scheduled in the Master Surgical Schedules and overtime generated by the Master Surgical Schedules, clustered according to the “minimum groups size” and “optimization criterion” parameter, compared to the overtime generated by the current planning policy.



We compare the performance of each cluster to the current planning policy. We use one-tailed two-sample t-tests to determine statistical significance at the confidence level α = 0,05. All clusters result in significantly more overtime than the current planning policy (see Table 6-2).

Table 6-2 Overtime created by each MSS cluster in excess of the overtime that results from the current planning policy

Cluster	Overtime generated by cluster – overtime generated by current planning policy (hrs/week)
No minimum sized groups / “daily peak” optimization criterion	1,3*
Minimum sized groups / “daily peak” optimization criterion	2,4*
No minimum sized groups / “cycle peaks” optimization criterion	1,0*
Minimum sized groups / “cycle peaks” optimization criterion	2,1*

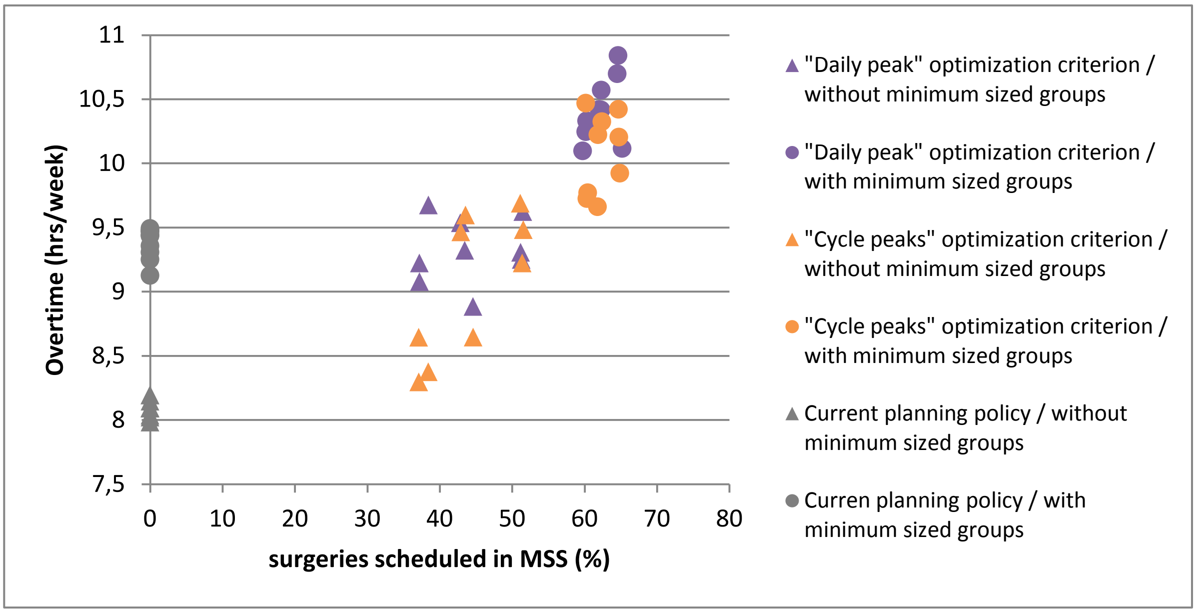
* indicates statistical significance at the confidence level α = 0,05

The overall increase in overtime is not what we expect to result from an MSS planning policy. We believe that the increase in overtime is not (only) a product of the MSS planning policy, but also due to the way we model surgeries.

The uncertainty in surgery duration for a case type is likely larger than the uncertainty in surgery duration of a surgery (because it also incorporates the uncertainty of what surgery is actually scheduled in that slot). The simulation software does not recognize what surgery is scheduled, but only what surgical case type this surgery belongs to. In practice, it is known what surgery is planned in a slot. This means the uncertainty in surgery duration in our model is larger than it is in practice.

To verify this theory we ran simulations of the current planning policy with the 18 different sets of surgical case types that we also use as input for the Master Surgical Schedules. In Figure 6-6 we again show the four MSS clusters, but now along with the 18 current planning policy versions.

Figure 6-6 Percentage of surgeries scheduled in the Master Surgical Schedules and overtime generated by the Master Surgical Schedules, clustered according to the "minimum group size" and "optimization criterion" parameter, compared to the overtime generated by the current planning policy, clustered according to the "minimum group size" parameter.



The amount of overtime resulting from the current planning policy cluster with minimum sized groups is 1,4 hours larger (on average each week) than the amount of overtime we previously obtained from the current planning policy. For the current planning policy cluster without minimum sized groups the difference is not significant. This is likely because the threshold protects against the increase in surgery duration uncertainty (which is dropped when creating minimum sized groups). We believe this confirms that the creation of case types contributes to the increase in overtime.

To make the comparison of the MSS performance to that of the current planning policy more meaningful, we choose to incorporate this increase in overtime in our model of the current planning policy as well. Thus, for each performance indicator, we compare the MSS performance to that of its current planning policy counterpart that had the same input of surgical case types. In this way both planning policies are subjected to the same flaw in our model. In Table 6-3 we show the differences in overtime we obtain in this fashion (all significant).

Table 6-3 Overtime created by each MSS cluster in excess of the corresponding current planning policy cluster

Cluster	Overtime generated by MSS cluster – overtime generated by corresponding current planning policy cluster (hrs/week)
No minimum sized groups / "daily peak" optimization criterion	1,2*
Minimum sized groups / "daily peak" optimization criterion	1,1*
No minimum sized groups / "cycle peaks" optimization criterion	1,0*
Minimum sized groups / "cycle peaks" optimization criterion	0,7*

* indicates statistical significance at the confidence level $\alpha = 0,05$

Opposed to the values we previously obtained, the results are now in favor of the creation of minimum sized groups. This is consistent with our previous statement, that the negative effect of creating case types on overtime is stronger for those clusters. The "cycle peaks" optimization criterion still performs best.

6.1.2 Ward performance

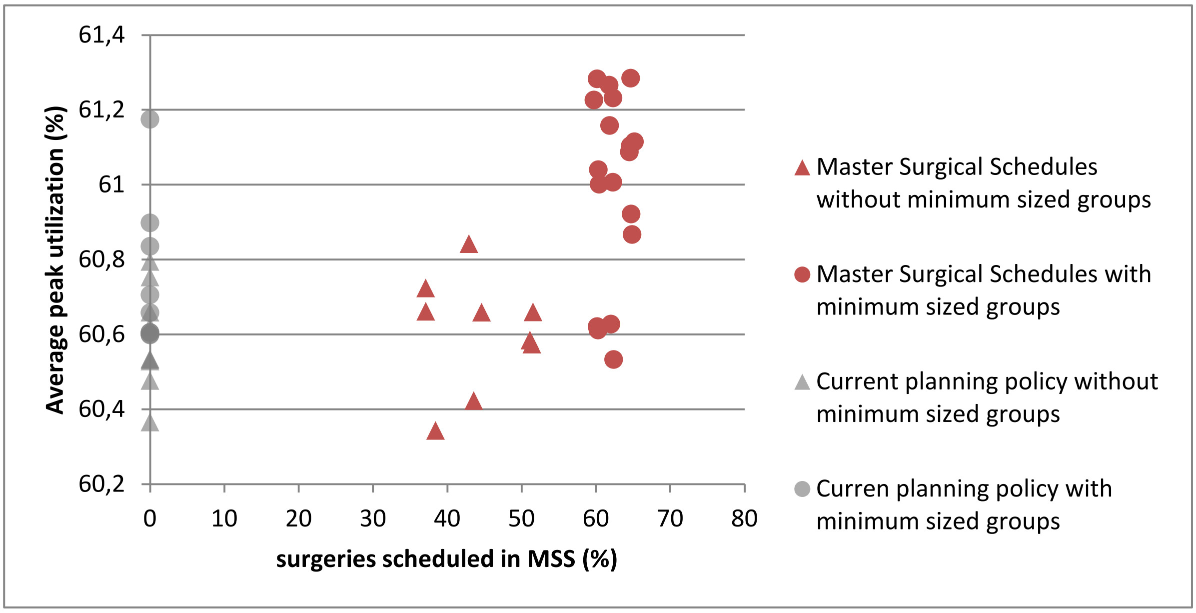
As we explained in Chapter 5, we judge the ward performance by the average daily peak utilization, the fluctuation in daily peak utilization, and the fluctuation in admissions and discharges. For each of these PIs we again determine what parameters are relevant to the outcome, and what combination of parameter values performs the best.

We proceed in the same fashion as Section 6.1.1. However, we limit ourselves to showing the graphs of the Master Surgical Schedules clustered according to all relevant parameters at once (i.e. all parameters whose different values produced a statistically significant difference in the PI outcomes of their Master Surgical Schedules). In Section 6.1.1 we showed the graphs of the Master Surgical Schedules clustered according to a single parameter as an example of our approach.

Average daily peak utilization

For this performance indicator only the creation of minimum sized groups shows a significant impact on the outcome (see Figure 6-7). The graph presents average peak utilization (as a percentage), averaged over all surgical wards.

Figure 6-7 Percentage of surgeries scheduled in the Master Surgical Schedules and average peak utilization resulting from the Master Surgical Schedules and current planning policy versions, clustered according to the "minimum group size" parameter.



We compare the performance of both MSS clusters to that of their current planning policy counterpart and obtain the results shown in Table 6-4. We show the difference in percentage points as well as the corresponding nr of beds.

Table 6-4 Difference in average peak height between the Master Surgical Schedules, clustered by the application of minimum sized groups, and the current planning policy, after correction for variation caused by creation of case types

Cluster	Difference in average peak utilization (percentage points)	Difference in average peak height (nr of beds, averaged per ward)
Minimum sized groups	0,3*	0,1*
No minimum sized groups	0,0	0,0

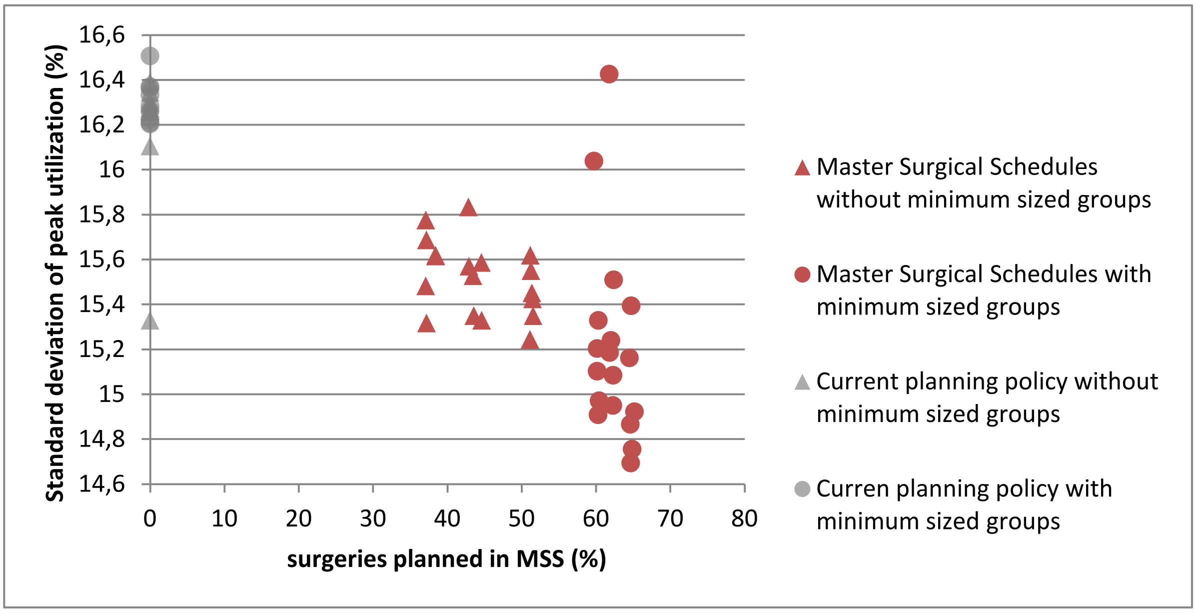
* indicates statistical significance at the confidence level α = 0,05

The t-tests show no significant difference in average peak utilization between the clusters without minimum sized groups. There is a statistically significant difference between the clusters with minimum sized grouping in favor of the current planning policy, but this difference is small. When we multiply the percentage points of utilization with the available capacity, and divide by the number of wards, we obtain that the average peak height is 1/10 of a bed higher at each ward.

Fluctuation in daily peak utilization

For this performance indicator, only the creation of minimum sized groups shows a significant impact on the outcome (see Figure 6-8). The graph presents the standard deviation in peak utilization (as a percentage), averaged over all surgical wards.

Figure 6-8 Percentage of surgeries scheduled in the Master Surgical Schedules and standard deviation of peak utilization resulting from the Master Surgical Schedules and current planning policy versions, clustered according to the "minimum group size" parameter.



We compare the performance of both MSS clusters to that of their current planning policy counterpart and obtain the results shown in Table 6-5.

Table 6-5 Difference in the standard deviation of the daily peak height between the Master Surgical Schedules, clustered by the application of minimum sized groups, and the current planning policy, after correction for variation caused by creation of case types.

Cluster	Difference in St Dev of peak utilization (percentage points)
Minimum sized groups	-1,1*
No minimum sized groups	-0,7*

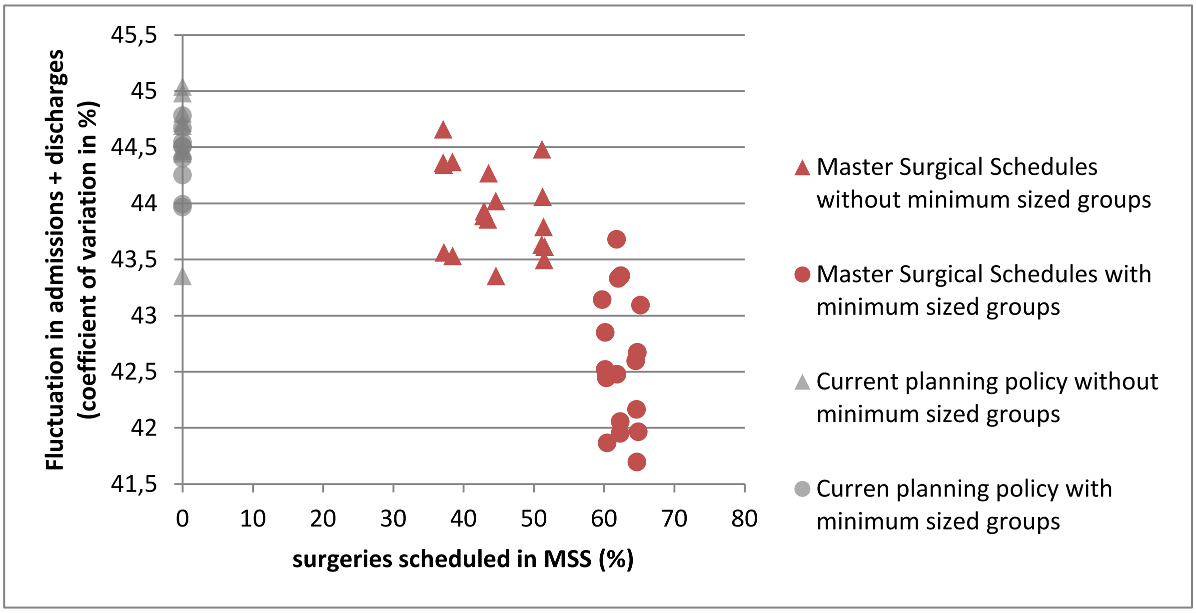
* indicates statistical significance at the confidence level α = 0,05

The t-tests show that both the Master Surgical Schedules with minimum sized groups, and the MSS clusters without minimum sized groups, result in less fluctuation in the daily peak utilization than the current planning policy. The effect is strongest for the Master Surgical Schedules with minimum sized groups.

Fluctuation in admissions and discharges

For this performance indicator, again, only the creation of minimum sized groups shows a significant impact on the outcome (see Figure 6-9). The graph presents the fluctuations in admissions and discharges as the coefficient of variation (measured as a percentage), averaged over all surgical wards.

Figure 6-9 Percentage of surgeries scheduled in the Master Surgical Schedules and fluctuation in admissions + discharges resulting from the Master Surgical Schedules and current planning policy versions, clustered according to the "minimum group size" parameter.



We compare the performance of both MSS clusters to that of their current planning policy counterpart and obtain the results shown in Table 6-6.

Table 6-6 Difference in the fluctuation of admissions and discharges between the Master Surgical Schedules, clustered by the application of minimum sized groups, and the current planning policy, after correction for variation caused by creation of case types.

Cluster	Difference in fluctuation of admissions and discharges (in percentage points of the coefficient of variation)
Minimum sized groups	-1,8*
No minimum sized groups	-0,6*

* indicates statistical significance at the confidence level α = 0,05

The t-tests show that both the Master Surgical Schedules with minimum sized groups and the MSS clusters without minimum sized groups, results in less fluctuation in the daily admissions and discharges than the current planning policy. The effect is strongest for the Master Surgical Schedules with minimum sized groups.

6.2 Evaluation of the parameter values we use for the MSS creation

In this section we discuss what combination of parameter values yields the most promising results, and thus, what parameter values we use to create Master Surgical Schedules for the 2012 scenarios.

We are not convinced that the values for threshold or weight are relevant to the performance of the resulting Master Surgical Schedules. This means we can choose which values to employ for these parameters based on other considerations (such as the percentage scheduled in the MSS), or again employ each of the values in the 2012 scenario. We maintain a broad scope and do the latter.

Master Surgical Schedules that we create with minimum sized groups, and optimize with the "cycle peaks" optimization criterion, show the least deterioration of OR performance (measured by the overtime). What optimization criterion we use does not influence any of the ward PIs. Therefore, based on the generated overtime, we limit ourselves to optimizing with the "cycle peaks" optimization criterion when creating Master Surgical Schedules for 2012.

The creation of minimum sized groups leads to less fluctuation in both the daily peak utilization and the amount of admissions and discharges to handle. It does show higher average daily peak utilization but we believe this difference is negligible. Therefore, we limit ourselves to applying minimum sized grouping for 2012.

This means we simulate both 2012 scenarios using 9 different Master Surgical Schedules.

6.3 Performance of the MSS and current planning policy in 2012 (current ward configuration)

For the 2012 we are only interested in what Master Surgical Schedules result in the best performance. We no longer attempt to determine the effect of different parameter values. Therefore, we no longer present clusters of Master Surgical Schedules and of the current planning policy. We compare each Master Surgical Schedule only to its current planning policy counterpart (created with the same surgical case types). We also present the results in more detail; we now focus on each ward separately. In addition to presenting the outcomes on each PI, we calculate the probability that there is a shortage of beds for each of the planning policies given the current capacities. We also calculate what capacity is needed to have sufficient beds on at least 90% of the days.

6.3.1 OR performance

Table 6-7 shows for each of the 9 Master Surgical Schedules, the increase in overtime generated in comparison to the current planning policy, and whether that increase is significant.

Table 6-7 Overtime created by each MSS in excess of the current planning policy (after correction for variation caused by creation of case types

MSS {weight;threshold(%)}	Overtime generated by cluster – overtime generated by current planning policy (hrs/week)
I-{0,5;5}	0,5*
II-{0,5;10}	1,7*
III-{0,5;20}	0,2
IV-{0,66;5}	0,8*
V-{0,66;10}	0,9*
VI-{0,66;20}	0,9*
VII-{0,8;5}	0,5*
VIII{0,8;10}	0,5*
IX-{0,8;20}	1,0*

* indicates statistical significance at the confidence level α = 0,05

Only one of the Master Surgical Schedules shows no significant increase in overtime. Since our aim is not to deteriorate OR performance, we limit our analysis for ward performance to that MSS.

6.3.2 Ward performance

Table 6-8 shows for each ward and each PI the outcome generated by both the MSS and the current planning policy.

Table 6-8 Values of each ward performance indicator, for each ward, compared between the MSS and the current planning policy

Performance Indicators	Simulation of	Wards							
		A6	A7	H2	RGC	B7	G2 (clinical)	D2	G2 (daycare)
Average peak utilization (%)	Current policy III	77,4	96,7	24,5	70,6	84,1	23,9	91,3	27,3
	MSS III	79,6†	95,6	24,9	71,7	83,5	24,0	92,7†	27,8
Fluctuation in peak utilization (St Dev)	Current policy III	14,8	16,7	12,3	21,6	16,6	11,9	20,8	16,7
	MSS III	13,4*	14,2*	12,9†	19,6*	16,4	11,4*	16,7*	15,6*
Fluctuation in adm+dis[1]	Current policy III	43,6	23,8	75,1	37,2	27,7	57,9	22,9	62,4
	MSS III	42,2*	23,0*	73,8	37,1*	26,9*	54,8*	17,7*	55,0*

Statistically significant improvements are marked with * and significant deteriorations are marked with †

[1] Coefficient of variation as a percentage.

The average daily peak utilization resulting from the MSS is higher for ward A6 and ward D2. However, for both wards the fluctuation of this peak decreases, and so does the fluctuation in admissions and discharges. The only ward for which the performance clearly decreases is ward H2.

We use the average daily peak utilization and the standard deviation of the daily peak utilization to predict the probability that on any given day, a ward has a shortage of beds (given the current capacities). For this calculation we assume that the daily peak utilization follows a normal distribution. We show the results in Table 6-9.

Table 6-9 For each ward, the probability that on any given day the allocated capacity is insufficient.

	A6	A7	H2	RGC	B7	G2 (Clinical)	D2	G2 (Day-care)
Current policy III	6%	42%	0%	9%	17%	0%	34%	0%
MSS III	6%	38%	0%	7%	16%‡	0%	33%	0%

‡ difference is not significant (both the difference in average peak utilization and standard deviation of peak utilization were not significant)

Wards A7, B8, and D2 show a decrease in the probability that they have a shortage of beds. None of the wards show performance deterioration based on these values. We also determine what capacity is needed for each ward to avoid a shortage of beds on 90% of the days (shown in Table 6-10).

Table 6-10 Beds needed for each ward to accommodate the daily peak demand with 90% probability.

	A6	A7	H2	RGC	B7	G2 (Clinical)	D2	G2 (Day-care)
Current policy III	32	39	7	17	35	8	24	5
MSS III	32	38	7	17	35	7	23	5

This points out that ward A7, the clinical section of the Child/youth ward (G2), and the day-care ward (D2) require fewer beds upon using an MSS. However, this is not yet sure because in our model of both the current planning policy and the MSS the amount of beds needed is higher than in reality, as we elaborate on in Section 6.5.

6.4 Performance of the MSS and current planning policy in 2012 (new ward configuration)

6.4.1 OR performance

Table 6-11 shows for each of the 9 Master Surgical Schedules, the increase in overtime generated in comparison to the current planning policy, and whether that increase is significant.

Table 6-11 Overtime created by each MSS in excess of the current planning policy (after correction for variation caused by creation of case types

MSS {weight;threshold(%)}	Overtime generated by cluster – overtime generated by current planning policy (hrs/week)
I-{0,5;5}	0,2
II-{0,5;10}	0,3
III-{0,5;20}	0,7*
IV-{0,66;5}	0,7*
V-{0,66;10}	0,4*
VI-{0,66;20}	0,6*
VII-{0,8;5}	0,1
VIII{0,8;10}	1,0*
IX-{0,8;20}	1,1*

* indicates statistical significance at the confidence level α = 0,05

Three Master Surgical Schedules show no significant increase in overtime. We again limit our analysis to the performance of these Master Surgical Schedules.

6.4.2 Ward performance

Table 6-12 shows for each ward and each PI the outcome generated by both the Master Surgical Schedules and their current planning policy counterparts.

Table 6-12 Values of each ward performance indicator, for each ward, compared between the Master Surgical Schedules and their current planning policy counterparts

Performance Indicators	Simulation of:	Wards							
		A6	A7	H2	RGC	B7	G2 (Clinical)	D2	G2 (Day-care)
Average peak utilization (%)	Current policy I	75,3	102,2	23,9	96,2	69,4	24,2	91,4	27,4
	MSS I	72,7	100,8*	25,1†	96,8	69,8	24,1	91,7	27,6
	Current policy II	71,1	101,3	24,6	96,6	68,0	23,6	91,2	27,3
	MSS II	74,1†	101,6	24,7	97,1	68,8	24,4†	93,0†	27,5
	Current policy VII	72,3	101,3	23,8	98,1	69,4	24,0	91,1	27,3
	MSS VII	72,6	100,7	24,7	98,1	69,5	24,0	92,8†	27,3
Fluctuation in peak utilization (St Dev)	Current policy I	17,7	21,5	12,8	18,8	14,0	12,4	20,7	16,8
	MSS I	17,7	17,8*	12,8	17,1*	14,7	11,6*	16,3*	14,9*
	Current policy II	17,3	21,1	12,8	18,4	13,8	12,1	20,5	16,9
	MSS II	17,3	18,6*	12,5	15,9*	13,2	11,5*	16,0*	15,1*
	Current policy VII	18,1	20,9	12,7	18,2	13,9	12,2	20,8	16,8
	MSS VII	17,6	18,5*	12,8	15,3*	14,0	11,7*	16,8*	14,7*
Fluctuation in adm+dis[1]	Current policy I	50,8	21,7	77,3	26,8	45,0	58,4	22,7	62,9
	MSS I	50,0	18,9*	73,4*	26,5	45,1	55,2*	17,3*	53,7*
	Current policy II	51,5	21,4	75,3	27,0	44,5	58,7	22,6	62,8
	MSS II	50,2	19,8*	75,1	26,1*	44,3	53,6*	16,8*	55,2*
	Current policy VII	50,6	21,2	77,7	26,6	45,5	58,7	23,1	62,1
	MSS VII	51,2	20,2*	76,0	25,7*	44,6	56,4*	17,9*	51,7*

Statistically significant improvements are marked with * and significant deteriorations are marked with †

[1] Coefficient for variation as a percentage.

The performances of the Master Surgical Schedules are similar based on the fluctuation of the daily peak utilization. Based on this PI, each MSS shows improvement for all wards except A6, H2, and B7. Each MSS also reduces fluctuations in admissions and discharges at wards A7, RGC, G2 (clinical and day-care), and D2. However, MSS I does not improve the performance of the RGC, but does improve the performance of H2. There is only one MSS that decreases the average peak utilization of a ward. Generally, an MSS appears to increase the average peak height.

We again predict the probability that on any given day, a ward has a shortage of beds. We show the results in Table 6-13. Note that again the difference we calculate cannot be guaranteed in some cases because the difference in both the average peak utilization and the standard deviation are not statistically significant.

Table 6-13 For each ward, the probability that on any given day the allocated capacity is insufficient

	A6	A7	H2	RGC	B7	G2 (Clinical)	D2	G2 (Day-care)
Current policy I	8%	54%	0%	42%	1%	0%	34%	0%
MSS I	6%‡	52%	0%	43%‡	2%‡	0%	31%	0%
Current policy II	5%	52%	0%	43%	1%	0%	33%	0%
MSS II	7%	53%‡	0%	43%	1%	0%	33%	0%
Current policy VII	6%	53%	0%	46%	1%	0%	33%	0%
MSS VII	6%	52%	0%	45%	1%	0%	33%	0%

‡ difference is not significant (both the difference in average peak utilization and standard deviation of peak utilization were not significant)

MSS I results in improvements for wards A7 and D2. MSS II results in no improvements, and deterioration for ward A6. MSS III results in improvements for wards A7 and the RGC.

Calculating the capacity needed for each ward to avoid a shortage of beds on 90% of the days results in the values that we show in Table 6-14

Table 6-14 Beds needed for each ward to accommodate the daily peak demand with 90% probability.

	A6	A7	H2	RGC	B7	G2 (Clinical)	D2	G2 (Day-care)
Current policy I	19	43	7	34	29	8	24	5
MSS I	19	41	7	34	30‡	8	23	5
Current policy II	18	43	7	34	29	8	24	5
MSS II	19	42	7	33	29	8	23	5
Current policy VII	19	43	7	34	29	8	24	5
MSS VII	19	42	7	33	29	8	23	5

‡ difference is not significant (both the difference in average peak utilization and standard deviation of peak utilization were not significant)

MSS I reduces the required capacity at wards A7 and D2. MSS II results in more capacity needed at ward A6, while decreasing the capacity needed at wards A7, D2, and the RGC. MSS III results in less capacity needed at wards A7, D2, and the RGC. Again, this is not yet sure, as we elaborate on in Section 6.5.

6.5 Discussion of simulation results

It is apparent from the experiments that for both the current and new ward configurations an MSS exists that levels the workload for nursing staff without deteriorating the OR performance. It is also plausible that fewer beds are needed in comparison to the current planning policy. However, we do not know by how much the capacities can be reduced.

The number of beds needed, resulting from our model, is higher than in reality for two reasons (for both the current planning policy and the MSS). First, in our model, peaks in bed utilization occur that only last for a few minutes. In practice a patient is likely discharged a few minutes earlier to prevent this peak. Second, the creation of surgical case types artificially increases the total amount of nursing days. Since this affects both the current planning policy and the MSS, it does not disprove the benefits of the MSS. However, we cannot determine the number of beds that can be saved by an MSS.

In our model, the largest bed reduction in comparison to the current planning policy is 3 beds in 2012 for both the current and new ward configuration. This is a less than the savings that result from Vollebregt's research. This is because his model had fewer restrictions. The most important difference is that in calculations, surgical beds are viewed as if they are all located in one ward, creating a pooling effect. Also, Vollebregt did not differentiate between adult and non-adults, and between elective and urgent surgeries. This allowed for larger case types and a higher percentage of surgeries scheduled in the MSS.

From our experiments we cannot conclude what settings to use in the creation of an MSS with respect to the weight and threshold we use in the grouping heuristic. The performance of those Master Surgical Schedules do differ, but not in a predictable way. This begs the question why these parameters have little influence on the outcome, and what other factor(s) cause their performance to vary.

In Appendix J we show that employing different values for the weight and threshold has little impact on the sets of surgery types we create with the heuristic. It is therefore plausible that there is another factor that influences the MSS performance. We investigated how similar Master Surgical Schedules are that we create using the same set of case types, but using different random numbers in the optimization step of the MSS. We re-created an MSS twice and inspection of the MSS revealed that there was little similarity in the arrangement of slots throughout the MSS cycle. We show this experiment in detail in Appendix K. Simulating the performance of both Master Surgical Schedules resulted in a statistically significant difference of 21 minutes overtime (average per week). We find statistically significant differences for 3 wards with the fluctuations of daily peak utilization, and for 5 wards with the fluctuation of admissions and discharges. Therefore, we believe that the product of the MSS optimization faze is not constant.

This discovery is both negative and positive. It is negative because we cannot point out how to create a well performing MSS solely through what values to use for the optimization parameters. It is positive because it leads to believe there may be Master Surgical Schedules that perform even better than the ones we found.

There are two options to find the best performing MSS. One option is to determine what values to employ for weight and threshold based on other considerations than the performance, and then, create multiple Master Surgical Schedules using those same settings. Which of those Master Surgical Schedules is the best performing can then again be determined in a simulation study. The other option is to use a heuristic such as simulated annealing, which might be able to produce more stable results. Then simulation studies may show what values are best for the weight and threshold parameters.

6.5.1 Limitations

In this section we discuss several limitations of the model we use, in order to better judge the merits of the simulation results.

We are unsure of the number of no-shows since there is no reliable registration available of such events. However it is likely that the number of no-shows is lower in reality than in our model (T. Meijer, head of admissions and OR planning, personal communication). We therefore expect that this does not decrease the benefits our model indicates.

The planning horizon we use for urgent surgeries is two weeks too long, and the planning horizon we use for elective surgeries is too short. In reality therefore, slots for urgent surgeries remain unfilled more often, and slots for elective surgeries remain unfilled less often. Since there are more elective surgeries we expect that this does not decrease the benefits our model indicates.

In practice, urgent surgeries are sometimes placed on the waiting list with a planning horizon smaller than two weeks (for instance when a surgeon requests that a patient is scheduled for surgery within four days). These planning horizons are not officially recognized, and on occasion will be problematic if an MSS is in place. The management should decide to either assign separate urgency categories to these surgeries or to make sure that the categories that are already defined are better enforced. In the first case, these surgeries must be excluded from the MSS. We have no data on the volume of surgeries to which this applies and are therefore unsure of the impact on the results.

In our model, the emergency surgeries are scheduled at the end of the day. In practice they often receive priority over the elective surgeries. When a surgery that is scheduled in the MSS is postponed for an emergency surgery, this might influence the MSS performance. However, we tested this and the MSS appears robust against changes in the order in which surgeries are scheduled. Even when the order of all MSS slots (within each OR-day) is shuffled within the MSS, the impact on the resulting utilization is small.

We did not include specific seasonal influences in our model. Seasonal influences can result in MSS slots remaining unfilled, in which case our results are too optimistic. However, we checked what the impact of seasonal influences would have been on an MSS, using the historical dataset of 2011 (see Appendix L) and conclude that in fact our model has a higher percentage of slots that remain empty, than would be the case in reality, due to seasonal influences (difference of 2,1 percentage points). This means our model incorporates more demand fluctuation than reality, and our results are too modest rather than too optimistic.

The reliability of our model is also closely linked to the quality of the dataset we use. We know that the data on emergency surgeries is not very reliable (see Appendix B). This is another reason why we cannot be sure how many beds can be saved by using an MSS.

In our model we currently disregard that patients sometimes stay at the ICU, before transferring back to their designated ward. This makes the predicted utilization that results from the MSS less reliable in reality, but only if such surgeries are included in the MSS.

In our model we assume that planners are able to "free-up" an extra surgeon for those surgeries that require multiple surgeons. This might be more difficult when an MSS dictates on what day to schedule such a surgery. On the other hand the MSS proves resilient against shifting surgeries within a day, so the planners are able to for instance plan such surgeries at the beginning or at the end of the day, before or after a surgeon sees patients at an outpatient clinic. These surgeries make up around 2% of the case-mix. Therefore we believe this assumption is of little consequence to the results we obtain from the experiments.

A final limitation of our model is that it does not include restrictions that are imposed by the availability of surgical instruments. Whether or not an MSS can be infeasible in this respect and, if so, whether it can be made feasible without deteriorating the OR and ward performance, remains to be seen. We expect this is not a bottleneck since most surgical case types consist of a variety of surgeries. Therefore the same rules that are currently in place to assure feasibility of the schedule can be used under the MSS planning policy.

6.6 Managerial implications

In this section we discuss the managerial implications of this study. In Section 6.6.1, we discuss the consequences of implementing the MSS for the work of surgeons. In Section 6.6.2, we discuss how planning and control functions must be adapted when an MSS is implemented. In Section 6.6.3, we discuss how the MSS should be kept up-to-date.

6.6.1 Consequences of implementing the MSS (for surgeons)

As we show in Appendix M, the MSS is robust against shifts in the sequence of surgeries within the OR-days. This means surgeons will still be able to operate on certain patients at the start of the day if there is a medical necessity to do so.

We also want to know if implementing the MSS makes the work of surgeons more repetitive. We investigate how often identical surgeries were scheduled on the same OR-day in the dataset of 2011 and compare this to the simulation of an MSS for 2011. We investigate this for general surgery, the specialty that has the most OR-time allocated. In the data set of 2011 the OR-days of general surgery contained 1,6 surgeries on average that were not unique on that OR-day.

From the 2011 surgery schedule that we create with an MSS we take the first period after the warm up periods as a sample. We then count the amount of case-types that are not unique on each OR-day. Given the surgeries contained within those case types, and their expected demand, we calculated the expected amount of non unique surgeries that schedule will contain. We do this three times, each time with other randomly generated patients that require surgery.

In Table 6-14 we show for each of the 3 runs the average number of non unique case types per OR-day, along with the expected number of non unique surgeries per OR-day.

Table 6-2 Repetitivity of surgical schedules under an MSS

Run	Average nr. of non unique case types per OR-day	Average nr. of non unique surgeries per OR-day (expected value)
1	0,5	0,1
2	0,9	0,3
3	0,7	0,1

Both the expected number of non unique surgeries per OR-day and the average number of non unique case types per OR-day are lower than the average amount of non unique surgeries scheduled per OR day in the data set of 2011. We believe this shows that the work of surgeons will become less repetitive upon implementing an MSS. We believe that scheduling identical case types on an OR-day is harmful to ward performance, and therefore, is avoided in the MSS optimization faze.

An important change in comparison to the current planning policy is that allocation of OR-time must now be done at the sub-specialty level, instead of the specialty level.

6.6.2 Execute the MSS (step 6)

In this section we explain how operational planning and scheduling rules should be altered upon implementation of an MSS.

The scheduling of (elective and urgent) patients for surgery is done on the operational off-line level after specialties have decided which surgeons use which OR-blocks. If an MSS is in place, it is important that this division of OR-blocks amongst surgeons is known at least 7 weeks in advance (the planning horizon for elective surgeries). This allows planners to alter the MSS if a surgeon is operating that does not perform all surgeries that are attributed to his sub-specialty.

Currently, patients are scheduled from the waiting list of the various surgeons, into the corresponding OR blocks on a first-come first-served basis. This is done two weeks in advance of the surgery date. Within this two week period alterations can still be made if there is an urgent demand for surgery (which has a two week planning horizon), or when patients cancel their appointment.

When an MSS is in place, planners should no longer limit themselves to planning surgeries for a single date. Instead they should find the first appropriate MSS slot for a patient within the planning horizon. Each day, planners can do this for the patients that have been put on the waiting list the day before. Surgeries that are not included in the MSS should still be planned each day for the OR date two weeks from then. The new planning rules for the central planner would be as follows:

- First, schedule patients with an urgent demand for surgery in the first appropriate MSS slot
- Second, schedule patients for elective surgery in the first appropriate MSS slot
- Third, schedule patients with an urgent demand for surgery for which no MSS slot can be found (within the planning horizon) into the first OR-day where its fits outside of the MSS
- Fourth, schedule patients for elective surgery for which no MSS slot can be found (within the planning horizon) into a feasible OR (outside the MSS) two weeks from then.

For those specialties that plan their own elective surgeries, a surgery date can be planned for a patient immediately after they are put on the waiting list for surgery at the outpatient department, for surgeries that are contained within the MSS. Those surgeries that are not contained within the MSS (or for which no slot is available within the planning horizon) should be planned where they do not create overtime together with the OR-time reserved for the MSS slots.

The deliberation between the planners and the schedule-coordinator of the OR department, to check the feasibility of the schedule, is still necessary. However, it will likely be quicker and lead to the disapproval of a schedule less often, depending on how much of the case mix is captured within the MSS. The MSS should be thoroughly examined on feasibility before implementation to decrease the possibility that any schedule is disapproved. An important check that is yet to be done is if the availability of instruments poses a problem for the MSS.

When ad hoc changes to the schedule are required on the on-line operational level, this can be done the same as in the current situation.

Currently, when less than 75% of an OR block is filled 14 days in advance, this block is returned to the head of admissions and OR planning and reallocated to a specialty with a long waiting list that has a surgeon available to operate on that day. This should be prevented when using an MSS. Therefore we recommend that Gelre Apeldoorn distributes the OR capacity evenly among the specialties (according to their case-mix requirements) before implementing an MSS. When it does occur that an OR block needs to be reallocated to another specialty, that specialty should admit its patients to the ward that is allocated to the specialty to which that OR block was originally assigned.

Scheduling patients into OR-days that belong to a reduction period can be done the same as in the current planning policy. However, this means that workload fluctuations increase during these weeks, and possibly more beds are needed (which is contrary to the principle of reduction), than when an MSS is in place. Gelre Apeldoorn now has the tools to design a suitable MSS within a day and therefore we recommend they investigate whether an MSS can be used during a reduction period at least 7 weeks before that reduction period starts. A pre-condition is off course that it is known at least 7 weeks in advance at which wards the capacity will be reduced and by how much. A problem with using an MSS during reduction periods might be that slots remain empty too often because patients are reluctant to accept a surgery date during holidays. In short, further research should be conducted to accurately predict the merits of creating an alternative MSS during reduction periods.

6.6.3 Update the MSS (step 7)

The MSS should be updated at least every year to adapt to changes in patient volume. Ideally the new MSS should be available at the beginning of the 7 week reduction period during the summer holiday. Since this reduction is as long as the planning horizon for elective surgeries, no surgeries need rescheduling because of changes in the MSS. The MSS should also be updated if either the case-mix changes (only if this affects the number of slots assigned to one of the case types), or the block-plan at the OR changes. If such changes are needed, a new MSS should be available 7 weeks in advance (due to the planning horizon). Otherwise there is a risk that patients are scheduled according to an MSS that is no longer feasible.

When creating a new MSS, historical data is needed on the performed surgeries in the most recent period of a year (ideally more, if the case-mix has not changed). Also, it needs to be clear whether any parts of the case-mix are expected not to follow the expected annual increase in patient volume of 3%. These data, along with the block-plan that will be in place in the period for which the MSS is made, serves as input for an Excel tool we developed that contains the grouping heuristic. Contained within the Excel tool is a step by step manual that guides the user through the process of importing, filtering, and repairing the data, creating case types from the data, and ultimately, creating surgery groups. The process results in a list that describes what surgeries are contained within each case type, and two text files that serve as input for the simulation software "OR manager", for which a manual is also available, which creates an MSS from the data in the text files and simulates its performance.

We recommend creating Master Surgical Schedules using the settings that worked best in this research: creating minimum sized groups and optimizing on "cycle peaks". Gelre Apeldoorn should decide which is more important: case types that are recognizable to planners, or scheduling more surgeries in an MSS. for the first they should employ a small threshold (5%). For the latter they should employ a large threshold (20%). We recommend using a weight of 0,5 because there is no evidence that favoring either comparability on OR-time or LOS leads to better results. In any case the settings used in the grouping heuristic should be the same each time an MSS is created. In that way the case types undergo only minor changes; otherwise planners might have difficulty adapting to a new MSS.

We also recommend making multiple Master Surgical Schedules from the resulting set of surgical case types. The performance results of each Master Surgical Schedule, generated from the simulation software can in turn be pasted into an Excel sheet that further guides the user through the process of interpreting the results. The best performing MSS can then be implemented.

For the best performing Master Surgical Schedules it should then be reviewed whether alterations need to be made to the instrumentarium or to the MSS that is ultimately chosen to be the best.

7. Conclusions and recommendations

In this chapter we recap what we have learned from this research. In Section 7.1 we answer the research questions that we introduced in Chapter 1. We also discuss to what extent we achieved our main goal, and what useful by-products result from the research. In Section 7.2 we discuss what new questions result from the research and what steps we recommend to be taken now.

7.1 Conclusions

We first answer the research questions one by one, thereby summarizing the knowledge obtained from this research. Then we discuss to what extent we achieved our main goal, and what useful by-products resulted from the research.

Q1. What are the basic principles of OR planning and what different forms of OR planning are known in the literature?

The goal of OR planning is efficient use of resources to satisfy the demand for surgery. It considers the dimensioning of required resources (strategic), the allocation of resources (tactical), the forming of planning routines and rules (tactical), assigning patients to an OR on a specific date and the actual scheduling of surgeries (i.e. determining the time and sequence in which patients are treated within a day) (operational off-line), and making ad hoc changes to the schedule when needed such as the scheduling of emergency surgeries (operational on-line) Hans et al. (2011).

Surgeons can claim OR-time for treating a patient on a first come first served basis, which is called an open block planning approach (van Oostrum et al., 2009). Alternatively, a closed block planning approach can be used (van Oostrum et al., 2009). In such an approach, blocks of OR-time (a block typically being a morning session, afternoon session, or a full day) are assigned either to a specialty or a surgeon prior to the actual scheduling of patients (Beliën & Demeulemeester, 2007; Magerlein & Martin, 1978).

The assignment of patients to an OR on a specific date can either be done by a centralized planner or by the specialties themselves (decentralized). The centralized planner has a broader scope, which transcends that of an individual specialty and the OR department. This creates opportunities to assign OR-time more efficiently and integrate the planning of external resources such as wards. The autonomy of surgeons, however, is reduced by centralized planning (van Oostrum et al., 2009). There may be many reasons why a surgeon prefers to treat patients in a certain order, which are unknown to the central planner. If possible, the autonomy of surgeons should be maintained (van Oostrum et al., 2009).

Q2. What are the advantages of an MSS and which steps in constructing it are known in the literature?

In an MSS, slots of OR-time are reserved for a specific surgical case type on the tactical level, allowing surgeons to decide which patient to treat in the slot. Each case type has an expected annual demand, surgery duration, and LOS at a specific ward, based on a set of surgeries that belong to that case type. Surgeries that belong to the same case type should use the same resources in a comparable quantity. This allows the central planner to design a recurring schedule of slots (for case types) that optimizes the utilization of the OR and the wards. Since the specific surgery to plan in such a slot is not imposed by the MSS, the advantages of centralized and decentralized planning are combined (van Oostrum et al., 2009).

Van Oostrum et al. provide an elaborate 7-step approach to create an MSS that recognizes that the desired scope for the MSS, and the desired solution techniques to apply, differ on a case-by case basis. We used this approach as a guideline for creating Master Surgical Schedules.

Q3. How can the performance of the OR department and wards be measured according to the literature?

Vissers & Beech (2008) argue that the performance of resource capacity planning can be assessed through three types of criteria:

1. Level of resource use
2. Fluctuation in resource use
3. Violations of resource restrictions

We select and adapt PIs from the literature and PIs used by Vollebregt that together cover all three criteria, for the performance of the surgical nursing wards and the OR department. However, we were not able to use all performance indicators in our experiments as we explained in Chapter 5.

Q4. How is resource capacity planning currently done at Gelre Apeldoorn and what is the resulting performance?

Gelre Apeldoorn currently uses a closed block planning approach for the allocation of OR-time to specialties. For some specialties the scheduling of patients is done centralized and for some specialties it is done decentralized.

Q5. How can we create a feasible MSS for Gelre Apeldoorn that decreases workload fluctuation and increases efficiency of the wards as much as possible?

We confine the scope of our MSS to the surgical specialties (excluding ophthalmology and anesthesiology) and the operating rooms and wards that are assigned to these specialties. Regrettably, we were unable to including surgical instruments in our scope to ensure feasibility of the created MSS. We create an MSS that adheres to the current allocation of resources to the specialties.

We use data on all surgeries performed in the year 2011, excluding, so called "reduction periods" to define a different sets of recurrent standard case types. For this we use a 4-step heuristic, based on a greedy algorithm, to define sub-sets of surgeries within the data set, which use the same resources in a comparable quantity, and abide by the same planning rules. Each sub-set defines a surgical case type. By employing different values for 3 parameters we use in this heuristic, we create 18 different sets of case types.

We use a constructive and an improvement heuristic to create two Master Surgical Schedules from each set of case types, by employing two different optimization criteria, which both aim to minimize the maximum amount of resources used as a result of the MSS. In this fashion we create 36 different Master Surgical Schedules, increasing our chances of finding the best performing one.

Q6. How can we approach an optimal MSS and how can we predict the performance of a proposed MSS, compared to that of the current schedule?

We compare the performance of the Master Surgical Schedules to the current planning policy, based on the performance indicators we defined, with a simulation model. First, we simulate each of the 36 Master Surgical Schedules for 2011 and discuss what values of what parameters we use in the creation of the Master Surgical Schedules generally lead to the best performing Master Surgical Schedules. Second, limiting ourselves to the promising values for these parameters, we create new Master Surgical Schedules for the period of summer 2012 to summer 2013. For these Master Surgical Schedules we predict the resulting performance in more detail, for each ward separately.

Q7. What are the benefits of implementing an MSS, compared to the current planning policy for the period of 2012-2013 with the current ward configuration and the new ward configuration?

For the period of the summer of 2012 to the summer of 2013 we succeeded in creating at least one MSS that levels the workload and increases the efficiency of the surgical nursing wards (for both the current and proposed new ward configuration). It is plausible that the efficiency increases enough to reduce capacity at some wards (up to 3 beds in total), but not yet sure, because of discrepancies between our model and reality as we explain in Chapter 6. Another point of uncertainty is the availability of surgical instruments. It remains to be seen whether an MSS is indeed feasible based on this aspect.

Our main goal was to *"Design a Master Surgical Schedule that levels the workload and increases the efficiency of the surgical nursing wards of Gelre Apeldoorn and does not deteriorate the OR department's efficiency".*

We conclude that we succeeded in this goal for both the scenario that Gelre Apeldoorn continues to use the current ward configuration and the scenario that they implement the current plans for a new ward configuration. However, there are a few important considerations.

The Master Surgical Schedules remains to be checked for feasibility judging by the available surgical instruments. Also, we cannot give an exact prediction of how much the efficiency increases and how much the workload is leveled.

7.2 Recommendations

In this section we discuss what new questions result from the research and what steps we recommend to be taken now.

Supplementary experiments that we performed (see Chapter 6) indicate that the outcome of the optimization step we use to create an MSS is not constant. Because of this we believe that an even better MSS should be possible than the ones we found. Also because of this, there are two parameters we use in the creation of an MSS for which we cannot argue what values lead to better performing Master Surgical Schedules. We recommend that Gelre Apeldoorn decides what values to use for these parameters based on considerations other than the resulting performance. Then, using the tools that resulted from this research, multiple Master Surgical Schedules should be created using those identical settings, after which the best one can be determined by a simulation study. Another option is to further improve the optimization step, for instance by implementing simulated annealing, to make the outcome of this step more constant.

As a by-product of this research, the tools that enable Gelre Apeldoorn to predict the impact of an MSS also enable them to predict the impact of other organizational changes. Examples are changes in the allocation of OR-time to specialties, and the allocation of surgical beds to specialties. We suggest this is used to further perfect these allocations before a definitive MSS is created.

Also, in the final weeks of this research, plans were made to redistribute parts of the case-mix between Gelre Apeldoorn, Gelre Zutphen, and the Deventer Hospital. These plans should be taken into account when creating the definitive MSS.

A final recommendation (at the risk of being redundant) is that Gelre Apeldoorn implements ways to make (reliable) data more easily accessible. The progress of this research was severely hampered by the absence of readily available case-mix data. We did provide a tool that is able to analyze the quality of surgical case-mix data and “repair” it to some extent, but ideally this information should be more reliable to begin with and more easily accessible (van Oostrum et al, 2009) if Gelre Apeldoorn wants to continue using Operations Management principles to increase efficiency. This off-course does not apply solely to case-mix data.

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Appendix A: Performance Indicator equations

In this appendix we present the equation we use to calculate each performance indicator.

OR department performance indicators

We refer to OR i on weekday *d(excluding weekends)* as O_{id} with capacity C_{id} (the amount of regular working hours).

Level of resource use

Utilization of OR time - *We define utilization as the total amount of time patients are in the OR during regular working hours divided by the total amount of regular working hours. We exclude emergency patients from this calculation.*

$$Utilization\ of\ OR\ time = \frac{\sum_{p=1}^{n}(\min\{T_p^{depart}, T_p^{schedule\ end}\} - T_p^{arrive})}{\sum_{d=1}^{200}\sum_{i=1}^{10} C_{id}} * 100\%$$

T_p^{depart}; Time at which patient p leaves the OR

T_p^{arrive}; Time at which patient p enters the OR

$T_p^{schedule\ end}$; Time at which the OR-schedule, of the OR where patient p undergoes surgery, ends

Fluctuation in resource use

Fluctuation in OR finish time: *Performance Indicator was not used (see Chapter 5)*

Violations of resource restrictions

Cancellations due to insufficient theatre time: *Performance Indicator was not used (see Chapter 5)*

Overtime - *We define overtime as the total amount of surgery time for elective and urgent surgeries that fell outside of regular hours as a percentage of the total amount of regular capacity available.*

$$Overtime = \frac{\sum_{eup=1}^{n}(\max\{T_{eup}^{depart} - T_{eup}^{schedule\ end}, 0\})}{\sum_{d=1}^{200}\sum_{i=1}^{10} C_{id}} * 100\%$$

T_{eup}^{depart}; Time at which elective/urgent patient *eup* leaves the OR

T_{eup}^{arrive}; Time at which elective/urgent patient *eup* enters the OR

$T_{eup}^{schedule\ end}$; Time at which the OR-schedule, of the OR where elective/urgent patient *eup* undergoes surgery, ends

Ward performance indicators

We refer to ward *i* on weekday *d (excluding weekends)* as W_{id} with capacity C_i.

Level of resource use

Average peak utilization of ward - *We average, for each ward, the daily peak number of beds divided by the capacity.*

$$Average\ peak\ utilization\ ward\ i = \frac{\sum_{d=1}^{n}(peak_{id}/C_i)}{n} * 100\%$$

$peak_d$; Peak nr of beds occupied at ward *i* on day *d*

Fluctuation in resource use

Fluctuation in peak utilization of ward - *We measure this, for each ward separately, through the standard deviation of the daily peak utilization.*

$$Fluctuation\ in\ peak\ utilization\ of\ ward\ i = \sigma(peak_{id})$$

Fluctuation in admissions and discharges - *We measure these through the coefficient of variation of the daily sum of admissions and discharges handled, separately for each ward (excluding weekends).*

$$Fluctuation\ in\ admissions\ and\ discharges\ of\ ward\ i = \frac{\sigma(peak_{id})}{\mu(peak_{id})}$$

Violations of resource restrictions

Ward overflow: *Performance Indicator was not used (see Chapter 5)*

Appendix B: Data gathering and validation

In this research we provide insight into how we gather case-mix data, and we provide insight into the quality of this case-mix data.

We use a year of data on surgical procedures performed at the OR department, which is retrieved from the hospital information system "SAP" by employees of the Medical Information Centre and presented in an Excel sheet. We developed an Excel tool specifically for analyzing the quality of these data and for repairing it to some extent. For a detailed description of this tool, a manual is available at the "regiebureau patientenlogistiek" at Gelre Apeldoorn. We also use the tool to transform data at the level of surgical procedures to data at the surgery level (surgeries can be composed of multiple surgical procedures). Then we use it to determine for each surgery the expected annual demand, the expected surgery duration, and the expected LOS. We also use the tool to create case types within the case-mix (see Chapter 4) but that is not the subject of this appendix.

The initial Excel sheet with data on surgical procedure should contain the following records for each procedure (the coded names are in Dutch, we provide a translation/explanation for each):

Coded names	Translation/Explanation
Ok_nummer	*Surgery number*
REA_locatie	*Location of the surgery (Gelre Apeldoorn/Gelre Zutphen)*
REA_operatiekamer	*Operating Room*
REA_OK_datum	*Surgery date*
REA_begintijd_OK	*Start of surgery (patient enters the OR)*
REA_eindtijd_OK	*End of surgery (patient leaves the OR)*
Operatieduur	*Surgery duration*
PAT_patientnr	*Patient number*
PAT_geboortedatum	*Birth date of patient*
Ctg_code	*Surgical procedure code*
Ctg_omschrijving	*Surgical procedure description*
Radiologisch_laborant	*Radiology lab-worker (present yes/no)*
REA_specialisme	*Performing specialty*
REA_uitvoerend_specialist	*Performing specialist*
REA_opname_dd	*Date of admission*
REA_opname_tijd	*Time of admission*
REA_opname_afdeling	*Ward of admission*
REA_ontslag_dd	*Date of discharge*
REA_ontslag_tijd	*Time of discharge*
REA_ontslag_afdeling	*Ward of discharge*
Zgv_nr	*Disease case number*

Coded names	Translation/Explanation
ORD_urgentie	*Medical priority*
ORD_datum_wachtlijst	*Date placed on waitinglist*
Klin_stat	*Clinical status (clinical/day-care/outpatient)*
ZCOMBI	*Was a second surgeon present?*
Wwyyyy	*Surgery week and surgery year*
Dagrooster	*OR roster to what specialty and surgeon was the OR allocated*
Combi	*Was a second surgeon present?*
Heroperatie	*Was the surgery on a patient that was already admitted for another surgery?*
Tot_ic_dagen	*Total number of days spent recovering at the ICU*
ORD_rontgen	*Was the use of X-ray equipment ordered?*

First we filter the data according to our scope. We discard surgical procedures that:

- Were performed at Gelre Zutphen
- Were performed at OR 5 or 6 (dedicated to Ophthalmology and Anesthesiology)
- Were performed before or after 2011, or in the reduction periods
- Were performed on patients that were admitted and discharged within one weekend
- Lacked a surgical procedure code registration
- Contain surgical procedure codes that are of a financial nature, are prosthetics codes, or are codes for procedures done at the laboratory.
- Were performed by a specialty that is beyond our scope
- Surgeries performed on patients that are already admitted for another surgery (they already have their LOS registered in the dataset)
- Surgeries that have no admission time and medical priority registered, and were not coupled to an admission order (assumed to be emergency surgeries on patients that are already admitted for another surgery)

This results in the case-mix as shown in the figure below. Note that some surgeries are registered as outpatient. These patients did require hospitalization and we corrected them by hand.

Case-mix categorized according to specialty, clinical status, and medical priority

		Medical priority			
Specialty	Clinical status	Elective	Urgent	Emergency	Grand Total
General surgery		1334	824	1092	3250
	Day-care	880	307	23	1210
	Clinical	448	517	1064	2029
	Outpatient	6		5	11
Gynecologie		477	99	294	870
	Day-care	185	51	5	241
	Clinical	289	48	289	626
	Outpatient	3			3
Oral surgery		207		9	216
	Day-care	187			187
	Clinical	7		9	16
	Outpatient	13			13
ENT		596	28	40	664
	Day-care	110	13	6	129
	Clinical	486	15	33	534
	Outpatient			1	1
Orthopedics		2249	177	216	2642
	Day-care	1045	104	9	1158
	Clinical	1204	73	205	1482
	Outpatient			2	2
Pediatrics		25	33	14	72
	Day-care	21	28	3	52
	Clinical	4	5	11	20
Plastic surgery		760	39	30	829
	Day-care	600	31	7	638
	Clinical	137	6	20	163
	Outpatient	23	2	3	28
Urology		496	185	50	731
	Day-care	190	40	3	233
	Clinical	302	145	47	494
	Outpatient	4			4
Grand Total		6144	1385	1745	9274

Of the remaining surgeries, 396 lacked both registration of the admission time and date and registration of the discharge time and date. In addition, 41 lacked only discharge time and date. Therefore, we could not determine the LOS for 437 surgeries (5% of all surgeries) of which 380 were emergency surgeries.

The surgery start time was missing for three surgeries. The surgery ending time was missing for 129 other surgeries. Thus, for around 1% of the surgeries we have no surgery duration. We also had to correct the surgery duration for 117 surgeries. Because they ended after the next surgery in the schedule of that OR-day had already started. We assumed that the OR staff forgot to register the surgery ending on time, and assume that those surgery ended 8 minutes (the changeover time) before the start of the next surgery.

We also know that the registration of the use of x-ray equipment is sometimes lacking. We corrected for this by manually registering X-ray usage in the dataset for surgeries that always require x-ray equipment according to the head of admissions and OR-planning.

Appendix C: Current block-plan

Gelre Apeldoorn uses a cyclical 2-week block plan for allocating OR-time to specialties. In the figure below we show the block-plan that is currently in effect.

Current allocation of OR-time to specialties or "block plan". Those OR blocks that are not allocated to the same specialty in both even and odd weeks are marked.

OR	1	2	3	4	5	6	7	8	9	10
Even weeks										
Mon. morning	GEN	PLS	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GYN
Mon. afternoon	GEN	PLS	PED*	ORTH	EYE	X	GEN	ORTH	GEN	GYN
Tue. morning	URO	PLS	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GEN
Tue. afternoon	URO	PLS	ENT	ORTH	EYE	X	GEN	ORTH	GEN	GEN
Wed. morning	X	ORAL	ENT	GEN*	EYE	ANE	GEN	ORTH	GEN	GYN
Wed. afternoon	X	ORAL	PLS	GEN*	EYE	X	GEN	ORTH	GEN	GYN
Thur. morning	URO	PLS	ENT*	ORTH	EYE	ANE	GEN	ORTH	GEN	GEN
Thur. afternoon	URO	PLS	ENT*	ORTH	EYE	X	GEN	ORTH	GEN	GEN
Fri. morning	URO	GEN	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GYN
Fri. afternoon	URO	GEN	X	ORTH	X	X	GEN	ORTH	GEN	GYN
Odd weeks										
Mon. morning	GEN	PLS	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GYN
Mon. afternoon	GEN	PLS	ENT*	ORTH	EYE	X	GEN	ORTH	GEN	GYN
Tue. morning	URO	PLS	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GEN
Tue. afternoon	URO	PLS	ENT	ORTH	EYE	X	GEN	ORTH	GEN	GEN
Wed. morning	X	X	ENT	ORTH*	EYE	ANE	GEN	ORTH	GEN	GYN
Wed. afternoon	X	ORAL	PLS	ORTH*	EYE	X	GEN	ORTH	GEN	GYN
Thur. morning	URO	PLS	GEN*	ORTH	EYE	ANE	GEN	ORTH	GEN	GEN
Thur. afternoon	URO	PLS	GEN*	ORTH	EYE	X	GEN	ORTH	GEN	GEN
Fri. morning	URO	GEN	ENT	ORTH	EYE	ANE	GEN	ORTH	GEN	GYN
Fri. afternoon	URO	GEN	X	ORTH	X	X	GEN	ORTH	GEN	GYN

Appendix D: Allocated OR-time to specialties

In the figure below we show the OR-time available to each specialty in the two-week cycle, for performing elective and urgent surgeries.

Allocated OR-time to each specialty within the two-week cycle

Program	Specialties								
	Ear- Nose – Throat (ENT)	General surgery	Gynecology & Obstetrics	Oral surgery	Orthopedics	Pediatrics	Plastic surgery	Urology	Total
Regular program (480 min.)	2	2	4	2	11		6	6	33
Morning program (240 min.)	5								5
Afternoon program (210 min.)						1	2		3
Extended program (540 min.)	2	6			4				12
Program with 100 min. of emergency slack (380 min.)		18			1				19
Friday program (360 min.)		2	2		2				6
Friday program with 100 min. of emergency slack (260 min.)		1							1
Total time (min.)	*3240*	*12020*	*2640*	*960*	*8540*	*210*	*3300*	*2880*	*33790*
Percentage of available capacity	*9,6%*	*35,6%*	*7,8%*	*2,8%*	*25,3%*	*0,6%*	*9,8%*	*8,5%*	*100%*

Appendix E: Allocation of OR-time to sub-specialties

The allocation of OR-time to sub-specialties is not regulated by the block plan we show in Appendix C and can differ each cycle. In our simulation model we require a block-plan at the sub-specialty level. General surgery has four sub-specialties for which we create the block-plan as that we show in the figure below.

Allocation of OR-days to the sub-specialties

OR	1	2	3	4	5	6	7	8	9	10
Even weeks										
Mon.	GE(e)						ONCO(n)		VASC(l)	
Tue.							TRAU(e)		ONCO(l)	GE(e)
Wed.				ONCO(n)			TRAU(e)		ONCO(e)	
Thu.							VASC(e)		GE(l)	ONCO(e)
Fri.		ONCO(f)					TRAU(e)		GE(e)	
Odd weeks										
Mon.	GE(e)						TRAU(e)		VASC(l)	
Tu.							TRAU(e)		ONCO(l)	GE(e)
Wed.							TRAU(e)		ONCO(e)	
Thur.			ONCO(l)				VASC(e)		ONCO(e)	
Fri.		ONCO(f)					TRAU(e)		GE(e)	

Gastroenterology (GE), Oncology (ONCO), Traumatology (TRAU), and Vascular surgery (VASC). Each is allocated either a **n**ormal schedule (n), a schedule with 100 minutes of **e**mergency slack (e), a schedule that terminates earlier on a **F**riday (f), or a schedule that terminates **l**ater (l).

We create this block plan by allocating each block of OR-time that is assigned to General surgery, to the sub-specialty that used that block the most in 2011. We then calculate the amount of OR-time each sub-specialty used in 2011 to treat their patients, as a ratio of the total time that General surgery had performed surgeries. We then make small adjustments to the initial allocation so that the allocation of OR-time reflects those ratios. This was done together with the head of admissions and OR planning.

Appendix F: Unrecognizable case types

In this appendix we show an example of the surgeries contained within a case type that was created with a threshold of 30% and an example of the surgeries contained within a case type that was created with a group size of 40 (values employed by Vollebregt). We believe such case types become unrecognizable for planners because the expected surgery durations of surgeries contained within the case types are too far apart. In our study we use lower threshold values and create minimum sized groups while employing a smaller minimum group size (20).

Example of surgeries contained within a case type after using a 30% threshold

Surgery type ID	Frequency	Expected surgery duration	Expected LOS
428	4	1:03	0,27
205	1	1:02	0,24
195	182	1:12	0,28
233	2	1:21	0,43
120	4	1:35	0,36
51	77	1:28	0,39
208	1	1:25	0,30
192	1	1:23	0,30
118	15	1:23	0,33
123	10	1:25	0,35
111	3	1:32	0,33

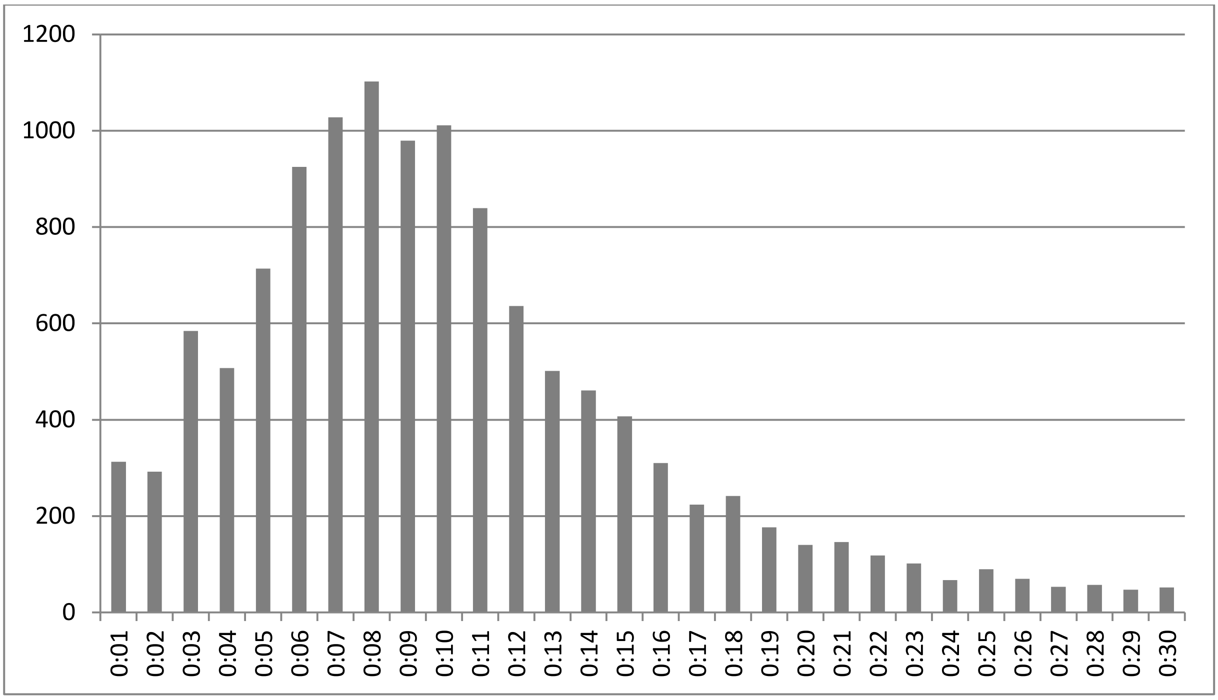
Example of surgeries contained within a case type after creating minimum sized groups with a frequency of 40

Surgery type ID	Frequency	Expected surgery duration	Expected LOS
403	1	0:16	0,24
188	1	0:34	0,29
1	9	0:36	0,37
375	8	0:40	0,25
69	9	0:44	0,31
405	2	0:48	0,27
201	1	0:53	0,34
53	1	1:04	0,34
194	13	1:07	0,28
117	1	1:30	0,41
49	19	1:30	0,43

Appendix G: Changeover time

We define the changeover time as the time between a patient leaving the OR and the next patient entering that OR. For the changeover time in our simulation model, we use the mode of all changeover times registered in 2011. We use the mode because it is a more robust measure than the average, which is in this case influenced by for instance lunch breaks. The changeover time we use is 8 minutes, based on the histogram depicted below.

Histogram of changeover times in 2011 (excluding Anesthesiology and Ophthalmology)

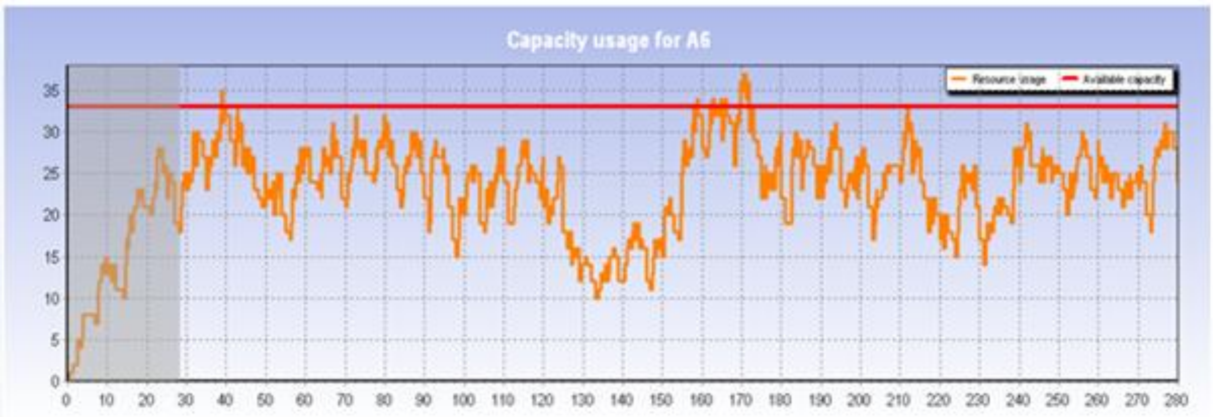


Appendix H: Determining warm-up period and number of runs

At the start of a simulation run, the wards are empty. In reality, most wards are not empty at the start of a new year. To correct for this discrepancy between the model and reality we discard the period that the model needs to reach a steady state, which is called the warm-up period.

In the figure below we show the number of beds occupied at ward A6 during a simulation run. The effects of the "empty start" are visible during the first two cycles of two weeks (28 days). Therefore, we determine that the warm-up period is 2 cycles. We determined the warm-up period based on ward A6 because it requires the most time to reach the steady state

Number of beds occupied throughout a year at ward A6 (screenshot from "OR manager")



Ward A6 also needed the most simulation runs (20) to produce reliable results. We determine the number of runs needed with the sequential procedure from Law (2007) to obtain a relative error of 0.025 and a confidence level of 0.95.

Appendix I: T-test results 2011

In this appendix we present the t-test results for the 2011 experiment, which we deem the most relevant. The other t-test results are available on request.

We present the outcomes for the comparison between the Master Surgical Schedule clusters that we clustered according to the threshold value, for the overtime PI, because these were the only t-tests that were inconclusive.

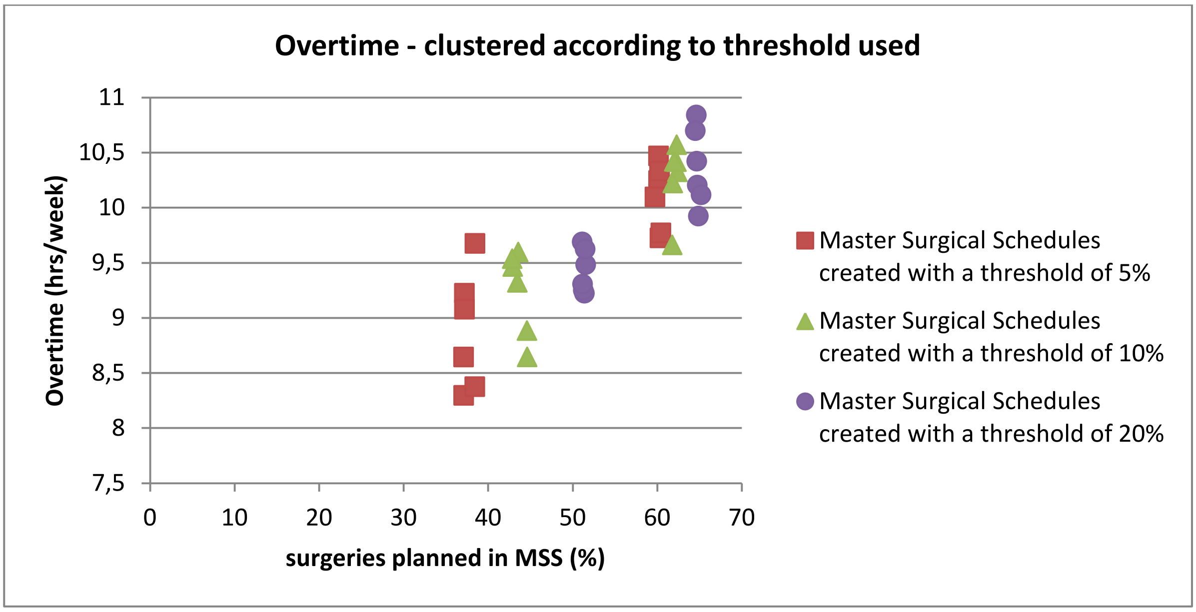
In the table below we show the one-sided two sample t-test results, for the t-tests we perform to gage the merits of employing several threshold values for the overtime. For each comparison we show the value P(T<=t). We overturn the hypothesis that both samples are drawn from a "population" with the same expected value for the mean, when P is smaller than 0,05.

P(T<=t) for each t-test between the Master Surgical Schedule clusters (clustered according to the threshold parameter)

Threshold	5%	10%	20%
5%		0,470746	0,014794
10%			0,037406
20%			

The amount of overtime produced is larger when using a threshold of 20%, than when using a threshold of 5% or 10% (according to our standards). The difference in overtime is not statistically significant between the 5% and 10% cluster. We believe these results are inconclusive because, even though they seem to indicate that employing a 20% threshold produces more overtime, we cannot conclude that the threshold value is a strong predictor for the overtime resulting from an MSS. We also base this on the graphical representation as shown below.

Figure 7-1 Percentage of surgeries scheduled in the Master Surgical Schedules and overtime generated by the Master Surgical Schedules, clustered according to the "threshold" parameter.



We did not discard the 20% threshold from our scope. In the 2012 scenarios

In our research we choose this was unconvincing and we did not limit our scope to creating Master Surgical Schedules with a 20% threshold. The only MSS for the 2012 scenario with the current ward configuration, that resulted in an overtime that was not larger than the current planning policy with statistical significance, turned out to be an MSS created with the 20% threshold. None of the three Master Surgical Schedules for the 2012 scenario with the new ward configuration, that resulted in an overtime that was not larger than the current planning policy with statistical significance, turned out to be created with the 20% threshold. We believe this confirms that the threshold parameter does not provide a reliable indication for the overtime resulting from an MSS.

Appendix J: Impact of weight and threshold on created case types

In this appendix we investigate how similar the sets of surgical case types are that we create after altering the effect and weight factors. For this comparison we only employ the 5% and 20% threshold, and the 0,5 and 0,8 weight factors since we expect the differences to be largest between these values. For the same reason we do not employ minimum sized grouping. In the table below we show for each combination of settings how many case types are created, and how many of these case types are identical compared to another combination of settings. It is clear that the sets show a lot of similarity. Particularly the effect of a different value for weight seems to make little difference. Closer inspection of the created case types also reveals that those types that do differ, often do not differ much (for instance, one surgery is transferred from one case type to another, causing 2 case types to be unidentical, but nevertheless still very similar). We conclude that altering the threshold and weight parameters has little impact on the sets of case types that are created in the heuristic. This explains why we were unable to determine which values for these parameters lead to superior performing Master Surgical Schedules.

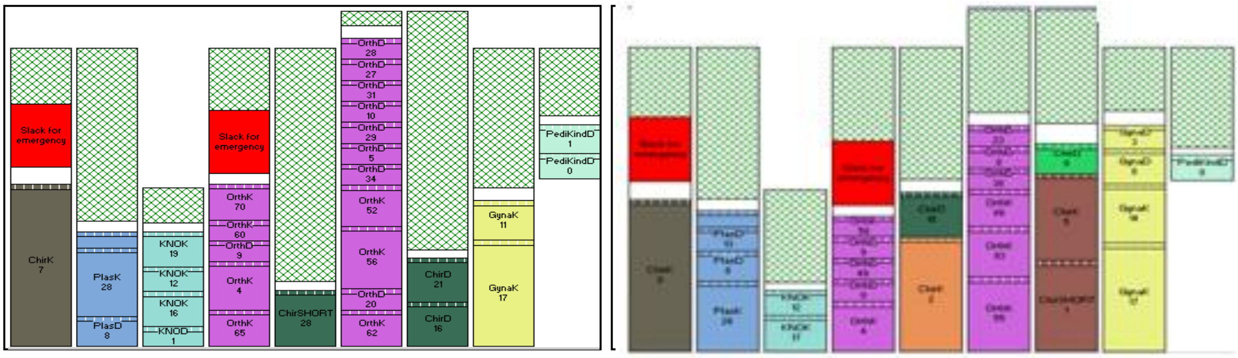
The amount of case types that are identical between the case type sets we create by alternating values for threshold and weight (i.e. the amount of case types that contain the same surgeries)

	{threshold used;weight used} (# case types created)			
{threshold used;weight used} (# case types created)	**{5;0,5} (220)**	**{5;0,8} (220)**	**{20;0,5} (193)**	**{20;0,8} (194)**
{5;0,5} (220)	-	122	101	105
{5;0,8} (220)		-	101	105
{20;0,5} (193)			-	141
{20;0,8} (194)				-

Appendix K: Stability of the MSS optimization faze

In this appendix we investigate how similar Master Surgical Schedules are that we create using the same set of case types, but with different random numbers in the optimization step of the MSS. We re-created an MSS twice and inspection of the MSS revealed that there was little similarity in the arrangement of slots throughout the MSS cycle. In the figure below we show the arrangements of MSS slots on the first Monday of the MSS cycle for both Master Surgical Schedules as an example.

Arrangement of slots on the first Monday of the MSS cycle, for two MSS cycles created from the same set of surgery types, but with other random numbers in the MSS optimization heuristic. Each vertical column represents an OR. The colored rectangles represent slots.



Simulating the performance of both Master Surgical Schedules resulted in a statistically significant difference of 21 minutes overtime (average per week). We present the ward performance outcomes in the table below, which also confirm that the product of the MSS optimization faze is not constant.

Values of each ward performance indicator, for each ward, compared between the MSS and the current planning policy

Performance Indicators	Simulation of:	Wards							
Average peak utilization		A6	A7	H2	B8	B7	G2 (Clinical)	D2	G2 (Day-care)
	Best performing MSS	78,4	95,3	25,5	71,6	83,9	24,4	92,8	27,4
	Regenerated MSS	77,6	95,9	25,3	71,5	83,6	23,7*	92,3	27,8
Fluctuation in peak utilization of ward (standard deviation):									
	Best performing MSS	14,9	14,9	13,06	19,8	15,7	11,6	17,2	15,2
	Regenerated MSS	14,0	14,8	12,1*	20,3	16,0	11,7	15,7*	14,5*
Fluctuation in admissions and discharges of ward (coefficient of variation):									
	Best performing MSS	42,1	23,5	73,4	33,1	26,9	55,0	17,9	54,7
	Regenerated MSS	44,5†	21,9*	75,2	33,5	26,2*	55,7	16,6*	50,8*

Statistically significant improvements are marked with * and significant deteriorations are marked with †)

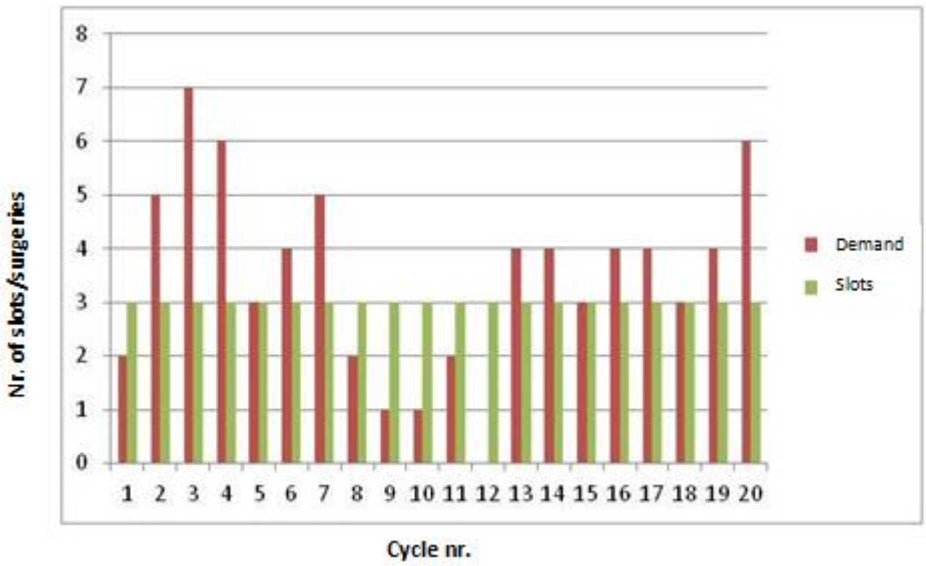
Appendix L: Effect of seasonal influences

In this research we model the flow variability by generating demand for each surgery with a probability that is equal to its case-mix percentage (see Chapter 5). We assume that this probability of demand is constant throughout the year (i.e. the effect of seasonal influences is negligible). In this appendix we explore whether this assumption decreases the validity of the outcomes of our simulation experiments. This is the case when more slots are filled in our model than in reality.

We check the assumption for the set of case types that was the input for the MSS that performed the best in 2012 with the current ward configuration. Only we create an MSS for the year 2011, to compare it to the realized case-mix.

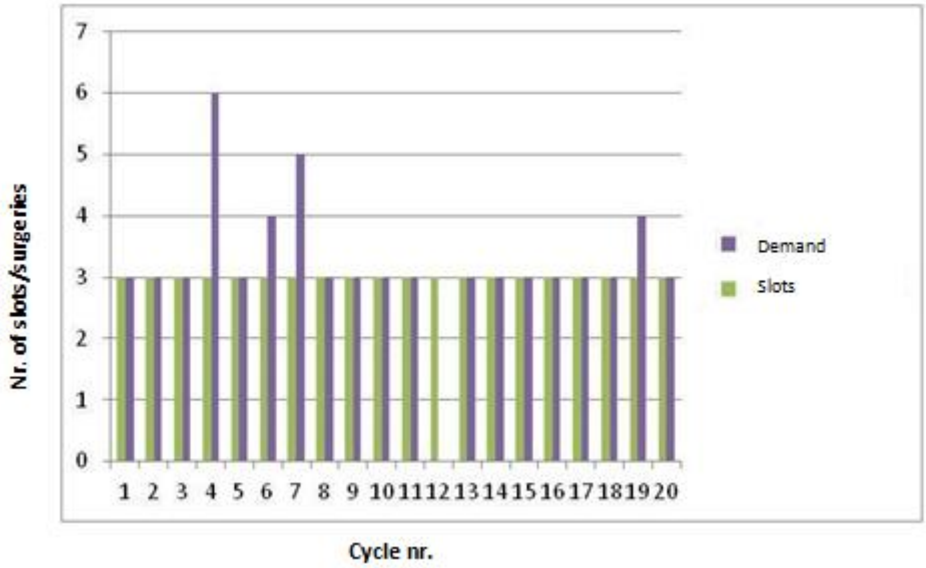
For each surgery in the historical case-mix we know the date that it was placed on the waiting list. We use this data to determine for each case type, the generated demand during each two-week cycle. In the figure below we show how this demand fluctuates throughout the year, along with the amount of available slots, as an example for one case type. Note that for some periods there is not enough demand to fill the slots.

Nr. of slots available and fluctuating demand during 1 year



However, the planning horizon allows us to distribute the demand more evenly over the slots, resulting in less slots remaining unfilled, as we show in the figure below.

Nr. of slots available and distributed demand during 1 year



Applying the MSS to the realization in this manner resulted in 2,3% of the slots remaining unfilled. Simulating the same MSS resulted in 5,4% of the slots remaining unfilled. We have to subtract from this the 1% no-shows we apply in our model. Therefore, the portion of slots that remain unfilled is 2,1 percentage points higher that would be the case in reality. This is contrary to what we would expect since there are no seasonal influences in our model.

Another difference between our model and reality is that the planning horizon for elective surgeries is 2 weeks shorter in our model. This makes it harder to redistribute peaks in demand. Apparently, this effect is stronger than the effect of seasonal influences on demand, resulting in more slots remaining unfilled in our model, than in reality. We conclude that disregarding the seasonal influences did not lead to results that were too optimistic.

Appendix M: Effect of altering the sequence of the surgeries within an OR-day on MSS performance

In our model the sequence in which surgeries are performed is fixed. In reality surgeons might prefer to treat patients in a different order. Also, in our model emergency surgeries are scheduled at the end of the day. In practice elective surgeries are often postponed because the emergency surgeries are prioritized. In this Appendix we investigate whether our results are too optimistic because we do not include such alterations to the surgical schedule.

To gage the effect of shifting surgeries we reapeat the simulations for the best performing MSS for 2012 with the current ward configuration, with the addition that we shuffle the surgeries on all OR-days before starting each simulation run. We then compare the results to those obtained without shuffling.

The experiment resulted in an average of 3 minutes more overtime in the shuffled MSS. A small difference which we know to be the consequence of clinical and flow variability (because shuffeling alone cannot affect the overtime in our model). We show the outcomes of the ward performance indicators in the figure below. Most differences in the PI outcomes are small and not statistically significant. While keeping in mind that in reality alterations in the sequence of surgeries will be much more subtle, we think that this experiment proves that an MSS is robust against such alterations.

Values of each ward performance indicator, for each ward, compared between the MSS with and without shuffling

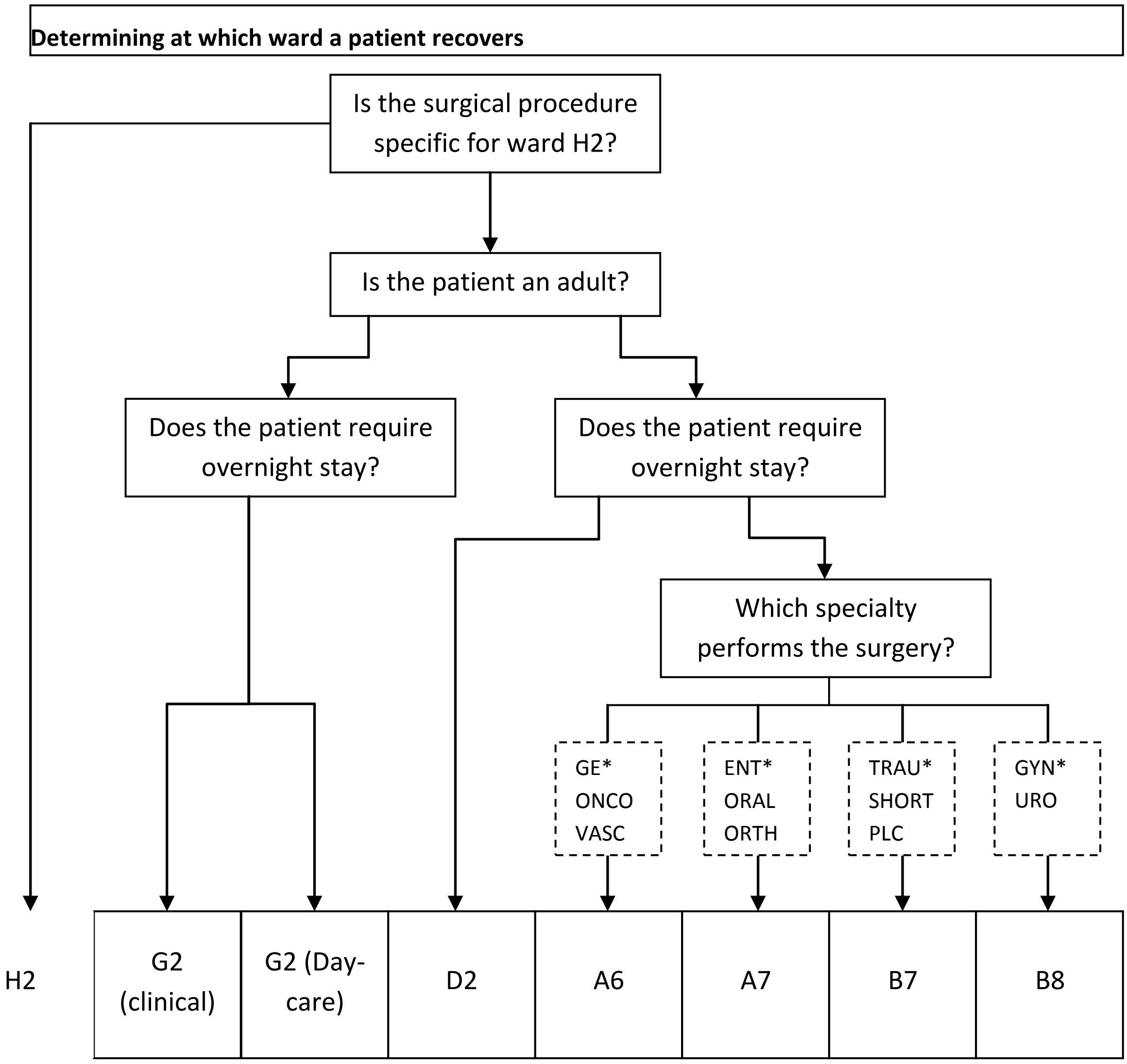
Performance Indicators	Simulation of:	Wards							
		A6	A7	H2	B8	B7	G2Klin	D2	G2Dag
Average peak utilization	Without shuffling	80,0	95,6	24,9	71,7	83,5	24,0	92,7	27,8
	With shuffling	80,1	96,3	24,6	72,0	83,2	24,0	91,1*	27,7
Fluctuation in peak utilization (St dev)	Without shuffling	13,4	14,2	12,9	19,6	16,4	11,4	16,7	15,6
	With shuffling	13,5	14,6	13,0	19,5	15,8*	11,5	16,6	15,0*
Fluctuation in adm+dis[1]	Without shuffling	42,2	23,0	73,8	37,1	26,9	54,8	17,7	55,0
	With shuffling	42,3	23,8†	74,6	36,0	26,8	56,0	17,9	53,3*

Statistically significant improvements are marked with * and significant deteriorations are marked with †

[1] coefficient of variation. Adm+dis, Admission and discharges

Appendix N: Determining at which ward a patient recovers

The figure below shows how we know at which ward a patient recovers. The allocation of wards to specialties is that of the current ward configuration.



*Specialty abbreviations: Gastroenterological surgery (GE), Oncology (ONCO), Vascular surgery (VASC), Ear-Nose-Throat (ENT), Oral surgery (ORAL), Orthopedics (ORTH), Trauma surgery (TRAU), Short-stay general surgery (SHORT), Plastic surgery (PLC), Gynecology (GYN), Urology (URO)