Reallocate operating room time among surgical services

The case of a public Portuguese hospital

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Abstract

Health care providers are facing a continuous increase in the complexity of their organizations mainly due to the increasing demand and to the development of new and expensive technologies. The operating room (OR) is a major challenge in the hospital and is important for the financial health of the hospital. Moreover, it has a large impact in several units of the hospital and on the workforce of the immediate downstream units. In the last decades, surgery demand has been increasing, forcing operating rooms to be more efficiently and effectively managed. This work is developed under a partnership with a Portuguese public hospital and aims to contribute to a major social impact, which is the reduction of patients on the waiting list Given the hospital restrictions in terms of space and human resources, this work focus on the reallocation of the operating room time among the surgical services, proposing a new master surgical schedule – a timetable with the number of slots, day and room in which each specialty should operate. This reallocation has as main objective to match demand and the existing capacity while maximizing the OR efficiency. This work proposes a mixed integer linear programming, with four distinct objectives; to maximize the allocated slots and aggregated preferences, to match supply and demand and to level the workload of up- and downstream units. A comparison of the actual allocation of slots with the one suggested by this approach is performed. Results show that the workforce is one of the major restrictions, suggesting a new distribution of the workforce among the specialties.

Keywords: Operating Room; Master Surgical Schedule; Capacity Planning; Resource Allocation; Waiting Time; Mixed Integer Linear Programming

Resumo

Atualmente os prestadores de serviços de saúde enfrentam uma crescente complexidade devido a um aumento na procura e ao desenvolvimento de novas e caras tecnologias. O bloco operatório é um dos grandes desafios de um hospital, visto tratar-se de um dos centros com maiores custos e de maior rendimento para o hospital. O bloco operatório tem inclusivamente um grande impacto nas unidades a montante e a jusante, sendo alvo de uma crescente pressão para atingir maiores níveis de eficiência. Este trabalho é desenvolvido em parceira com um hospital público português e tem como principal objetivo a diminuição da lista de espera para cirurgia. Tendo em conta as restrições em termos de recursos humanos e de espaço, este trabalho propõe realocar os tempos cirúrgicos pelas especialidades, criando um novo plano operativo onde os tempos cirúrgicos afetos a cada especialidade, em que dia e em que sala operam. Esta realocação tem com objetivos adequar a oferta à procura ao mesmo tempo que maximiza a eficiência do bloco operatório. Este trabalho apresenta um modelo em programação linear inteira mista com três objetivos distintos: maximizar o número de tempos alocados e as suas preferências agregadas, distribuir dos tempos de acordo com a procura e nivelar a utilização das unidades adjacentes ao bloco operatório. O último capítulo apresenta resultados, comparando-os com os valores atuais do hospital. Os resultados mostram que os recursos humanos são a maior restrição para uma melhor adequação da oferta à procura, sugerindo uma nova distribuição dos cirurgiões pelas especialidades.

Palavras-chave: Bloco Operatório; Planeamento Agregado; Planeamento da Capacidade; Alocação de recursos; Tempo de espera; Programação Inteira Linear Mista

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List of Abbreviations

BOR - Behavioral Operations Research

CMP - Case-Mix Problem

DRG – Diagnosis Related Group

EPE – Entidade Pública Empresarial

GDP - Gross Domestic Product

HESE – Hospital do Espírito Santo de Évora

ICU – Intensive Care Unit

ILP – Integer Linear Programming

INE - Instituto Nacional de Estatística

LoS – Length of Stay

MILP – Mixed Integer Linear Programing

MP – Mathematical Programming

MSS - Master Surgical Schedule

OR – Operating Room

OR/MS – Operations Research/ Management Science

ORL – Otorhinolaryngology

PACU – Post-Anesthesia Care Unit

SG – Surgical Group

SIGIC - Sistema Integrado de Gestão de Inscritos para Cirurgia

SNS - Serviço Nacional de Saúde (National Health Service)

SS – Surgical Suite

SSP - Surgical Schedule Problem

STKH – Stakeholders

TMRG - *Tempo Máximo de Resposta Garantida* (Maximum response time)

US – United States

1. Introduction

1.1 Problem Contextualization

Health care providers are facing a continuous increase in the complexity of their organizations. This complexity can be related with the evolution of two main variables: the increasing demand and the development of technologies in the health sector. Demand tends to grow with the population aging and with chronic conditions that have become more prevalent (Brandeau et al., 2004). According to the European Commision (2017), some of the society current practices, as poor diet and lack of exercise, are among the leading causes of avoidable death in Europe, contributing also for the increase in the demand for health care. On the other hand, technologies development, to extend life and improve health, are bringing high costs to the institutions. People are not only consuming more health services but are also consuming more intensive health services (Brandeau et al., 2004). These factors influence the budget of health care institutions and require a better use of the resources, demanding a more efficient and effective management.

According to Brandeau et al. (2004), in many high-income countries, health care spending has significantly outpaced economic growth. The authors give the United States (US) as an example: in 1960 the US spent 5% of the Gross Domestic Product (GDP) in health care and 14,1% of the GDP in 2001. In Portugal, according to Instituto Nacional de Estatística (INE), the costs related to health have also increased. The cost per capita, from 2000 to 2015, experienced a growth from 736,79€ to 1012,63€ which means 1.4 times higher. These costs are justified by the increase in the cost of medicines and medical devices, and also by the number of patients (Ribeiro et al., 2011). This increase in costs, caused by volume and equipment, requires an efficient use of the available resources.

Within the services provided by hospitals, surgical activity is a major center of costs and revenues. Surgical suites (SS) represent more than 40% of hospitals costs and profits and are considered by some authors as the engine of the organization (Beliën & Demeulemeester, 2007; Blake & Donald, 2002). The complexity of this activity is not only related with the planning of different surgeries with different patients within the same physical and scarce space but also with the large number of other services that it compromises. This activity has up- and downstream implications and dependencies between human and material resources. An example of these implications is to assure enough recovery beds and nurses to the patients that finish surgery. Moreover, surgery involves highly specialized medical staff and equipment which have high costs associated. Among the variables of complexity mentioned before, this activity includes a high level of variability and uncertainty related to demand, stakeholders and material availability.

Surgical activities have not only an intrinsic high complexity but also a large social responsibility. According to Hans & Vanberkel (2012), many patients in a hospital undergo surgical interventions in their care pathway, contributing substantially to the patient's health. To guarantee quality of health care, surgical activities should be held in a certain time frame. This time corresponds to the days, months or even years in a waiting list for surgery. A greater service level is achieved with a lower number of days that a patient waits to the procedure. This work aims to develop a model to optimize the use of the available SS resources while matching surgical supply and demand, and therefore to reduce the waiting list of surgical procedures.

1.2 Master Dissertation objectives

The main goal of this work is to reduce the overall waiting list of a public Portuguese hospital, reallocating operating room time among different surgical services. To achieve this goal, the objective is to develop a mathematical model that can be generalized, creating value not only for the case study but also for other public hospitals and to the scientific literature on the topic.

Furthermore, the mathematical model aims not only to create an MSS to the following planning period but also to create a tool to better allocate resources within the SS and to better adapt to the supply and demand. This tool should be useful for the next years and therefore should flexibly adapt surgical supply to changes in demand and staff availability.

1.3 Methodology

To accomplish the main objectives of this work, this dissertation follows these steps:

(1) describe the Portuguese hospital under study, characterizing the hospital in terms of: organization, available health services, demand and existing problems; the SS, including physical characteristics, stakeholders involved in the surgical procedures and surgical planning; health on the Portuguese environment, describing the economic environment and the structure of the surgical context;

(2) analyze the previous researches that have already been published on this topic: a brief literature review on the contributions of operations research/management science (OR/MS) in health care, a literature review on the SS management and planning concerning different levels of decisions (strategic, tactical and operational) and SS up and downstream facilities;

(3) create a mathematical model capable of solving the case study challenges for upcoming years and with the possibility of being generable to other hospitals, with literature and stakeholders' insights

(4) collect and treat data to validate and implement the model;

(5) perform a sensitivity analysis, to better advise the decision makers;

(6) compare results with the current distribution of the operating room time, providing some recommendations.

1.4 Master Dissertation structure

The structure of this dissertation is organized in six chapters:

1) Introduction: in the present chapter it is presented a contextualization and motivation of the problem, the objectives of the master dissertation and the methodology to be followed;

2) Case Study: describes the general characteristics of the hospital, the characteristics and the management structure of the SS, and the current Portuguese health care environment;

3) Literature Review: this chapter contains a review of the literature which can contribute to reach the objectives of this work. This includes OR/MS contributions in health care and SS planning and management;

4) Model Development: describes the objectives of the mathematical problem and then presents the model formulation;

5) Computational Results: this chapter validates the model and analyses the quality of the solutions, and compares the results with the current data;

6) Conclusions and future work: discussion of the main results and conclusions of this master dissertation followed with guidelines for future research.

2. Case study

This chapter aims to describe the hospital under study. The objective is to describe and understand how the installed capacity can be optimized in the SS of this case study and how a demand-capacity balance can be achieved, considering surgeons and other stakeholders' preferences, regarding the planning and scheduling of surgeries.

Section 2.1 presents a general description of the hospital, to understand the environment in which the SS is integrated. In Section 2.2 the structure and planning of the SS are described. The hospital is contextualized into the Portuguese environment in Section 2.3 and in Section 2.4 the SS is analyzed according to the Portuguese requirements. Section 2.5 ends the chapter with the main conclusions.

2.1 Hospital do Espírito Santo de Évora (HESE)[1]

Hospital do Espírito Santo de Évora (HESE) is a public hospital located in Évora, in the region of Alentejo Central. The hospital was one of the first hospitals of the region and it has been in constant change since the end of the XV century. Until 1974 the hospital was managed by Santa Casa da Misericórdia and since then it is managed by the Portuguese State. Besides management changes, the hospital had several physical changes and has been getting more responsibilities towards the community. In 1974 it was categorized as civil and county hospital of Évora, and since 2008 it is classified as a central hospital. According to the Portuguese general health department (Silva & Lopes, 2009), a central hospital is characterized by having highly differentiated medical specialties. Usually, this type of hospital should be able to treat all the clinical situations, unless exceptional cases that can only be treated in specialized hospitals (in HESE's case, neurology). Moreover, a central hospital can support scientific research and it can be linked with medical universities.

With such an amount of responsibility, the hospital must cover many clinical services such as: specialties, external appointments, hospital admission, examinations and analysis, daycare, urgency, pharmaceutical service and telemedicine. The hospital offers 26 specialties: anesthesiology, SS, cardiology, surgery, ambulatory surgery, pediatric surgery (only in the region), plastic surgery (only one in the region), convalescence, medical specialties, stomatology, gastroenterology, hematology, medicine 1, medicine 2, physical medicine and rehabilitation, nutrition and dietetics, nephrology, obstetrics, ophthalmology, oncology, orthopedics, otorhinolaryngology, pediatrics, pulmonology, psychiatry and mental health, stroke unit, Intensive Care Unit (ICU) and urology.

[1] The information presented in this subsection is available at the webpage of the HESE's (2017) : http://www.hevora.min-saude.pt/ (in Portuguese, consulted in May 2018)

HESE, as a central hospital, covers a wide region that can be divided into areas of direct influence and indirect influence. Reporting numbers of 2016, the former area includes around 157.746 people, that corresponds to Évora district (red region in Figure 1). The latter includes 325.237 people that corresponds to the areas of Alto Alentejo, Baixo Alentejo and Litoral Alentejo (dark blue, orange and light blue regions highlighted in Figure 1). The areas which are further away from the hospital make use of it when there is the need for more specific treatments. An example is the cardiology interventions since HESE is the only, in the region of Alentejo, that has an ICU for cardiology interventions.

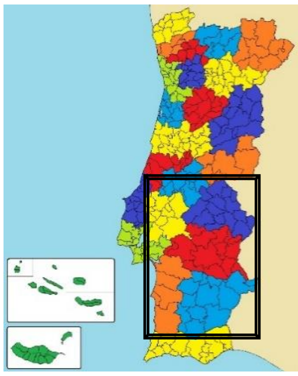


Figure 1 – HESE's area of influence

Table 1 outlines the production of HESE in 2015 and 2016 and the variation between the two years. Hospitals' production is usually presented using a system called diagnosis-related group (DRG). DRG classifies hospital patients in groups with similar clinical conditions and resource allocation. This system has been used in Portugal to catalog all procedures carried out in health care institutions, helping on the identification of all the procedures, surgical or medical, and the related used resources. Table 1 is divided in Hospitalization DRG and Ambulatory DRG, dividing HESE production in procedures for patients who need hospitalization – also called inpatients - and for patients who return home after the received treatment - outpatients. In 2015, HESE performed 4.906 inpatient surgeries and 4.210 outpatient surgical. Thus, a total of 9.116 surgeries were performed in 2015, which means approximately 36 surgeries per day (from Monday to Friday) and 7,2 daily surgeries per operating room.

Table 1 - HESE production in 2015 and 2016. Source of data: HESE's annual report 2016

Production	2015	2016	Δ Homologous
Hospitalization DRG			
Medical DRG	8.160	8.322	2.0%
Surgical DRG	4.906	4.688	(4.4%)
External Appointments	207.658	207.261	(0.2%)
Urgency (attendances)	72.340	75.961	5.0%
Ambulatory DRG			
Ambulatory Medical DRG	5.334	4.779	(10.4%)
Ambulatory Surgical DRG	4.210	4.212	0.02%

With rising importance to the region, HESE expanded its facilities over the years. The hospital is currently composed of three main buildings split in two complexes separated by a national road (see Figure 2). The oldest building, Espírito Santo (number 3 in Figure 2) has more than 500 years and comprises the administrative services, special exams center, service of physical medicine and rehabilitation and the department of outdoor psychology and mental health. The second building was built in 1975 (number 2 in Figure 2). It is located next to Espírito Santo building and has most of the hospitalization services, the diagnostic and therapeutic complementary means, the pediatric and general urgency, the surgical suite, the ambulatory surgery, the convalescence unit and the service of clinical pathology and imaging.

The newest building, Patrocínio (number 9 in Figure 2) accommodates the medicine and psychiatric internments, immunohemotherapy service, the neurology, the technology and informatic system services, the social service and the user office, the external appointments, the radiotherapy unit, the oncology, the user management service, archive and the kitchen. The remaining buildings (4, 5, 6, 7, 8 and 10) are the pharmacy, hemodialysis building and family health units. Number 1 and 8 locate the entrance for the two complexes.

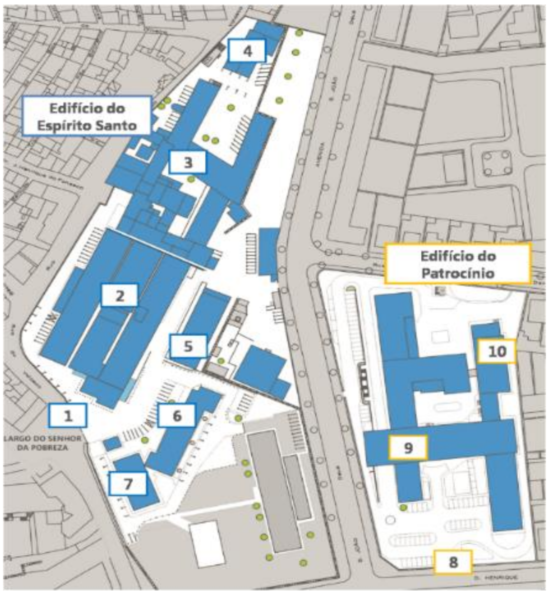


Figure 2 – HESE's Plant

2.2 Surgical Suite

The SS is the service with larger costs and revenues (Cardoen, Demeulemeester, & Beliën, 2010). It is commonly a bottleneck in the health care chain (Malik et al., 2015) and therefore, an efficient use of the SS is essential for the good functioning of the hospital as a whole (Brandeau et al., 2004). However, managing the surgical suite can be difficult due to the different stakeholders that it comprises and to the conflicting priorities of each one of them (Cardoen et al., 2010). Moreover, the surgical suite has a great impact on other activities within the hospital (Beliën & Demeulemeester, 2007).

After an introduction of the hospital and the perception of the hospital production, this section characterizes the HESE surgical suite. The section describes the SS physical characteristics (Section 2.2.1), then the staff needed for surgical activities (Section 2.2.2), and finally the management and planning of the SS taking into consideration the physical characteristics and the stakeholders (Section 2.2.3).

2.2.1 Physical Characteristics

HESE has two SS, the central SS and the child and maternal SS. Only the central SS is part of the analysis of this work. The central SS is

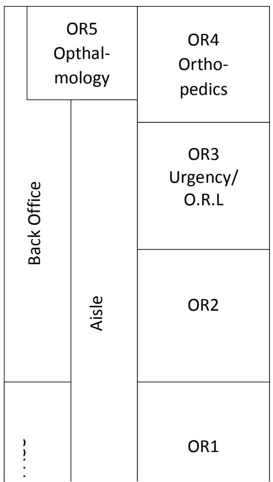


Figure 3 – HESE's SS Plant

composed of 5 operating rooms (ORs) and a post-anesthesia care unit (PACU). These ORs serve 8 surgical specialties which consist of general surgery, urology, orthopedics, ophthalmology, plastic surgery, pediatric surgery, otorhinolaryngology (ORL) and stomatology. To organize the SS each OR is reserved for one or more specialties: ORs 1 and 2 are usually for general surgery, urology, stomatology, pediatric surgery and plastic surgery; OR 3 is reserved for urgencies and for ORL interventions; OR 4 is reserved for orthopedic interventions; and OR 5 is reserved to ophthalmology, due to its small dimensions. Figure 3 demonstrates the physical distribution of the ORs in HESE. The reservation of each OR to one or more specialties provides stability to the medical staff and turn the organization of material and specific equipment easier. As an example, all the specific equipment to perform orthopedic surgeries is in OR 4.

The child and maternal surgical suite are on a different floor. It has one OR for obstetrics and gynecology and one PACU. Besides these two surgical suites the hospital has peripheral areas where interventions on cardiology, vascular surgery and gastroenterology are performed.

2.2.2 Healthcare Professionals

The surgical suite requires different types of healthcare professionals. HESE's SS plans the surgical activity according to three main stakeholders who are vital for a surgical procedure: surgeons, anesthesiologists and nurses. To manage the SS, it is essential to understand the stakeholders' functions, their role and objectives within the SS. By understanding the behavior of each group of professionals it is easier to understand some possible existing conflicts. This section characterizes each one of the three professional groups to better understand the SS's dynamics.

Surgeons

According to Brandeau et al. (2004), hospitals depend on their surgeons for a steady flow of patients and revenue. Surgeons are not only responsible for the surgical procedure, but also for the previous and subsequent activities. Surgeons must take responsibility from the minute the patient has the first appointment till the hospitalization, deciding which should be the treatments that a patient should undertake before and after surgery. Therefore, surgeons must divide their time in appointments, SS, internments and urgency. For each one, it is required by the hospital a minimum number of hours per week: 6 hours of appointments, 6 hours of SS, 4 hours to check their patients in internments, and 12/24 hours of urgency. Moreover, each surgeon is associated to a surgical specialty in accordance to his/her qualifications.

To organize the work of each specialty, a head of service is nominated per specialty. This surgeon has the duty to monthly organize the set of surgeons among the available ORs, allocating them in the available slots (combination of day and shift, morning or afternoon).

The number of surgeons per specialty, operating in the central SS, is depicted in Table 2. Surgeons are one of the major constraints for the distribution of the slots. To assign a slot for a specialty one must guarantee the availability of at least two surgeons on that slot. For example, observing Table 2 and according to the hours that each surgeon can be in the SS (6 hours), plastic surgery cannot have more than one weekly slot assigned, as this specialty only has two available surgeons.

Table 2 - Number of surgeons per specialty

	General Surgery	Ophthalmology	Orthopedic	Stomatology	Urology	Pediatric Surgery	Plastic Surgery	ORL
# of Surgeons	16	10	5	3	4	2	2	4

<u>Anesthesiologists</u>

Anesthesiologists perform all anesthetic and analgesic techniques to all different surgical specialties, comply with the urgency schedule and execute other activities in the perioperative medicine (e.g. anesthesia consultation).

Anesthesiologists must be scheduled, within the SS, into elective and non-elective (urgent) surgeries. When concerning elective surgeries, anesthesiologists have a head of service who monthly organizes the professionals into different slots. Urgency service requires two anesthesiologists 365 days, 24 hours/day. Currently HESE has seven available anesthesiologists for the urgency schedule, which guarantees three days of urgency. HESE has shortage of anesthesiologists, not only to guarantee the urgency service but also for the elective surgeries, resulting in cancellation of allocated slots and hence cancellation of surgeries and reduced occupancy rate. To unbalance the scarcity on both services, HESE subcontracts anesthesiologists from outside the hospital. These professionals must be included in the analysis due to the difficulties that HESE faces to contract effective and not effective anesthesiologists, requiring a more efficient allocation of the anesthesiologists.

<u>Nurses</u>

Like the other medical staff, nurses must also manage their time in many activities. Surgical nurses provide care to patients before, during and after the surgical procedure. Contrary to surgeons and anesthesiologists, nurses are not allocated to each surgery but to shifts. HESE has currently 48 nurses which are scheduled into 3 shifts (morning, afternoon and night), with 8 hours each. The night shifts are composed by only four nurses to guarantee medical staff in case of emergencies. In charge of the schedule of each nurse is the head nurse which organizes a weekly schedule one month in advance.

Each surgery requires the presence of three nurses: scrub nurse, circulating nurse and anesthetist nurse. Therefore, besides the organization in terms of shifts, the head nurse should delegate to each nurse a specific function. The difficulty inherent in this distribution is the different tasks that each type of surgery requires, especially for the scrub nurse. So, in addition to the previous rule, the head nurse also tries to allocate each scrub nurse to the type of surgery that he/she has more specific knowledge and experience.

These professionals have distinct functions within the SS and different objectives as well. The manager of the SS may want the most throughput at least cost, surgeons want a fast turnover, a low cancellation rate and on-time starts. Head nurses may focus more on flexibility to move cases around, disposable supply costs/case, the percentage of cases in compliance with flash sterilization policy, and having adequate reserve capacity for add-on cases or emergency cases (Macario, 2006). To successfully manage the SS, it is required to handle the different objectives and possible conflicts, integrating them into the planning phase.

2.2.3 Planning

As previously mentioned, an efficient use of the SS is essential for the good functioning of the hospital as a whole (Hulshof et al., 2012). Therefore, planning is needed. "The planning process provides the information top management needs to make effective decisions about how to allocate the resources in a way that will enable the organization to reach its objectives" (Hämäläinen et al., 2013).

Central SS of HESE and its 5 ORs are equipped to receive elective surgeries, meaning surgeries which are scheduled in advance, and non-elective surgeries, i.e. emergencies. Besides this distinction, elective surgeries are also divided into surgeries performed to inpatients or to outpatients. Surgeries for outpatients are called ambulatory surgeries (or outpatient surgery). In this type of procedure, patients are admitted, operated on and discharged during the time frame of one working day (6 to 8 hours) (IAAS, 2014). Some Portuguese hospitals have an SS dedicated to this type of surgeries (e.g. Hospital Garcia da Horta, Almada). At HESE's, due to lack of space, this is not possible and so the central SS performs both kinds of procedures.

To do the monthly surgeries' plan, HESE's SS uses an approach, referred in the literature, as block scheduling. This approach reserves each OR to one or more specialties, in a plan that is repeated every week. This plan is known as a Master Surgery Schedule (MSS) (Guerriero & Guido, 2011).

The implemented plan in the hospital is given in Table 3 and is in force for a long time. To build the current MSS, the number of doctors per service and data of the past performed surgeries were considered. Despite the construction of the first MSS had taken into consideration relevant facts, from that moment on, only some slight changes have been done to the original MSS. Therefore, no extensive study was done to continuously improve the MSS and to adjust it to the current reality of the hospital, concerning the evolution of the demand and the changes in the number of surgeons among the specialties. Slight changes were part of some occasional efforts as an attempt to meet a huge or accumulated demand in a specific specialty.

Table 3 – HESE's current Master Surgical Schedule

Day/Room	1	2	3	4	5
Mon	General Surgery	Urology	Urgency	Orthopedics	Ophthalmology
	General Surgery	General Surgery			
Tue	General Surgery	General Surgery	Urgency	Orthopedics	Ophthalmology
	General Surgery (Breast Surgery)	Plastic Surgery			Ophthalmology
Wed	Plastic Surgery	Pediatric Surgery	Urgency	Orthopedics	Ophthalmology
	General Surgery (Varices)	Urgency	O.R.L.		
Thu	General Surgery	General Surgery	Urgency	Orthopedics	Ophthalmology
	Urgency	Urology	O.R.L.		
Fri	General Surgery	Stomatology General Surgery (Implantofix)	Urgency	Orthopedics	
Sat	Urgency				
Sun					

The current MSS is divided into two slots of 6 hours (from 8 am to 2 pm, and from 2 pm to 8 pm), and only one specialty can be allocated to each slot. Surgeons, anesthesiologists and nurses must staff each slot to perform the scheduled surgeries. Moreover, the hospital has always to guarantee one room for urgency surgeries due to the hospital's responsibilities as a central hospital.

The current MSS has blank (empty) slots dedicated for additional surgeries. These surgeries are performed under a special program from the Government, implemented to reduce the waiting lists. In this program surgeons, anesthesiologists and nurses are paid under a fee-for-service system since it is a complement to their regular schedule. Therefore, these surgeries are not included in their annual contract with the hospital, and they are paid for each performed surgery. These blank slots allow professionals to raise their working hours, and consequently their remuneration, decreasing the difficulties that the hospital might have on human resources.

Programmed surgeries, additional surgeries and urgency surgeries are all accounted in a national database called Sistema Integrado de Gestão de Inscritos para Cirurgia (SIGIC), that contains information on all the patients that are waiting for surgery. This system manages the patients registered for surgery, defining priorities and determining objectives in terms of time (maximum and average) waiting for surgery (ACSS, 2011). As mentioned before, additional surgery, despite the different funding system, is also included in SIGIC, meaning that patients on the waiting list may be operated under the regular system (programmed surgery) or under the additional program (additional surgery). Urgency surgeries are also accounted in this system although in a different manner. Due to the almost inexistent waiting time for surgery, this type of patients is only registered in the system after the surgery, as patients are already operated. These differences are represented with arrows in Figure 4. The green arrows indicate the surgeries that are programmed according to SIGIC, so the information flow goes from the system to the SS schedule. The orange arrow indicates that the information flow goes from the SS schedule to the SS schedule to the SIGIC, as these surgeries are not programmed but must be registered in the database.

To conclude, surgeons and anesthesiologists are monthly allocated in the correspondent time

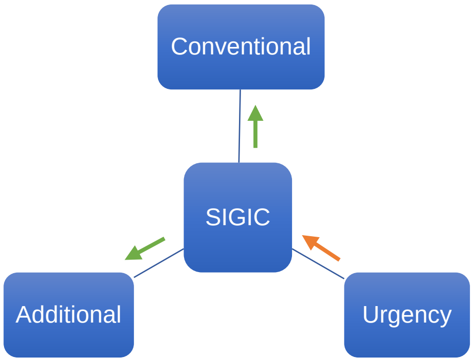


Figure 4 – SIGIC Database Information Flow

slots of their specialty in the MSS, according to the schedule designed by the head of the corresponding service, whereas nurses are scheduled by shifts. Besides the surgeries performed within the reserved slots, additional surgery occurs in the slots not reserved for any specialty (blank slots), treating both patients that are registered in the Portuguese national health service database. The following section adds the context where the hospital is integrated and highlights the main challenges and obligations that the hospital must achieve.

2.3 Portuguese Environment

HESE, as a public hospital, faces some financial restrictions. According to Penedo et al., 2015, the actual national context imposes an additional effort to make the best use of the installed capacity.

The increase in health costs is a reality in many occidental countries, mainly in Europe. This increase has been putting a huge pressure in the national deficits, leading to measures of cost control, bearing in mind the long-term sustainability of the health system (Castro et al., 2017). By the end of the 90s (twentieth century) and at the beginning of this century, several measures were taken by the European Union (EU) with the objective of halting the increase in health costs, while increasing efficiency (Castro et al., 2017).

Following the new EU's guidelines, in 2011 the State published a reform purposing to reshape the structure of the national health system (Serviço Nacional de Saúde, SNS), in an attempt to reduce costs and increase efficiency (Ribeiro et al., 2011). One measure that followed this restructuring is the classification of some hospitals as public corporate entities (Entidade Pública Empresarial, EPE), which allows management independency while keeping State funding. HESE is one EPE hospital. The main objective of this measure is to make hospitals more responsible for their expenditures and motivate them to be more efficient (Ribeiro et al., 2011). Therefore, hospitals have more flexibility to manage their assets, but the funding is obtained from the State, meaning that all actions are tied to the financing obtained. Following the previous line of thinking, the State demands reduction of costs, advising rationalization and reorganization of the services (Penedo et al., 2015). Services should organize internally their human and material resources to maximize returns while avoiding waste. Nevertheless, the quality of the health care provided to the population must not be put into jeopardy by the reduction of the expenses and cost control. Thus, the organizations should find ways to reduce the operational costs, while increasing the quality and effectiveness of the health provision.

SS is one facility with higher impact in increasing health costs. As mentioned by some authors (Hans & Vanberkel, 2012; Macario et al., 1995; Yahia et al., 2014), the SS can represent about 40% of hospitals' total cost. The weight of the SS in the cost structure of health care organizations can be explained by high fixed costs due to installations, specific and highly sophisticated equipment, and with the highly qualified and diversified professionals required to perform a surgery (Penedo et al., 2015).

Nowadays, according to the Health Ministry, hospitals should direct 29% of the State funding to the surgical activity (Penedo et al., 2015). Besides the highly related costs, SSs are an important key to the financing of health care organizations (Penedo et al., 2015). According to Hans & Vanberkel (2012), many patients undergo surgical interventions, making surgical interventions important for the economics and revenues of a hospital. The financing of hospitals is highly related with the performance of the SS, requiring its integration in the strategy of the hospital. The hospital strategy must guarantee the efficiency and quality of the SS and must take into consideration the dimension of the added value that the professionals bring into the system (Penedo et al., 2015). It is essential to reduce waste and promote an efficient use of the health care resources in parallel with a demanding quality control. Therefore, despite the restrictions mentioned before, there are some minimum service levels that the hospital must guarantee. Regarding the surgical suite, the State imposes a maximum response time for patients waiting for a surgery. The technical name used by the Portuguese national health system is Tempo Máximo de Resposta Garantida (TMRG), meaning the maximum time that a patient should wait for their respective medical or surgical care. This management tool, when regarding the surgical activity, is divided into three categories: elective

surgery, elective surgery for oncologic diseases, elective surgery for cardiologic diseases (Portaria nº 153/2017, 2007). The TMRG for each category is presented in Figure 5.

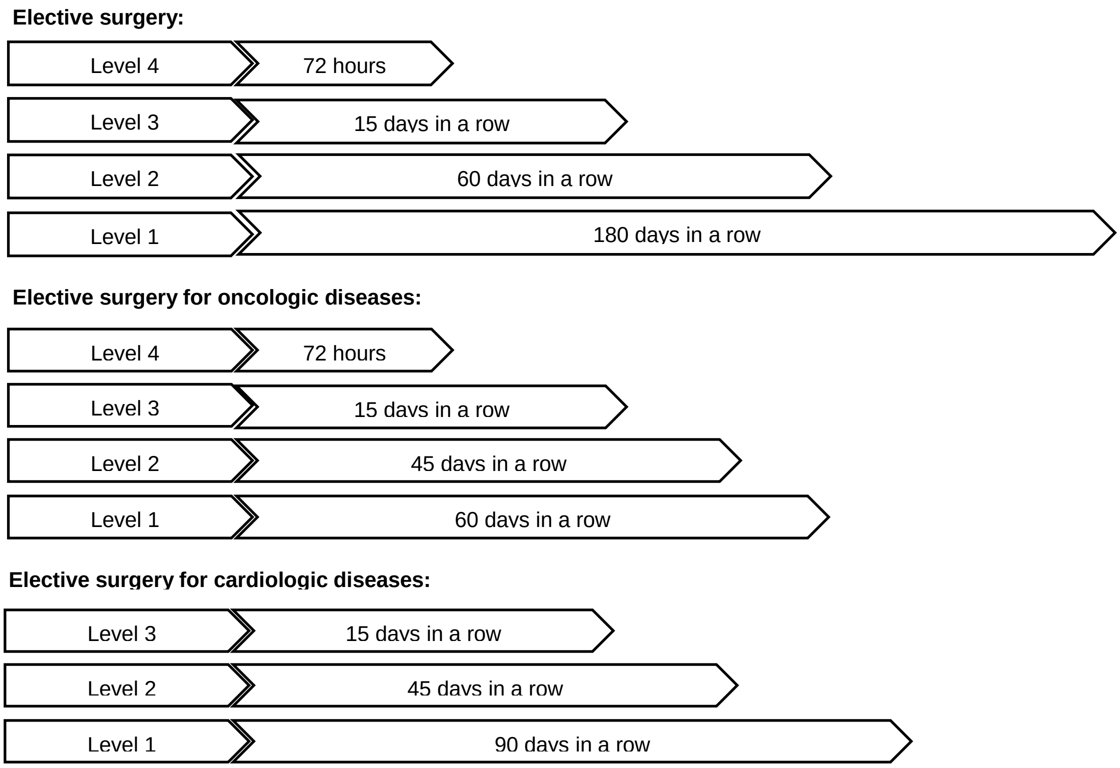


Figure 5 - Maximum waiting time guarantee for surgery -Source: Portaria n.º 153/2017

2.4 Comparison of the Surgical Suite Numbers and the Portuguese Ministry of Health Requirements

The objective of this chapter is to compare HESE's waiting list with the TMRG presented in the last section and analyze the correspondent results.

The numbers showed in the previous section are fixed by the Portuguese Ministry of Health (Portaria nº 153/2017, 2007) where the days are counted from the day the need for surgery is established and the patient is registered in the waiting list (SIGIC).

The hospital has not been able to provide surgical services on time (according to TMRG) to all its patients. Table 4 presents the number of patients waiting for surgery in October 2017, grouped by the number of waiting days and by surgical specialty. In October 2017, more than 1.224 people were waiting for more days than the legally accepted for elective surgeries with priority level 1 - 180 days (6 months) - for their surgical procedure. These figures suggest the need for changes in the management of the SS – concerning not only the reallocation of the slots but possibly an increase on the SS workforce.

Table 4 - Number of patients waiting for surgery per specialty in October 2017. Source: HESE

Specialty	Below 180 days	From 180 days to 270 days	From 270 days to 360 days	More than 360 days	Total number of patients waiting for more than 180 days	Total number of patients on WL
General Surgery	635	214	39	11	264	899
Plastic Surgery	193	60	1	0	61	254
Stomatology	6	2	1	6	9	15
Ophthalmology	747	210	34	64	308	1055
Orthopedics	278	134	16	16	166	444
Otorhinolaryngology (ORL)	182	96	48	77	221	403
Pediatric Surgery	143	45	1	0	46	189
Urology	87	57	24	68	149	236
Total	2271	818	164	242	1224	3495

The reasons for a high number of patients waiting for surgery may be among three factors: a low number of healthcare professionals, as surgeons, anesthesiologists and nurses; an inefficient use of the SS; or an unbalanced allocation of the slots by the specialties. The SS workforce has already been introduced in Section 2.2. However, the staff availability might not be the only reason for the high number of patients on the waiting list. A specialty can have a sufficient number of surgeons and yet not be able to use the SS efficiently. In HESE, this factor is greatly influenced by the low number of anesthesiologists and sometimes nurses, which are usually the reason for the cancellation of some slots. In 2017, 127 slots were canceled, where 79 were due to unavailability of anesthesiologists and 48 of nurses. Table 5 presents the occupancy of the five ORs of the central SS.

Table 5 - Average occupancy rate of central SS ORs in 2017. Source: HESE

	OR 1	OR 2	OR 3	OR 4	OR 5	Total
Number of allocated hours per week of the SS	48	48	12	30	36	198
Average number of used hours per week of the SS	31,9	33,6	10	21	2,4	102
Occupancy rate	66,5%	70,0%	83,3%	70,0%	6,7%	51,5%

ORs 1 and 2 are the rooms with more allocated hours, with 48 hours each. These two ORs are allocated to the specialties of general surgery, pediatric surgery, plastic surgery, urology and stomatology. The low occupancy rate is mainly due to the unavailability of human resources, especially anesthesiologists, which causes the cancellation of the allocated slots and the respective planned surgeries. The cancellation of these slots decreases the throughput and thus contributes to an increase of the waiting list. OR 5, allocated to ophthalmology, has the lowest occupancy rate (6,7%) due to, mainly, lack of anesthesiologists or nurses. Table 4 shows that ophthalmology is the specialty with the higher number of patients on the waiting list (1055) suggesting that this low occupancy rate may be the reason for this high number.

Besides the analysis in terms of the occupancy rate of each OR and the workforce of each specialty, an analysis in terms of distribution of the allocated slots can also be made. Bearing in mind the main objective of this work, to reduce the waiting list, the allocation of slots may be defined by the number of patients on each specialty waiting list. As it is not possible to meet all the demand and turn the waiting list into zero, a good way to define the allocation of the slots is by the percentage of the waiting list that each specialty holds. As an example, ophthalmology had, in October 2017, 1055 patients waiting for surgery on a total of 3495 patients, corresponding to, approximately, 30% of the waiting list. Consequently, ophthalmology should have 30% of the available slots (30% of the 29 available slots per week). Furthermore, this allocation should also consider surgeries average time by specialty, as specialties with longer surgeries can perform fewer surgeries in a slot (6 hours) than the others with shorter cases. The proposed distribution of slots consists in the comparison between the percentage of the waiting list which each specialty holds times the average time of the corresponding surgeries ($\% \, WL \times average\ time\ surgery$), and the percentage of the current allocated slots times the time of each slot ($\% \, alloated\ slots \times time\ of\ the\ slot$).

According to Figure 6, there are some slight differences between supply and demand. The greatest difference is in specialties ORL and urology, where demand is higher than the supply. On the other hand, ophthalmology, orthopedics and pediatric surgery have a bigger supply than their demand. General surgery, plastic surgery and stomatology are the specialties with a better match. Despite the low differences in terms of percentage, a difference of 3% on the allocation of the slots affects, in the example of ORL, 3,5 patients per week and therefore 42 patients a year. A better balance between supply and demand results in fewer days waiting for surgery and consequently in a better service level.

To assure a good service level of the SNS, the government has a policy which allows the reallocation of patients to other hospitals. This reallocation is valid from the day after of the maximum allowed by the TMRG. With this permission, the longer the patients wait the bigger their willingness to be allocated to a hospital with shorter waiting lists which includes private hospitals. The finances of the hospital are affected by this policy, as the hospital loses the financing from the State for that surgery. According to this policy, the hospital can deal with the waiting list in different ways with regard to the number of days each patient is waiting for surgery. As an example, the hospital may prefer to reduce the waiting list concerning only the patients that are within the period that is defined by the TMRG. Others can assume that patients are not going to ask to be reallocated to another hospital, if they will have to wait less than 270 days and, therefore, the hospital may also want to reduce the waiting list that reaches these patients.

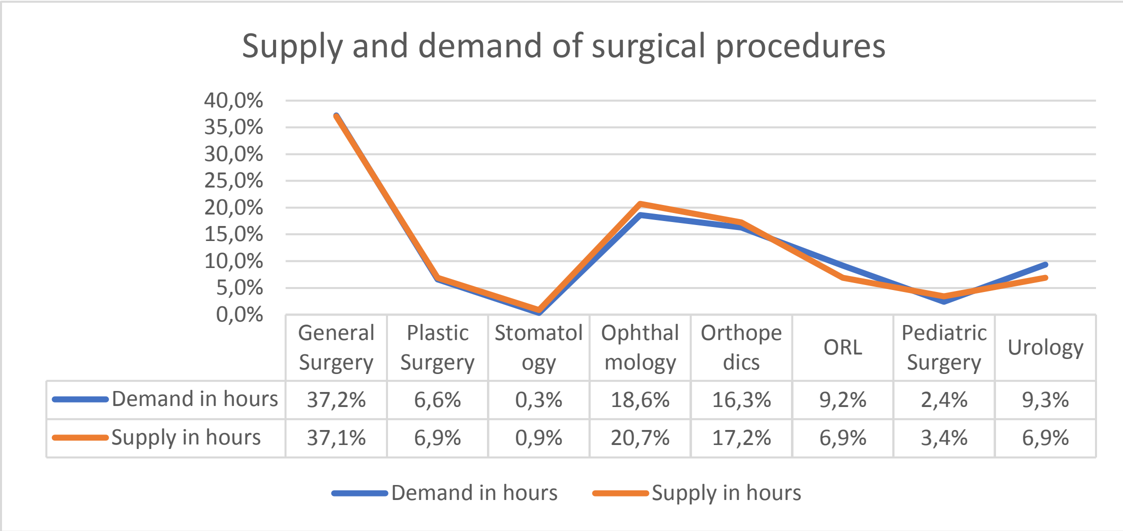


Figure 6 - Percentage of allocated blocks per specialty and respective percentage of the overall waiting list

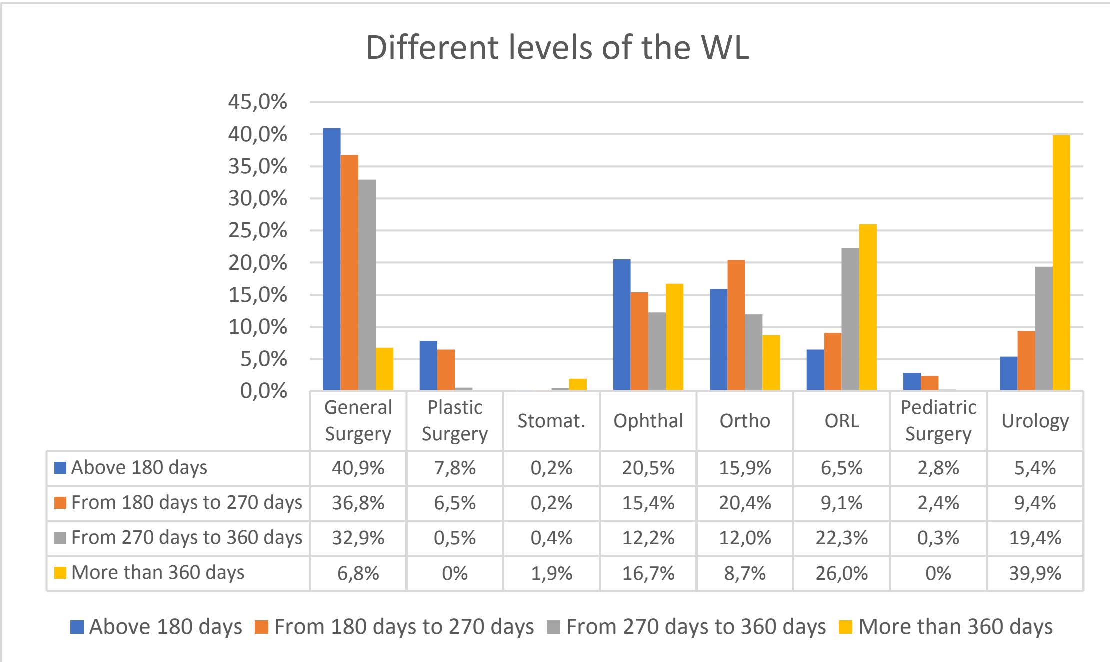


Figure 7 - Percentage of patients on HESE's waiting list grouped by number of waiting days and surgical specialty

According to each strategy, the previous definition of the allocation of the slots – to balance the percentage of the waiting list of each specialty with its percentage of allocated slots - can vary. For example, if the hospital wants to reduce the number of patients that are waiting for more than a year, the comparison must be made between the yellow bars from Figure 7 and the orange line in Figure 6. In this case, urology should be the specialty with the highest share due to its higher percentage of patients waiting for surgery for more than a year. If the strategy is to reduce the number of patients waiting between 270 and 360 days, general surgery should be the specialty with the highest share. The same would happen if the hospital intends to reduce the patients waiting within the TMRG.

2.5 Conclusions

The SS is a highly complex facility, comprising several stakeholders with different and sometimes contradictory objectives. To ensure quality and efficiency it is necessary to effectively manage the SS and try to align the objectives of the different stakeholders with the ones of the institution. After understanding the current state of the Portuguese health system, some legal restrictions as the TMRG, and the role of HESE on the health care provision to the Portuguese population, one can conclude that the hospital hasn't been able to fully achieve its responsibilities and therefore some changes are required in the way HESE's SS is planned and organized. This chapter focuses on understanding the possible gaps of HESE's SS management. Considering HESE's workforce, OR's occupancy rate and the balance of surgical supply and demand, few conclusions can be quickly highlighted. Ophthalmology has a percentage of allocated slots above the percentage of surgical demand, suggesting that the high number of patients on the waiting list is not due to the number of hours that the specialty has available to operate, but because of its low occupancy rate. This last consideration determines not only a reason for the high waiting list, but also that this dissertation should not only focus on balancing the supply and demand, but also on building a tool to turn the SS more efficient and effective. This effectiveness can be done by better allocating the hospital workforce or by analyzing if an efficient management of the SS requires more staff. The problems tackled in Section 2.4 are of capacity planning, and thus the next chapter focuses on a literature review centered on capacity planning problems on the SS.

3. Literature Review

This chapter aims to introduce literature related with the problem under study described in the previous section, by analyzing some articles related with the tactical level of decisions in the SS management. This chapter is organized into three main sections. Firstly, Section 3.1 briefly presents the areas and topics analyzed by OR/MS within the health subject. Secondly, Section 3.2 introduces the topic of interest, the SS, detailing the areas within the SS that are presented in the literature. Finally, Section 3.3 concludes the chapter.

The literature search is based on the following surveys on operating room planning and scheduling: Samudra et al. (2016), Guerriero & Guido (2011), Hulshof et al. (2012), and Cardoen et al. (2010). These reviews analyze relevant papers until 2014, demanding an additional research for the literature published from 2015 to 2018. The search from literature within this period is based on Google Scholar, Science Direct and Pubmed using keywords such as MSS, Master Schedule, Capacity Planning, Time and Operating Room, contributing to 6 additional articles regarding the tactical level of the operating room planning and scheduling.

3.1 Health Care and Operations Research

The performance of health care industry has a significant impact on the quality of human life, thus healthcare professionals face the challenging task to organize their processes more effectively and efficiently (Hulshof et al., 2012). Efficiency and effectiveness are required due to the limited available resources to face the increasing demand of the past few years. Allied with the growing demand, the costs to follow recent technologies and the cost of better prescription drugs turn the task even more difficult (Brandeau et al., 2004). Besides the willing to reduce costs and improve financial assets, hospitals must maximize the level of patient satisfaction (Cardoen et al., 2010). To overcome the challenge, “The Science of the Better”, as OR/MS is usually denominated, can play an active and key role.

Brandeau et al. (2004) state that, to be able to provide the best health care, with the limited available resources, policymakers need effective methods for planning, prioritization, and decision making, as well as effective methods for management and improvement of health care systems.

Health care systems can be characterized by its complexity and by the enormous pressure to cut costs (Brandeau et al., 2004). The need for efficiency, due to financial pressures, and the complexity within health care organizations makes them, hospitals in particular, an important and rich area for the development and use of OR/MS tools and frameworks. These tools help to identify capacity needs and ways to use existing capacity more efficiently and effectively (Brandeau et al., 2004).

Some authors have already schematized the different planning problems that can arise in health care organizations.

According to Brandeau et al. (2004), planning and management decisions in health care systems can be grouped into two areas: *health care planning and organizing*, and *health care delivery*. *Health care planning and organizing* addresses relatively high-level policy decisions about the economics and structure of health care systems and other aspects of public policy regarding health care systems. *Health care delivery*, where this report can be included, addresses decisions about two topics: *management of health care operations* and *clinical practice*. This way of organizing health care problems can be seen in Figure 8.

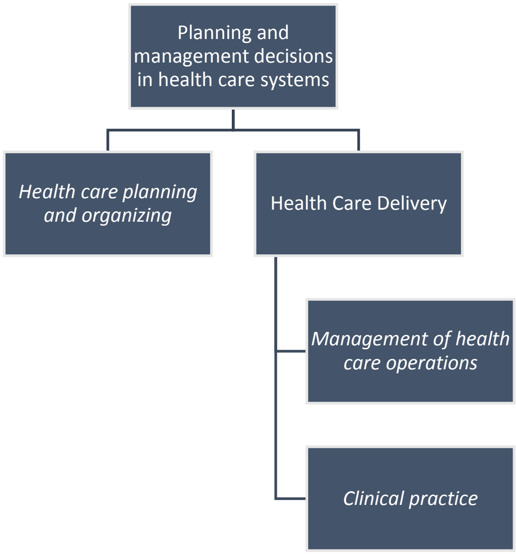


Figure 8 - Schematic vision of health care problems by Brandeau et al. (2004)

Management of health care operations deals with problems that concern the operations which include planning and manage of the various facilities. The problems can go from a high-level of decision as the design of health care supply chain or design of facilities, to decisions of medium term as capacity planning, process selection or equipment evaluation and selection. It can also include problems of short-term decisions such as capacity management, scheduling and workforce planning, inventory management and management of system performance and quality (Brandeau et al. 2004). This project focus on the capacity planning problem, included in the medium-term or tactical decisions.

On the other hand, *clinical practice* is related with planning and management problems that clinicians face when dealing with patients. This involves assess health risks, diagnose their diseases and conditions. Clinicians must design and plan treatment for their patients. For example, they must assess how a disease is likely to progress in a patient and then select appropriate drugs and dosages, as design other aspects of a treatment regimen.

Hans et al. (2012) propose a framework (Figure 9) which divides health care planning and control in 4 managerial areas and 4 hierarchical levels, considering various external environmental factors. The authors create a framework that includes not only hospitals but other health care institutions and various management areas, criticizing other frameworks by paying attention to only some aspects and some organizations. Four managerial areas are considered: 1) medical planning, 2) resource capacity planning, 3) materials planning, and 4) financial planning. Within each managerial area, 4 hierarchical decision levels exist: strategic, tactical, offline operational, and online operational. Management approaches of health care organizations are different from country to country. To engage more than one environment, this framework considers seven external factors that influence decisions:

- Social factors (e.g. education, social mobility, religious attitudes);
- Technology (e.g. medical innovation, transport infrastructure);
- Economic factors (e.g. change in health finance system);
- Environmental factors (e.g. ecological, recycling);
- Political factors (e.g. change of government policy, privatization);
- Legislation / Legal (e.g. business regulations, quality regulations);
- Ethical factors (e.g. business ethics, confidentiality, safety);
- Demographics (e.g. graying population, life expectancy, obesity).

This project may be included in the managerial area of *Resource Capacity Planning* and in *Tactic* hierarchical level surrounded by the Portuguese legislation and demographics.

Hospitals and other health care organizations are complex systems with many areas where OR/MS can make the difference. The next section analyzes the existing literature for planning and management of the SS, identifying how the literature is organized and detailing the literature that focuses on the tactical level of decision.

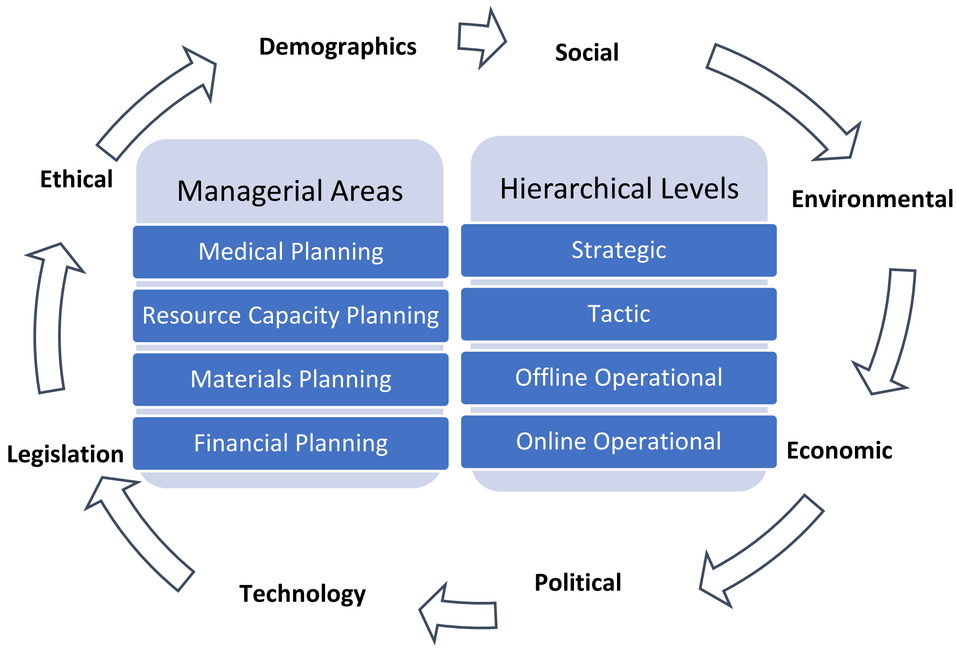


Figure 9 - Framework for health care planning and control by Hans et al. (2012)

3.2 Surgical Suite and Operations Research

The SS is one of the services, in a hospital facility, that consumes more resources and is, as well, the largest revenue center (Cardoen et al., 2010), reaching both around 40% of the hospital financial resources (Denton et al., 2007; 2005; Macario et al., 1995). This consumption can be related with a large amount of specialized medical equipment (e.g. anesthetic machine, OR table, lighting general and special) and with the required specialized medical staff composed of surgeons, nurses and anesthesiologists. To deal with these costs, it is important to use the resources in an effective and efficient way, leading to its maximum utilization and reduced waste. Thus, the SS requires planning to analyze points of inefficiency and management towards optimization.

Macario et al. (2001) approach the profitability of the SS. They state that profitability can vary with the different surgical cases or among surgeons, meaning that costs can be higher or lower according to the type of operation and person that is operating, concluding that to increase or achieve profitability, managers need to increase the hours of lucrative cases.

Marjamaa et al. (2008) underline another aspect of the efficiency, which is the optimization of the whole chain of processes involved in the treatment of a patient, taking into account more than just the surgical cases. To reach the overall optimization it is important to understand the dramatic impact that the SS has on many other activities within hospitals (Beliën & Demeulemeester, 2007). These activities can be included in facilities as preoperative wards and post-operative wards, dealing with balancing of nurses, beds and materials.

As a complex system, the SS has several management and planning challenges spread along different levels of patient flow and in different levels of decision. This section intends to clarify the differences between the various levels of patient flow and decision.

To help to define the patient flow associated with the surgical intervention, patients should also be classified. Patients can be divided into three different groups: inpatients, outpatients and emergency patients (Brandeau et al., 2004). Emergency patients can also be called non-elective patients, as the inpatient and outpatient can be aggregated into elective patients (Samudra et al., 2016). Each type of patient has different flows inside the hospital (Hulshof et al., 2012; May et al., 2011), that can be represented as in Figure 10.

Taking into account the overall flow of each type of patients, the literature considers different aspects: some authors take into consideration only one type of patients, others both. Moreover, literature differs on the chosen facilities to optimize, either only on the SS, either upstream, downstream or both.

Besides the literature division concerning different types of patients and other facilities than the SS, the literature also addresses different levels of decisions when concerning planning and management. These levels of decision are the three hierarchical categories: strategic (long-term), tactical (medium-term) and operational (short-term) (Choi & Wilhelm, 2014; Guerriero & Guido, 2011; Yahia et al., 2014).

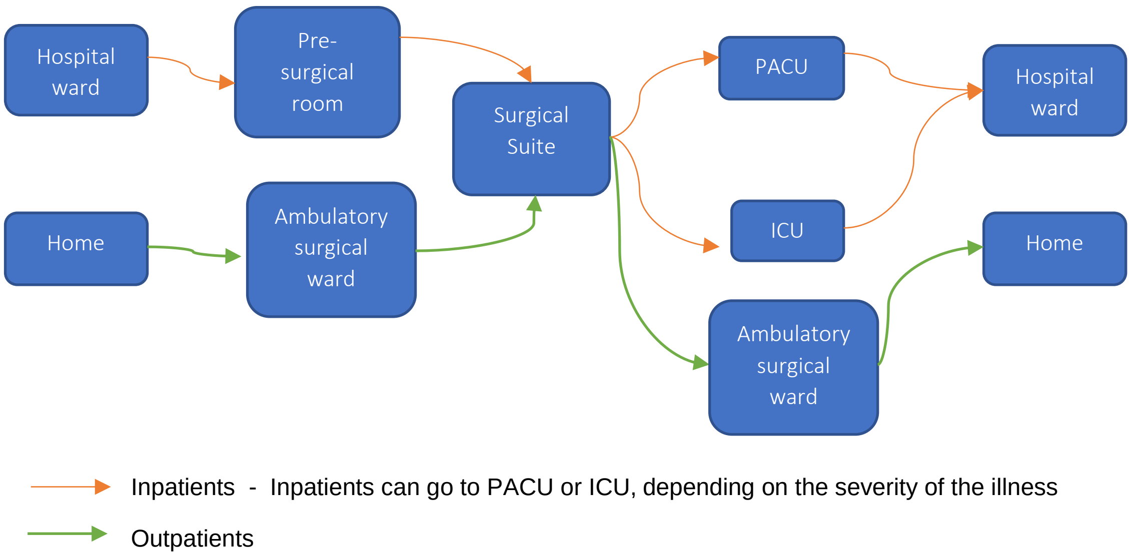


Figure 10 - Flow of different patients inside the hospital

Decision Levels

- Strategic level – this level of decision aims to reach the strategic goal of the organization (Hans & Vanberkel, 2012). Strategic decisions are usually long-term decisions which consider the future and try to plan the expected events in the most accurate possible way. With that purpose, strategic planning is based on historical data for a time horizon of typically one or more years. According to Guerriero & Guido (2011), at this level, the problems are mainly resource allocation problems. These problems can involve decisions as capacity dimensioning of the SS, acquisition of resources for the several ORs, and dimensioning of other departments resources as ward beds. It also involves number and types of surgeries to be performed, the medical staff and the related costs. The decisions regarding the number and cases to be performed, taking into consideration related costs and expected demand, are usually called Case-Mix Problem (CMP).

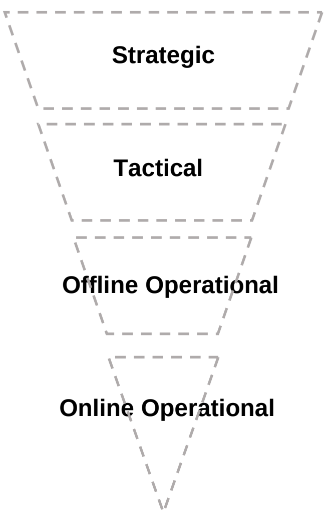


Figure 11 - Hierarchical Decision Levels

- Tactical level - Also known as the medium-term decision level, this decision level works on the outputs of the decisions on the strategic level. Given the limits defined strategically, tactical decisions must plan staff, patients and resources, both in the SS and in the related facilities. It can be traduced in a Master Surgical Schedule Problem (MSSP). An MSS defines the number and type of available ORs, the hours that ORs are open, and the surgeons or the surgical groups (SGs) to whom the OR time is assigned (Dellaert & Jeunet, 2017; Guerriero & Guido, 2011).
- Operational level – The operational level of decision deals with daily problems. Contrary to the other levels of decisions, this operational level deals with known patients and with real-time issues. The Surgical Schedule Problem (SSP) is the main problem at this (offline) level of decision. A Surgical Schedule is a timetable of elective patients for a day or a week, considered the MSS implemented at the tactical level. The SSP includes the assignment of patients to the ORs, the order of the surgeries or the starting scheduled time, and reservation of specialized equipment. This schedule can be modified due to non-expected events, as longer or shorter surgery durations, cancellation of a surgery or occurrence of urgent cases (Dellaert & Jeunet, 2017; Guerriero & Guido, 2011) – online decisions.

3.2.1 Tactical Level

The main objective of this work is the reduction of the surgery waiting list, reallocating operating room time among different surgical services which means designing a new MSS that is able to fit the available resources and match the demand and supply for surgeries. An MSS is a timetable which allocates operating room time to specialties or surgical groups. Thus, it aggregates similar types of operations into time slots. An operation type is a group of operations using the same resources, though the number of resources used may differ (Vissers & Beech, 2005).

MSS is the most used system. Nevertheless, the management of the SS time can follow three different strategies: block scheduling, open scheduling, and modified block scheduling.

In the block scheduling strategy, time slots (i.e., a combination of an OR, a day and a period) are assigned to a specialty or to a surgeon group (Samudra et al., 2016). This is the strategy of an MSS and this approach is used by several authors in several contexts (e.g. Beliën & Demeulemeester, 2007; Blake et al. 2002; Santibáñez et al. 2007) for providing a higher stability to managers and to the medical staff. This stability affects managers by giving a more predictable pattern of bed occupancy, in the pre- and post- operative room, required staff and required material (Agnetis et al., 2012).

Open scheduling allows surgeons to use any of the time slots (OR, day and period) according to their needs. This approach allows more flexibility, which means that it follows the dynamic of the evolution of the waiting lists, and it can also increase the efficient utilization of the ORs (Agnetis et al., 2012). Liu et al. (2011), based on the model created by Fei et al. (2010), develop a heuristic approach to solve an operating room scheduling problem with open scheduling strategy. This heuristic has as objective to maximize the operating room's efficiency and minimize the overtime cost. This is based on the idea that no time slot is reserved for a particular surgeon, and therefore, surgeons can use all available time slots and compete for OR time. Their results are positive, especially in the cases where the SS has large dimensions, enabling the algorithm to find always feasible and good quality solutions. Open block scheduling is divided in two phases. In the first phase, surgeons mention where it would be suitable to make the procedure, and in the second phase, the manager of the SS defines which are the cases to be performed within each time slot using, typically, the first-come-first-served rule. This strategy is mostly used in fee-for-service systems.

Modified block scheduling tries to achieve the benefits of both previous strategies: stability and flexibility. There are two ways of implementing this strategy. The first one consists in booking some slots and leave the remaining open. The second one is to first use a block strategy but then release unused block times at some agreed time before surgery (e.g. 72h) (Fei et al., 2010; Guerriero & Guido, 2011). According to Yahia et al. (2014), there are few authors mentioning the application of this approach. Kharrajal et al. (2006) study the application of two different approaches that fit in a block scheduling strategy and in a modified block scheduling strategy. This paper studies the difference between grouping or not grouping the surgeons in SGs, concluding that to group surgeons has better results in terms of overtime and additional costs, but not concluding about the strategies for the SS time management.

HESE uses a block scheduling strategy as is the case of most of the public hospitals in Portugal. Thus, the following analyzed literature includes only block scheduling and modified block scheduling, due to the impossibility to implement an open schedule approach.

3.2.2 Block Scheduling and Modified Block Scheduling

The literature on SS planning shows a wide range of methodologies that fits within the domain of OR/MS. The methodology related to the construction of an MSS may combine models to formulate the problem and approaches to obtain good solutions. The complexity of the SS, the consequences of planning the SS on several units and the interests and perspectives of different stakeholders result in multiple possible objectives. Guerriero & Guido (2011) define the three most important criteria for the construction of an MSS:

- Equity assignment among SGs;
- Minimization of hospital/ staff costs;
- Bed leveling in up and downstream units.

Along with these criteria, other objectives can be found in the literature. The next section analyzes some papers regarding the objectives, models and approaches. All the papers are summarized in Table 39 (Appendix 1).

3.2.2.1 Objectives When Constructing an MSS

Progress in the literature are attached to the constant desire to find good solutions to new problems. In that way, each challenge differs from the remaining, either in the way the problem is solved or by the different objectives that another author proposes to answer. Therefore, the tendency, considering a certain period, is either the achievement of better results or the increase of problems complexity. This section presents a literature review regarding the objectives and methodologies. To help the reader following this task, Figure 12 outlines the objectives used in the literature when constructing MSSs. The figure is divided into four areas: one area which includes objectives related to up-stream units (1), one area with objectives related to down-stream units (16-18) and two areas considering the SS (2-15). Within the SS the objectives can be general (2-10) or related to ways of assign SS time among the SGs (11-15). The numbers in the text relate to the objectives in Figure 12.

The earlier articles, included in this literature review, concentrate their objectives on issues related with only the SS. An example is Blake & Donald (2002). This article focuses on the equitable distribution of time blocks among the SGs (criteria 2 in Figure 12). In this study, the allocated time for each SG is an input and the model minimizes the difference between the actual value and the target level, by implementing an integer linear programming (ILP) model and an improvement heuristic approach.

Agnetis et al. (2012) takes another step and assigns block times to SGs with the possibility to dynamically adapt the number of hours allocated to each SG according to the current state of the waiting list (15). An ILP model is proposed, with restrictions concerning upper and lower bounds on allocated time per SG, staff and resources. To solve the model, a simulation and scenario analysis approach is implemented. A simulation model considers the trade-off between the required flexibility to offer quality of service to the patients and the required stability that should be provided to the medical staff (4). Regarding also only the SS, Day et al. (2012) differs from the previous papers since it combines open-access scheduling and dedicated slots, and minimizes underutilized OR time (6) and overtime (5).

The last two decades have seen a grown emphasis for reducing the number of patients in the waiting lists and an important public policy tool to tackle this issue has been to specify a maximum waiting time (Malik et al., 2015) as is the case in Portugal with TMRG. The differences between the following articles lie on slight different objectives and on different methods to reach those objectives. Mannino et al. (2012) balance the patient queue lengths among different specialties (15) and minimize overtime (5) when the queues have fixed maximum lengths. To cope with these problems a mixed-integer linear programming (MILP) model is formulated along with a robust approach which takes into account the variability of the demand. Vansteenkiste et al. (2012) apply a due-time model followed by a constructive algorithm, whereas Holte & Mannino (2013) use a MILP model with a row and column generation approach. Both papers have the main objective of reducing waiting time for surgery (15). In contrast with Agnetis et al. (2012), Holte & Mannino (2013) try to find an MSS that is suitable for a longer time period (e.g. one to few years), where the challenge is to find one MSS that reduces the waiting list for surgery for all the included periods.

In 2007, articles gained a new dimension when Beliën & Demeulemeester (2007) and Santibáñez et al. (2007) added down-stream units to the SS capacity planning problem. This inclusion is justified by the large consequences that the SS has on many other units within the hospital. Beliën & Demeulemeester (2007) optimize the MSS in order to level the expected ward occupancy (16) with a mathematical programming (MP) model. To obtain solutions for the model, three heuristics (repetitive MILP heuristic, quadratic MILP heuristic and simulating annealing) and a dynamic programming are applied. On the other hand, Santibáñez et al. (2007), explore trade- offs between OR availability, bed capacity, surgeons' booking privileges, and waiting lists in a hospital network.

Van Oostrum et al. (2008) also consider downstream units and formulate an ILP model to maximize OR utilization. To increase utilization avoiding overtime (5) and cancellations (10) the authors assign planned slacks and level the requirements for hospital beds in downstream units, such as wards and ICUs, respectively. The proposed solution approach makes it possible to add restrictions imposed by hospital staff and to consider other types of hospital resources than beds (18).

Zhang et al. (2009) distinguish from other papers as being the only to study the impact that the SS has on upstream units. The main objective is to minimize inpatients' length of stay (LoS) in the wards waiting for the surgery when constructing a weekly MSS (1). A MILP model, based on the work of Blake & Donald (2002), is constructed. The difference lies in the determination of the hours allocated to each SG as a decision to minimize LoS before surgery, whereas Blake & Donald (2002) use the time of each SG as an input. The optimal solution is then inserted in a simulation model to catch the uncertainty that is associated (e.g. surgery time, demand, arrival time, and no-show rate of outpatients).

Recently Guido & Conforti (2017) use a multi-objective ILP model to take into account trade-offs among underutilization of OR capacity (6), balanced distribution of OR time among SGs (2), minimization of surgeries' waiting times (15) and overtime working hours (6). The authors obtain solutions in the Pareto front by using a genetic algorithm.

After the discussion on the objectives and methodologies, the literature is now classified according to the characteristics of the problem. These characteristics are summarized in Table 40 (Appendix 2) containing information on: types of patients included (Non-/ elective patients; In/out patients), time horizon of the constructed MSS (MSS T. Horizon), inclusion of the up and downstream units (Up/ down streams), consideration of patients LoS (LoS), reserved OR for emergency surgeries (OR for emergency), inclusion of the stakeholders in the decision-making process (STKH), type of uncertainty (Uncertainty), and type of data (Data).

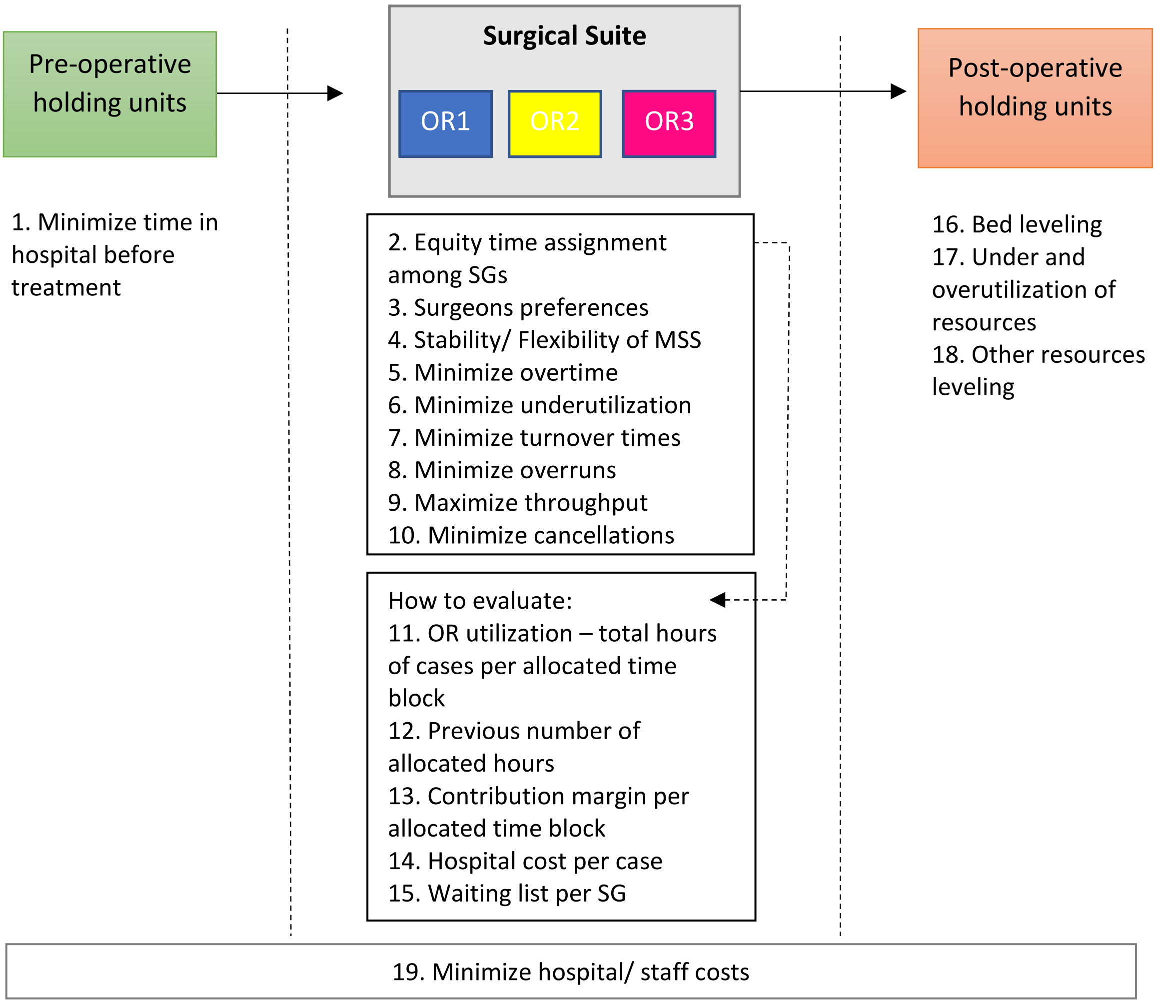


Figure 12 - Objectives used in the literature for constructing MSSs. The numbers are used when describing the different papers in the text to be easily identified in the figure.

3.3.2.2 Common Characteristics on Problems when Constructing MSSs

Plan and manage an SS is a complex activity. The complexity of this activity is not only related to the planning of different surgeries with different patients within the same physical and scarce space but also with the large number of other services that it compromises. For this reason, authors tend to reduce the problem, limiting variables and focusing on smaller problems.

One way to reduce the problem is by choosing to model only elective patients. Few authors consider non-elective patients in their studies since most of the cases have a dedicated room to non-elective patients. The arrival of urgent patients to the hospital is uncertain. Therefore, the uncertainty related to this kind of patient can be hard to compute which brings a second reason for the lack of papers dealing with non-elective patients.

Elective patients can be inpatients or outpatients. Although not many authors indicate which type of elective patients they are considering (more than half of the examined articles do not specify this distinction), these type of cases have some features that can largely impact the choice of the scheduling technique (Samudra et al., 2016). Besides the fact that outpatients do not overnight, outpatient surgeries often consist of more standardized procedures. Vansteenkiste et al. (2012) study the reallocation of OR time based on medically defined surgical waiting lists. For that purpose, it considers both in- and outpatients, where outpatient surgeries have dedicated ORs, and therefore are allocated separately.

Contrarily to the previous authors, Zhang et al. (2009) consider both types of patients. For dealing with the uncertainty of the non-elective patients, an OR is reserved for this emergency cases. However, if this single OR is not available, due to another emergency, an OR for elective surgeries must be used, and, as result, some elective surgeries may be postponed and rescheduled to a later date. Van Veen-Berkx et al. (2016) discuss this topic in more detail, defending that dedicated ORs for non-elective cases are beneficial for the hospital. On the other hand, Wullink et al. (2007) defend the opposite. With a discrete-event simulation testing both alternatives, the study indicates positive results concerning three performance indicators: waiting time, overtime, and cost-effectiveness of the OR. Malik et al. (2015) follow the same idea, creating a schedule that is already prepared for the eventual disruptions caused by emergent cases.

The consideration of up- and downstream units also divides the analyzed literature almost in half. The decision to incorporate other services besides the SS is usually related with the consequences that the SS has in these other wards. As argued by Beliën & Demeulemeester (2007), Cappanera et al. (2014) and Santibáñez et al. (2007), bed capacity and nursing staff requirements depend on the operating room schedule. These authors consider the resources of downstream facilities when allocating SGs to certain time blocks. Besides them, almost all of the most recent articles (Collins, Davies, & Skorupski, 2017; Dellaert & Jeunet, 2017; Malik et al., 2015; Penn, Potts, & Harper, 2017) have incorporated up and downstream services into their models, or just mention as further research (Guido & Conforti, 2017).

The LoS is another characteristic that can be related with downstream facilities and inpatients. Adan et al. (2009) study the influence of using stochastic LoS instead of a deterministic, based on a model of previous papers (Adan & Vissers, 2002; Vissers et al. 2005) that focus on the generation of an MSS. To study the LoS, the study divides the patients into two major groups: children and adults, where adults have two other characteristics divided into three or four levels - the LoS in the OR (in hours) and the LoS in the ICU (in days). This approach has positive results when considering the deviation between targeted and realized utilization of resources, that converts in 40% decrease of deviation. Furthermore, Fügener et al. (2014) construct an MSS considering multiple downstream units and a stochastic LoS modeled by discrete empirical distributions, easily obtained from historical records.

In the health context, it is of extreme importance to consider the stakeholders in the decision analysis due to the special characteristics of the hospital hierarchization. The hierarchy of a hospital, differs from the ordinary organizations, since it does not follow a strict hierarchy, but a balanced power between different interest groups, with different views about what is the best throughout (Lagergren, 1998; Vissers & Beech, 2005). These groups include the top management, the manager of the SS and the stakeholders that take part in surgeries. Moreover, Samudra et al. (2016) underline that the existing OR/MS models for health care institutions are not usually used, since the existing research problems and solutions do not include performance measures which are in line with the most important objective(s) according to the stakeholders (Samudra et al., 2016). The importance of the stakeholders is recognized by some authors who decided to include stakeholders on their models. Collins et al. (2017) address a problem of distributing new OR time among the surgeons. To distribute this new OR time it is necessary to guarantee the availability of physical space, nursing, OR staffing and anesthesia support. Regarding these implications, the authors consider important to meet and notify a multidisciplinary leadership team to bring all these elements to the decision-making process. The notification of the stakeholders is part of a standardized protocol to distribute the new OR time that tries to align institutional goals with those of the clinicians, allowing institutions to create a fair and transparent process. Moreover, Van Oostrum et al. (2008) refer to an intensive cooperation with the clinicians and SS managers. This cooperation is responsible for creating and implementing a framework for cyclic SS planning allowing the construction of an MSS that can handle constraints imposed by health care processes.

The inclusion of the stakeholders in the OR/MS methods is a newly emerging discipline (Becker, 2016). This discipline is known as Behavioral Operations Research (BOR) and has been used by some authors as Becker (2016), Brocklesby (2016)**,** (Franco & Hämäläinen, 2017) and Hämäläinen et al. (2013) who study the inclusion of stakeholders in OR/MS models, including how methods are used by OR/MS actors and how methods should be presented to actors in order to improve their interpretation and deployment. Till now, no author has implemented or studied these recent inclusive methodologies in the health care sector.

3.3 Conclusions

This chapter presents a literature review to understand which studies have already been carried out on the tactical planning of the SS and more specifically on models to improve MSSs in hospitals.

It is presented an overview of the role of OR/MS on healthcare and how is the literature organized. The review focuses on the tactical planning problems of the SS. According to the collected papers (from 2002 to 2017), it is possible to recognize an evolution of the literature. Nowadays the planning of the SS takes into consideration more than just the optimization of the schedule of the SS. Issues such as up- and downstream units, stakeholders and uncertainty are now considered. However, some points have never been studied together. This work covers the gap in the literature, integrating some of these important issues. The assembled objectives are the allocation of the slots according to the overall waiting list, as Malik et al. (2015), the distribution of slots according to the preferences of the stakeholders (surgeons), as Penn et al. (2017), and including restrictions of up- and downstream units in terms of capacity and human resources as Dellaert & Jeunet (2017).

4. Model Development

The previous two chapters present the case study and analyze previous researches on this topic. Chapter 2 outlines the major requirements of the hospital, and Chapter 3 shows how have those problems been tackled in the literature. This chapter presents a mathematical model to solve HESE's challenges, regarding the MSS, learning from previous papers and adapting them to this case study, while adding value to the literature.

The main objective is to develop a model to build a new MSS for HESE, aiming to reduce the number of patients waiting for surgery. Sections 4.1 and 4.2 introduce the insights gathered on informal interviews, giving an overall explanation of the objectives and the related constraints. Section 4.3 presents the mathematical model and Section 4.4 underlines the main conclusions.

4.1 Formulation of the objective functions

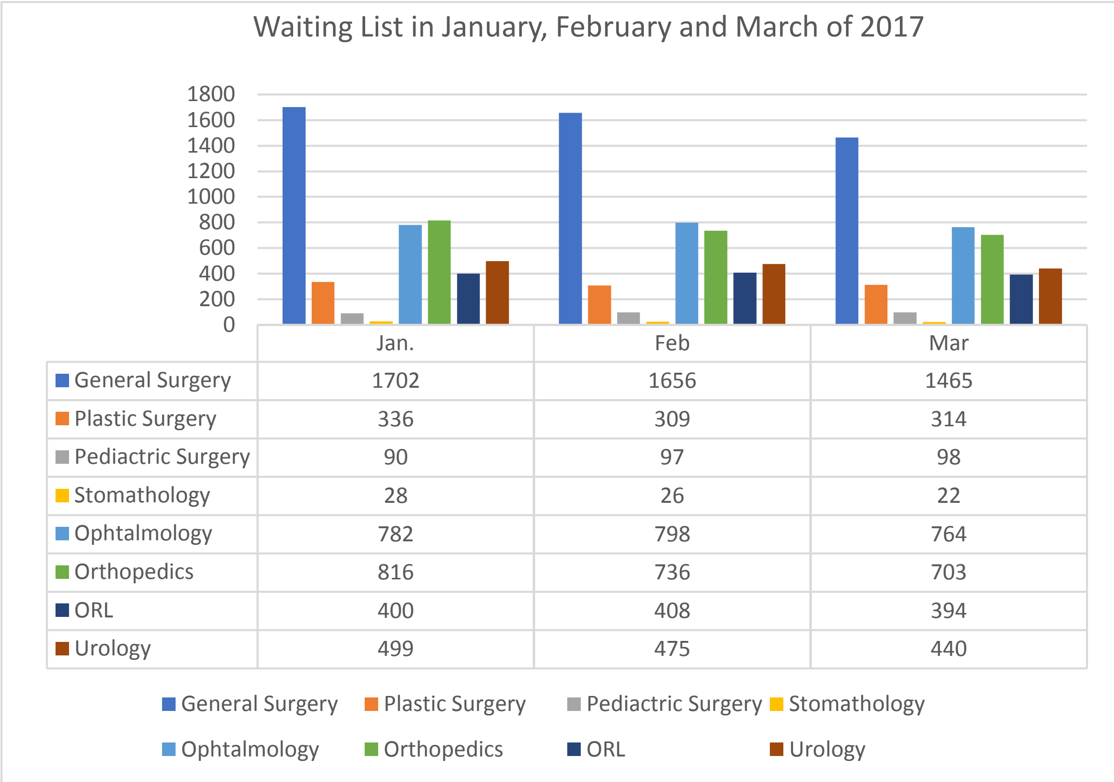
To propose a new and better MSS implies to understand which characteristics of the SS must be considered, implying the recognition of the case study problems aligned with the characteristics covered by the literature.

4.1.1 Resume of HESE's needs

HESE´s SS is a unit that lives from the daily adaptation of the stakeholders, to reach their patients' needs and to cover the hospital shortages. Therefore, in order to build a new and better MSS it is required knowledge of the current difficulties and challenges that the SS faces. This section presents key information on the dynamics of the SS gathered through interviews. These interviews were conducted in the hospital between October 2017 and July 2018, allowing the perception of the organization of the hospital and of the SS. Important insights were given by the SS manager, surgeons, anesthesiologists and nurses. These interviews have greatly assisted this study in understanding the objectives and the constraints which the model should tackle.

The interviews started with the higher question, the waiting list. It is of the interest of the hospital the reduction of the waiting list, to guarantee the best and effective health service to its patients.

Figure 13 depicts the waiting list in hours of surgery, meaning the number of patients in each month and each specialty multiplied by the average surgery duration of each specialty. This figure illustrates the actual demand of each of the specialties in January, February and March, depicting the differences between the demand of some specialties. As an example, general surgery has 1702 hours of waiting list and orthopedics has 816 hours of waiting list. These 900 hours of difference suggest an unbalanced waiting list, where demand is not equally distributed by the operating room time. To balance the distribution general surgery should have more hours of the operating room time in order to decrease its waiting list.



	Jan.	Feb	Mar
General Surgery	1702	1656	1465
Plastic Surgery	336	309	314
Pediactric Surgery	90	97	98
Stomathology	28	26	22
Ophtalmology	782	798	764
Orthopedics	816	736	703
ORL	400	408	394
Urology	499	475	440

Figure 13 - Waiting List in number of hours of surgery in January, February and March of 2017

The first two objectives intend to maximize the number of allocated slots, represented by expression (1), and to guide that allocation to a distribution close to the distribution of the demand, represented by (2).

$$\max \sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R} x_{smwdbr} \tag{1}$$

$$\min \sum_{s\in S} \frac{(t_{sm}^{-} + t_{sm}^{+})}{t_{sm}} \tag{2}$$

Expression (1) maximizes the number of allocated slots, where the decision variable x_{smwdbr} is equal to one if a given slot (identified by $mwdbr$) is allocated to a specialty s.

Expression (2), aims to distribute the available slots in a way that each specialty reduces the number of patients waiting for surgery according to the size of its waiting list. For that, the model computes a target (t_{sm}), indicating the number of slots that each specialty should have allocated each month regarding the available operating room time.

$$t_{sm} = \frac{P_{sm} \times asd_s}{\sum_s (P_{sm} \times asd_s)} \times slots_m \tag{3}$$

The target for each specialty is the number of patients waiting for surgery of that specialty (P_{sm}) times the average duration of surgeries of that specialty (asd_s), divided by the total demand. Then to convert that share into slots, the percentage of the demand is multiplied by the total number of available $slots_m$ $(number\ of\ ORs \times number\ of\ days \times number\ of\ shifts)$. Expression (3) represents how t_{sm} is calculated. Briefly, the target allocates to each specialty the percentage of the waiting list that each specialty holds times the available slots.

Due to restrictions which involve medical professionals, physical constraints and stability of the MSS it is impossible to reach the computed target. Therefore, the model allows a certain deviation from the target (t_{sm}^{+}, t_{sm}^{-}). The second objective, represented by expression (2), is the minimization of those deviations.

Other issue brought up to discussion, and that linked all the interviews, is the urge to understand the needs of the stakeholders. The unchanged MSS has created some habits on the daily life of all medical professionals related with the preferences in terms days and shifts that each doctor prefers to work on. These preferences gave rise to the third part of the objective function. Expression (4) maximizes the preferences of surgeons (i) and anesthesiologists (a), forcing the model to allocate specialties to the slots that anesthesiologists and surgeons prefer.

$$\max \sum_{s \in S} \sum_{w \in W} \sum_{d \in D} \sum_{b \in B} \sum_{r \in R} \left(\frac{\sum_{i \in I} k_{isdb}}{|k_{isdb}|} + \frac{\sum_{a \in A} k_{adb}}{|k_{adb}|} \right) x_{smwdbr} \tag{4}$$

4.1.2 Literature Insights

Along with the interviews, a literature review on surgical suite management and planning was carried out, creating awareness to other problematics not revealed in the interviews, such as the connection of the surgical suite with other facilities. This characteristic, not underlined by the stakeholders, is of great importance to turn the model more general and feasible to other hospitals, or to future HESE's environments. Expression (5) represents the minimization of under and overutilization, (UU_{zq} and OU_{zq}, respectively) of the up and downstream rooms, referred in this work as units z. This objective intends to level the occupation of these rooms when constructing the MSS.

$$\min \sum_{z \in Z} w_z \sum_{l \in L} (UU_{zl} + OU_{zl}) \tag{5}$$

4.2 Important factors, restrictions

While Section 4.1 introduces the objectives, this section reflects some restrictions, as well as important assumptions, which were brought up with the undertaken interviews.

As an outcome of the several interviews it is possible to group the following restrictions and assumptions in 2 groups:

- Constraints related to medical professionals;
- Constraints related with stability of the MSS.

The first group of constraints is present in almost all papers in the literature. During the interviews, one of the addressed topics was the complexity in scheduling medical professionals related with the shortages in anesthesiologists and surgeons. This shortage is greatly related with the few professionals that exist in the hospital's region and with the inherent difficulty to find more professionals.

The second group of constraints is related with the intention to match supply and demand. The total demand and the demand of each specialty varies over the year, as shown in Figures 14

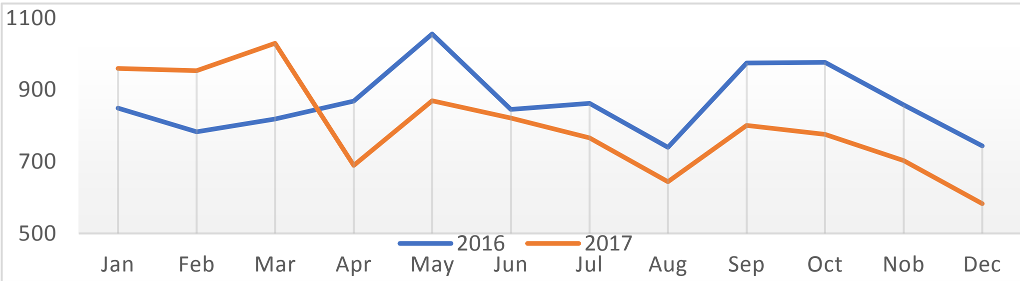


Figure 14 - Evolution of the number of new patients waiting for surgery in 2016 and 2017

and 15, respectively.

This variability, ideally, should be reflected in the used capacity, meaning that the number of slots allocated to each specialty should vary according to its monthly demand. However, the hospital requires a certain stability of the MSS, motivating the second group of restrictions. This required stability relates with another problematic. To reduce the number of slots allocated to a specialty it is necessary to reduce the number of surgeons of that specialty in the SS. This can be done by dismissing the professionals, which is not recommended, reduce their weekly working hours or allocating those SS working hours to other services. These options require big

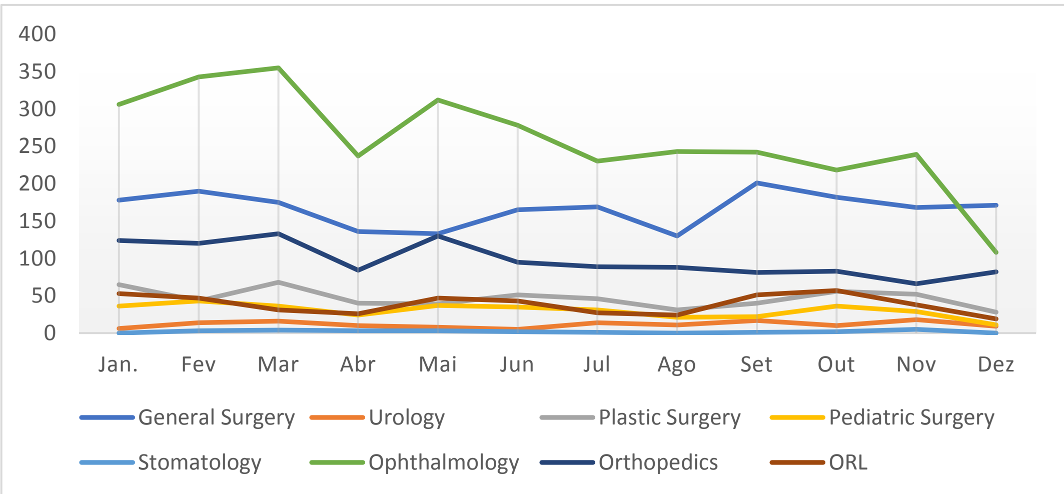


Figure 15 - Evolution of the number of patients on the waiting list for surgery in 2017 by specialty

changes in the organization of the entire hospital and therefore, are not considered in this study, concluding that the perfect match is not possible. To deal with this required stability, the model has parameter Δ_m, which indicates the number of allowable changes from a month to another.

Having in consideration the allowable changes, the model suggests a non-cyclic MSS, which changes from month to month. Furthermore, the current HESE's MSS is also not cyclic from week to week. The MSS is not a replication of the MSS of the previous week due to the low demand of some specialties, as stomatology, or due to low availability of surgeons, as pediatric surgery, requiring only one slot per month. However, again, the MSS should be as stable as possible, meaning that the MSS should be as similar as possible over the month. To guarantee this stability the model receives a parameter for weekly stability (Δ_w).

Relevant assumptions

Coming back to the information collected in the interviews, discussions with surgeons and anesthesiologists have revealed relevant information:

- it is preferable to not assign the same doctor to morning and afternoon slots. This is related with the duration of 6 hours of each slot, and the associated tiredness;
- HESE's SS has restrictions in terms of the ORs distribution among the specialties: OR 5 is only feasible for ophthalmology surgeries, due to its small dimensions, and OR 4 is preferable to orthopedics, as this specialty requires big volume equipment and OR 4 is the one with higher dimensions (see Figure 3 in Section 2.2.1);
- OR 1 is the most convenient room as is the closest to the recovery room and from the SS door, facilitating the passage of patients;
- nurse scheduling does not restrict greatly the allocation of slots, and therefore can be excluded from the model.

Based on the previous statements regarding the interviews and the literature, the model regards:

- Maximization of the number of allocated slots, restricted by the availability of surgeons and anesthesiologists;
- Balance between supply and demand, restricted by the stability needed from a month to another;
- Balance of the utilization of the up- and downstream units;
- And maximization of stakeholder's satisfaction.

4.3 Multi-objective mixed integer programming model

This section sets out the formulation of the mathematical model, listing: assumptions, indices and sets, parameters, decision and auxiliary variables, the objective function and restrictions. Sections 4.3.2, 4.3.3, 4.3.4, 4.3.5 list indices, parameters, decision and auxiliary variables, leaving their explanation for Sections 4.3.6 and 4.3.7, when presenting the objective function and the model restrictions. According to the organization of this work, the indices and parameters are also divided in general and in up- and downstream units. First, all the hospital concerns were modeled and, in the end, to turn the model more general, up- and downstream units were considered.

4.3.1 Assumptions and problem characteristics

- Each surgeon is allocated to a specialty;
- Patients are allocated by specialty;
- Each month has a defined number of weeks a priori;
    - This definition intends not only to facilitate the modeling but also to be in accordance with reality. The planning of the SS is made week by week, regardless of the day of the week of the end of the month, resulting in months with 4 weeks and months with 5 weeks.
- A slot is defined by its month m, week w, day d, shift b and operating room r;
    - The necessity of including month and week in the definition of a slot - normally defined with day, OR and shift - is related with non-cyclicity of the MSS from week to week and from month to month. This is related with the changes in demand and in surgeons and anesthesiologist’s availability (example vacations).

4.3.2 Indices and sets

Table 6 – General indices and sets

Index $\in$ Set	$Description$
$d \in D$	$Days\ from\ Monday\ (d = 1)\ to\ Friday\ (d = 5)$
$w_m \in W_m$	$Weeks\ of\ each\ month\ m$
$m \in M$	$Months$
$r \in R$	$Operating\ rooms$
$b \in B$	$Shifts$
$s \in S$	$Specialties$
$i \in I$	$Surgeons$
$a \in A$	$Anesthesiologists$

This section presents, in Tables 6 and 7, the general and up- and downstream indices and sets.

4.3.3 Parameters

***Table 8** – General parameters*

Parameters	*Description*
$slots_m$	$total\ number\ of\ slots\ on\ month\ m$: $slots_m = \lvert R\rvert \times \lvert B\rvert \times \lvert D\rvert \times \lvert W_m\rvert$
asd_s	$average\ surgery\ duration\ for\ specialty\ s$
λ_s	$average\ number\ of\ operated\ patients\ per\ slot\ (mwdbr)\ and\ specialty$: $\lambda_s = \frac{slot\ duration}{asd_s}$
P_{sm}	$number\ of\ patients\ of\ specialty\ s\ waiting\ for\ surgery\ on\ the\ first\ day\ of\ each\ month\ m$
t_{sm}	$target\ allocation\ for\ each\ specialty\ s\ per\ month$: $t_{sm} = \frac{P_{sm} \times asd_s}{\sum_s (P_{sm} \times asd_s)} \times slots_m$;
d_{sd}	$number\ of\ available\ surgeons\ from\ specialty\ s\ on\ day\ d$;
da_d	$number\ of\ available\ anesthesiologists\ on\ day\ d$
k_{isdb}	$preference\ score\ specified\ by\ surgeon\ i\ of\ specialty\ s\ for\ day\ d\ on\ shift\ b$
k_{adb}	$preference\ score\ specified\ by\ anesthesiologist\ a\ for\ day\ d\ on\ shift\ b$
ai_{ismwdb}	$\begin{cases} 1, if\ surgeon\ i\ of\ specialty\ s\ is\ available\ on\ month\ m, week\ w, on\ day\ d\ shift\ b \\ 0, \quad otherwise \end{cases}$
aa_{amwdb}	$\begin{cases} 1, if\ anesthesiologist\ a\ is\ available\ on\ month\ m, week\ w, on\ day\ d\ shift\ b \\ 0, \quad otherwise \end{cases}$
wwi_{is}	*number of times that a surgeon i of specialty s can go to the OR in a week*
wwa_a	*number of times that an anesthesiologist a can go to the OR in a week*
Δ_w	$weekly\ stability$
Δ_m	$monthly\ stability$
$\alpha_{1,2,3}$	$weighted\ parameters\ for\ objectives\ (1), (2) and\ (3)\ respectively$: $to\ adjust\ the\ model\ to\ the\ values\ of\ different\ hospitals, or\ for\ the\ user\ to\ explore\ the\ various\ objectives$

This section presents, in Tables 8 and 9, the general and up- and downstream parameters.

Table 8 presents the general parameters, which are needed as inputs to the model when not regarding up- and downstream units. Some of these parameters need further explanations:

1. The number of slots ($slots_m$) is different from month to month due to the different number of weeks along the year.
2. asd_s is an average of the durations of all the surgeries of each specialty (aggregated plan). The consideration of an average is due to the level of decision that this problem

tackles. As a strategic-tactical problem there is no need to know the average duration of each type of surgery within each specialty, but only the average of all within each specialty.

3. λ_{sm} is the average number of operated patients per slot, calculated from the total duration of a slot (6 hours) divided by the average duration of a surgery by specialty. This number regards again an average due to the level of decision.

Table 9 presents the parameters related to the third objective, which intends to minimize the under and overutilization of the up- and downstream units.

Table 9 - Parameters

$Parameters$	$Description$
g_s	$probability\ that\ a\ patient\ of\ specialty\ s\ is\ admitted\ in\ the\ ICU\ immediately\ after\ surgery;$
$c_s^z(n)$	$probability\ that\ a\ patient\ from\ surgery\ of\ specialty\ s\ stays\ n \in \{1, \dots, N_s^z\}\ days\ in\ unit\ z$
d_{sn}^z	$probability\ of\ a\ patient\ of\ specialty\ s\ in\ the\ ICU\ to\ be\ discharged\ from\ the\ unit\ z\ on\ day\ n$
e_{sn}^Q	$probability\ that\ a\ patient\ of\ specialty\ s\ is\ in\ pre-ward\ on\ day\ n$
e_{sn}^I	$probability\ that\ a\ patient\ of\ specialty\ s\ who\ had\ surgery\ on\ day\ 1\ is\ in\ the\ ICU\ on\ day\ n$
e_{sn}^{OW}	$probability\ that\ a\ patient\ of\ specialty\ s\ who\ had\ surgery\ on\ day\ 1\ is\ in\ a\ ward\ on\ day\ n$
e_{smn}^{IW}	$probability\ that\ a\ patient\ of\ specialty\ s\ who\ had\ surgery\ on\ day\ 1\ is\ in\ a\ ward\ on\ day\ n\ after\ staying\ m\ days\ in\ the\ ICU$
e_{sn}^W	$probability\ that\ a\ patient\ of\ specialty\ s\ who\ had\ surgery\ on\ day\ 1\ is\ in\ a\ ward\ on\ day\ n$
F_{sl}^z	$distribution\ on\ the\ lth\ day\ of\ a\ cycle\ of\ the\ number\ of\ recovering\ patients\ of\ specialty\ s\ in\ the\ unit\ z$
$\bar{F}_l^z$	$distribution\ of\ the\ number\ of\ recovering\ patients\ in\ unit\ z\ on\ day\ l\ of\ the\ MSS\ cycle$
w_z	$relative\ weight\ of\ unit\ z$
u_z	$a\ non-negative\ number\ such\ that\ the\ normalized\ weights\ w_z\ sum\ up\ 1$
C_{zl}	$available\ capacity\ of\ unit\ z\ on\ day\ l$
U_{zl}	$target\ utilization\ of\ unit\ z\ on\ day\ l$

4.3.4 Decision Variables

This section presents, in Table 10, the decision variables.

Table 10 *- Decision Variables*

Variables	$Description$
x_{smwdbr}	$\begin{cases} 1, if\ specialty\ s\ is\ assigned\ on\ month\ m, week\ w, on\ day\ d, to\ shift\ b, OR\ r \\ 0, otherwise \end{cases}$ $\forall\ s \in S, m \in M, w \in W_m, d \in D, b \in B, r \in R$
t_{sm}^{-}	$number\ of\ slots\ allocated\ to\ specialty\ s\ below\ its\ target\ on\ month\ m$ $\forall\ s \in S, m \in M$
t_{sm}^{+}	$number\ of\ slots\ allocated\ to\ specialty\ s\ above\ its\ target\ on$ month m $\forall\ s \in S, m \in M$
UU_{zl}	$under - utilization\ of\ unit\ z\ on\ day\ \ell \quad \forall\ z \in \{Q, I, W\}, \quad l \in L$
OU_{zl}	$over - utilization\ of\ unit\ z\ in\ day\ \ell \quad \forall\ z \in \{Q, I, W\}, \quad l \in L$

4.3.5 Auxiliary Variables

This section presents, in Table 11, the auxiliary variables

Table 11 *– Auxiliary variables*

Variables	$Description$
y_{smwdbr}	$\begin{cases} 0, if\ the\ specialty\ s\ remains\ on\ the\ same\ slot\ (m, w, d, b, r)\ from\ week\ 1\ to\ week\ w \\ 1, \quad otherwise \end{cases}$ $\forall\ s \in S, m \in M, w \in W_m, d \in D, b \in B, r \in R\ \ l \in L$
j_{smwdbr}	$\begin{cases} 0, if\ the\ specialty\ s\ remains\ on\ the\ same\ slot\ (m, w, d, b, r)\ from\ month\ 1\ to\ month\ m \\ 1, \quad otherwise \end{cases}$ $\forall\ s \in S, m \in M, w \in W_m, d \in D, b \in B, r \in R$
w_{sm}	$\begin{cases} 0, \quad if\ t_{sm}^{-}\ is\ greater\ than\ zero \\ 1, \quad if\ t_{sm}^{+}\ is\ greater\ than\ zero \end{cases} \quad \forall\ s \in S, m \in M$

4.3.6 Objective Function

In this section, each objective (1), (2), (4) and (5) is explained in better detail along with some examples using a small instance. The objectives are summed, and the model objective function (6) is obtained. Thus, the function represented in expression (6) is a weighted sum of the objectives. The ability to weight the various objectives is desirable to turn the model more general and useful to more than this hospital in particular.

$$\max \alpha_1 \sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R} \underbrace{\left(\frac{\sum_{i\in I}\, k_{isdb}}{|i|}+\frac{\sum_{a\in A} k_{adb}}{|a|}\right) x_{smwdbr}}_{1} - \alpha_2 \underbrace{\sum_{s\in S}\frac{(t_{sm}^{-}+t_{sm}^{+})}{t_{sm}}}_{2}$$
$$\underbrace{-\,\alpha_3 \sum_{z\in Z} w_z \sum_{l=1}^{L}\left(UU_{z,l}+OU_{z,l}\right)}_{3} \tag{6}$$

The model objective function consists of three objectives:

1 - Maximize the number of allocated slots and their associated aggregated preferences (objectives (1) and (4));

2 - Minimize the difference between the number of allocated slots per specialty s and its target t_s (objective (2));

3 - Minimize the weighted sum of expected under- and over-utilization of up- and downstream units (objective (5)).

Objective 1

$$\max \sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}\left(\frac{\sum_{i\in I}\, k_{isdb}}{|i|}+\frac{\sum_{a\in A} k_{adb}}{|a|}\right) x_{smwdbr} \tag{7}$$

The first objective, represented by expression (7), maximizes the number of allocated slots and the associated preferences. Each surgeon i and anesthesiologist a has been asked, through a form, which are their preferences, between 1 – least preferable slot - and 5 – most preferable slot -, regarding the day and shift that they preferer to work on. Parameters k_{isdb} and k_{adb} record the preference in terms of day d and shift b of the surgeon i of specialty s and of anesthesiologist a. This objective allocates each specialty in the slots when the aggregated preference is higher.

Expression (7) sums all the preferences (k_{isdb} and k_{adb}) and then divides by the number of surgeons ($|i|$) or anesthesiologists ($|a|$). The use of an average value is to avoid the allocation of slots to a certain specialty due to the number of surgeons. Let's imagine two specialties: specialty A with two surgeons and specialty B with 11 surgeons. If all surgeons of specialty A attribute 5 points to a certain slot a, and all surgeons of specialty B attribute 1 point to the same slot a, the second specialty would have the slot a. The model would, therefore, allocate a specialty with preference 1 to a slot instead of a specialty with preference 5. Therefore, the function takes the average of the scores and allocates to that slot the specialty which has a higher aggregate preference.

To exemplify, Table 12 represents fictitious preferences of four fictitious surgeons of general surgery and Table 13 represents fictitious preferences of two fictitious surgeons of pediatric surgery in terms of day and shift they prefer to operate. Looking at the average preference of each specialty to each slot, Monday morning slot is allocated to pediatric surgery, as it has a bigger aggregate preference ($5 > 3{,}5$); and Monday afternoon slot is allocated to general surgery ($3 > 2$).

Table 12 - Fictitious preferences of 4 surgeons of general surgery on Monday and Tuesday

General Surgery	*Monday*		*Tuesday*	
	Morning	Afternoon	Morning	Afternoon
AB	1	5	1	5
BC	5	1	5	1
CD	3	3	5	1
DE	5	3	5	1
Total	14	12	16	8
Average	3,5	3	4	2

Table 13 - Fictitious preferences of 2 surgeons of pediatric surgery on Monday and Tuesday

Pediatric Surgery	*Monday*		*Tuesday*	
	Morning	Afternoon	Morning	Afternoon
EF	5	3	1	5
FG	5	1	5	1
Total	10	4	6	6
Average	5	2	3	3

Objective 2

$$\max\left[-\sum_{s\in S}\frac{(t_{sm}^{-}+t_{sm}^{+})}{t_{sm}}\right] \tag{8}$$

The second objective, represented by objective function (8), minimizes the difference between the number of allocated slots per specialty s and its target t_{sm} and is equivalent to expression (2). This objective is related with the need to balance supply and demand. The target t_{sm} sets the number of slots that each specialty should have according to the available slots ($number\ of\ ORs\ \times\ number\ of\ shifts\ \times\ number\ of\ days\ in\ the\ week$), and to the monthly demand of each specialty. Due to restrictions in terms of space and medical staff, it is not possible to fill all available slots. Therefore, the model allows some positive and negative deviations from the target, t_{sm}^{+} and t_{sm}^{-}, respectively. As the objective is to distribute the slots as close as possible to the computed targets, the model minimizes the relative deviation from the target.

Table 14 provides an example. In this example, there are three different specialties with different number of patients waiting for surgery. Looking at the number of patients on the waiting list, one can see that specialty one (S1) has a higher number of patients than the other specialties, therefore, this specialty should have more operating room time than the others.

Additionally, it is also important to consider the average surgery time that a surgery lasts. A specialty with shorter surgeries can perform more surgeries in the same slot, and therefore will need less operating room time. Following this reasoning, the share of the slots is calculated on the multiplication of the number of patients and average surgery duration. S1 has 800 patients, and on average each one of them occupies 2,15 hours of the OR, resulting in 1729,89 hours of surgery. This number represents 80% of the 2153,18 hours of total demand, suggesting that S1 should have 80% of the available slots, and therefore 32 slots in this example.

Table 14 - Fictitious number of patients waiting for surgery for three fictitious specialties

Specialties	S1	S 2	S 3	Total
Patients on the waiting list	800	239	167	
Average surgery time	2,15h	1,35h	0,39h	
Demand × Average surgery time	1720,89 h	322,12 h	110,17 h	2153,18 h
Percentage demand	80%	15%	4%	100%
Target	32	6	2	40

Objective 3

$$\max -\sum_{z\in Z} w_z \sum_{l=1}^{L}(UU_{zl} + OU_{zl}) \tag{9}$$

The third objective, represented by expression (9), models the relation between the allocation of specialties across the slots, and the consequences of those allocations in the up- and downstream units. Expression (9) is equivalent to expression (5).

As this topic has not been sufficiently explained previously, the next figures and tables motivate the inclusion of this objective.

Figure 16 depicts the possible paths of a patient which undergoes surgery. Every patient begins his path in the pre-ward, where she/he can stay more than a day. After being seen by a doctor the patient goes to the operating room. After surgery and according to the illness severity, the patient can be directed to the ICU or to the corresponding ward for one or more days. After the ICU the patient can be transferred to the corresponding ward or can be directly discharged.

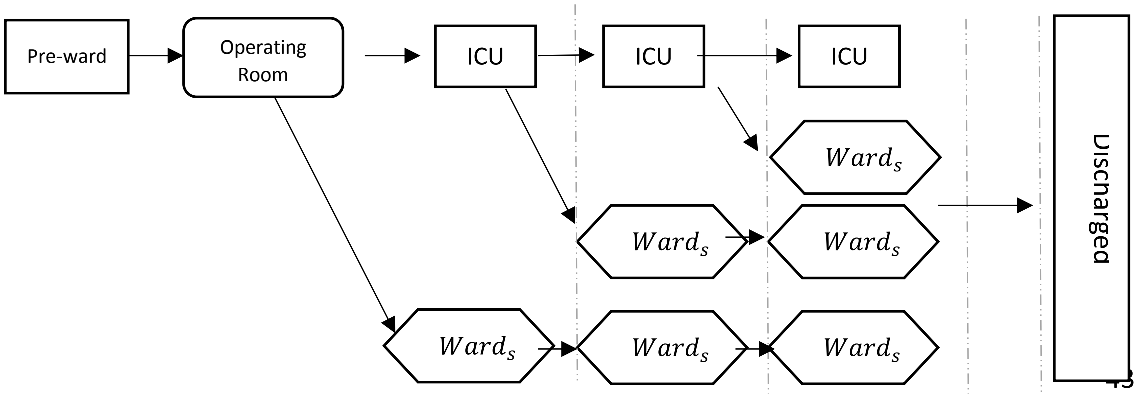


Figure 16 – Patient paths based on Fügener et al. (2014)

When discharged to the ward, the patient is allocated in the ward of his specialty s.

Tables 15, 16 and 17 provide examples that motivate the inclusion of the third objective in the MILP. Table 15 simulates the operation of 5 patients in only one day, and Tables 16 and 17 the distribution of patients who are operated in different days.

Table 15 shows the distribution, across the different up- and downstream units, of five patients of a certain specialty who were operated on day one of the MSS of a certain specialty. The example provided in the table assumes that in each day one patient is discharged to the next room, except from the pre-ward to the OR that is assumed that all the patients stay only one day in the pre-ward. Furthermore, on the day of surgery two patients go directly to the ICU and three to the ward. Therefore, on day two one patient is discharged from the ICU to ward, remaining one in this unit, and in the ward one patient is discharged and another is admitted from the ICU, remaining three patients in this unit.

Table 15 - Distribution of 5 patients who had surgery on day 1 over up- and downstream units

Units/Days of the MSS	1	2	3	4	5	6
Pre-ward	5					
Intensive Care Unit	2	1	0			
$Ward_s$	3	3	3	2	1	0

After simulating the distribution of five patients operated on day one, Tables 16 and 17 simulate the operation of 16 patients, of a certain specialty, spread along the first four days, depicting the distribution of all patients on the first 8 days. The difference between the two tables is the days where the patients are operated. The number of operated patients on a certain day is equal to the number of patients in the pre-ward, as they do not stay more than one day in the unit.

Table 16 – Distribution of 16 patients who had surgery on days 1,2,3 and 4 over up- and downstream units

Units / Days of the MSS	1	2	3	4	5	6	7	8
Pre-ward	3	5	3	5				
Intensive Care Unit	1	2	2	2	1	0		
$Ward_s$	2	5	6	8	6	4	2	1

Table 17 - Distribution of 16 patients who had surgery on days 1,2,3 and 4 over up- and downstream units

Units / Days of the MSS	1	2	3	4	5	6	7	8
Pre-ward	5	5	3	3				
Intensive Care Unit	2	3	2	1	0			
$Ward_s$	3	6	8	9	6	2	0	

These two tables illustrate the differences on the overall distribution of patients, in the up- and downstream units, that result from the different allocation of the patients along the days of the MSS (3,5,3,5/ 5,5,3,3). The example creates awareness for the importance to incorporate the leveling of the occupancy of the different units, showing how the distribution of patients can affect the daily utilization of each unit. The objective, in expression (9), minimizes overutilization and underutilization of up- and downstream units, represented by the decision variables OU_{zl} and UU_{zl}, respectively, which are related with the variable x_{smwdbr}.

4.3.7 Constraints

The section is divided in several subsections which group the constraints according to their characteristics. Section 4.3.7.1 underlines operational constraints, 4.3.7.2 depicts the constraints related with the balance between supply and demand, 4.3.7.3 presents the constraints that promote stability to the MSS, and 4.3.7.4 introduces the constraints to balance the occupancy level of up- and downstream units.

4.3.7.1 Operational constraints

This section lists the constraints that restrict the MSS due to operational characteristics, as constraints of physical space and medical staff.

Overlap:

$$\sum_{s \in S} x_{smwdbr} \leq 1 \quad \forall\, m \in M, w \in W, d \in D, b \in B, r \in R \tag{10}$$

The constraints *overlap* guarantee that each slot ($mwdbr$) can only be allocated to one specialty s. Therefore, as shown in constraints (10), the sum of variables x_{smwdbr} must be zero or one when summing on the specialty.

Resources:

Availability of human resources is one of the greatest constraints on the allocation of the slots to specialties. The two workforces considered in this model, are the ones that currently introduce more obstacles in the organization of the SS, surgeons and anesthesiologists.

<u>Surgeons:</u>

According to the Portuguese Health Regulation Authority (ERS, 2016), a surgical procedure mustn't be conducted by only one surgeon. Thus, it is recommended by the same institution that a surgical procedure shall be conducted by two surgeons (ERS, 2016). Therefore, to allocate a slot to a certain specialty, the number of available surgeons must be greater or equal than 2, as written in constraints (11).

$$2\sum_{r \in R} x_{smwdbr} \leq \sum_{i \in I} ai_{ismwdb} \quad \forall\, s \in S, m \in M, w \in W, d \in D, b \in B \tag{11}$$

This set of constraints is illustrated below:

$$2\sum_{r} x_{smwdbr} \leq 4 \tag{12}$$

When the number of available surgeons of a given specialty is four ($\sum_{i \in I} a_{ismwdb} = 4$), the number of slots ($\sum_{r} x_{smwdbr}$) can only be one or two (constraints (12)). In the example of Figure 17, only two morning slots could be occupied.

Shift / OR	**OR 1**	**OR 2**	**OR 3**
Morning			
Afternoon			

Figure 17 – Example constraints (12)

Based on the interviews, which recommend allocating a surgeon in only one slot per day, the model dictates that the same surgeon cannot operate in two consecutive slots, i.e. on a morning slot and afternoon slot in the same day. This restriction is represented by constraints (13).

$$2\sum_{b \in B}\sum_{r \in R} x_{smwdbr} \leq d_{sd} \ \forall \ s \in S, m \in M, w \in W, d \in D \tag{13}$$

Constraints (13) guarantee that the number of slots allocated in a day is not higher than the number of available surgeons on that day. For example, if there are only two available surgeons on the day illustrated in Figure 18, only one of the six slots can be occupied. If this restriction was removed, the model would allocate two slots, one in the morning and other in the afternoon.

Shift / OR	**OR 1**	**OR 2**	**OR 3**
Morning			
Afternoon			

Figure 18 – Example constraints (13)

Additionally, it is important to restrict the number of times that a surgeon can operate. Usually, a surgeon has 40 hours of weekly workload, which is split in 6 hours in the OR, 6 hours to appointments, 4 hours to visit his patients in the internment and 24 hours for emergency. Sometimes, due to different reasons, some surgeons do not allocate their hours in this way, resulting in different times that each one can visit the OR. ww_i defines the number of times that a surgeon can operate in a week and constraints (14) defines that all slots allocated to each specialty s in a certain week are limited by the number of times that a specialty can visit the OR.

$$2\sum_{d \in D}\sum_{b \in B}\sum_{r \in R} x_{smwdbr} \leq \sum_{i \in I} wwi_{is} \ \forall s \in S, m \in M, w \in W \tag{14}$$

The next restrictions are similar to the ones that affect surgeons, following however different rules.

Anesthesiologists:

Contrarily to surgeons, during a surgical procedure it is only necessary one anesthesiologist in the room (ERS, 2016). To allocate a slot to a certain specialty it is necessary to guarantee the availability of one anesthesiologist in that day d and shift b. These constraints are formulated in (15).

$$\sum_{r\in R} x_{smwdbr} \leq \sum_{a\in A} aa_{amwdb} \;\forall\, m \in M, w \in W, d \in D, b \in B \tag{15}$$

$$\sum_{b\in B}\sum_{r\in R} x_{smwdbr} \leq \, da_d \forall\, m \in M, w \in W, d \in D \tag{16}$$

As surgeons, anesthesiologists cannot operate in two consecutive slots, i.e., cannot operate on a morning slot and afternoon slot on the same day. This restriction is represented by constraints (16). Constraints (17) restricts the number of allocated slots in a week to the number of times that all the available anesthesiologist can go to the OR in a certain week.

$$\sum_{s\in S}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R} x_{smwdbr} \leq \sum_{a\in A} wwa_a \,\forall\, m \in M, w \in W \tag{17}$$

Non-negativity:

Non-negativity constraints represented by constraints (18) – (23) assure that the deviations variables (t_{sm}^{-}, t_{sm}^{+}) and UU_{zl}, OU_{zl} are positive, and x_{smwdbr}, w_{sm}, j_{smwdbr} and y_{smwdbr} take values 0 or 1.

$$t_{sm}^{-}, t_{sm}^{+} \geq 0 \quad \forall \; s \in S, m \in M \tag{18}$$

$$UU_{zl}, OU_{zl} \geq 0 \quad \forall \; z \in Z, l \in L \tag{19}$$

$$x_{smwdbr} \in \{0,1\} \,\forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{20}$$

$$w_{sm} \in \{0,1\} \,\forall\, s \in S, m \in M \tag{21}$$

$$j_{smwdbr} \in \{0,1\} \,\forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{22}$$

$$y_{smwdbr} \in \{0,1\} \,\forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{23}$$

4.3.7.2 Constraints to balance demand and supply

The following constraints are related with the need to match the available capacity to the demand, and therefore are related with the second objective (constraints (2)). To match demand and the available capacity, the model computes a target t_{sm} that reflects the percentage of the demand that each specialty holds and attributes the equivalent slots. Due to operational constraints, it is impossible to fill all the slots in the MSS. For this reason, the model allows some deviations, restricted in the constraints above.

Here the model has two variants, one that turns the model more general and other closer to the case in study. In the general variant, represented by constraints (20), the target is computed in number of hours of the operating room time (constraints (21)), in order to be feasible to hospitals with a different number of hours for each slot. To this end, the number of slots is multiplied by the average surgery duration (asd_s).

The more particular model (constraints (22)), which is the one which is implemented in the hospital under study, computes the target in number of slots, as slots have all the same duration. In this case, the target is computed in number slots as illustrated in (3).

$$\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}(x_{smwdbr} * \mathrm{asd}_s) + t_{sm}^- - t_{sm}^+ = t_{sm} \quad \forall\, s \in S, m \in M \tag{24}$$

$$t_{sm} = \frac{P_{sm} \times asd_s}{\sum_s (P_{sm} \times asd_s)} \tag{25}$$

$$\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R} x_{smwdbr} + t_{sm}^- - t_{sm}^+ = t_{sm} \quad \forall\, s \in S, m \in M \tag{26}$$

Furthermore, it is necessary to guarantee that when one of these variables is greater than zero the other must be zero.

$$t_{sm}^- \geq 0 \implies t_{sm}^+ = 0 \tag{27}$$

$$t_{sm}^+ \geq 0 \implies t_{sm}^- = 0 \tag{28}$$

Constraints (27) and (28) must be linearized:

$$t_{sm}^- \leq M \times (1 - w_{sm})\ \forall\, s \in S, m \in M \tag{29}$$

$$t_{sm}^+ \leq M \times w_{sm}\ \forall\, s \in S, m \in M \tag{30}$$

It is important to note that M is sufficiently large number so that the constraints are always satisfied. The value of M depends on the constraint and must be larger than the upper bound of the left-hand side.

Lower bound:

These constraints determine a lower bound on the number of slots monthly allocated to each specialty. The motivation for the inclusion of these constraints is to guarantee that each specialty has at least one allocated slot every month. As the model allows negative deviations from each target, it is possible that, in order to achieve a better value for the objective function, the allocation of slots to a given specialty equals to zero. To avoid that, constraints (31) is introduced. These constraints oblige that each specialty has at least one slot allocated, each month m, even if a specialty has a very low target (i.e. one slot). Constraints (31) sum all the slots in a month, meaning in weeks, days, shifts and ORs and makes it greater or equal than one to all specialties and months.

$$\sum_{w \in W} \sum_{d \in D} \sum_{b \in B} \sum_{r \in R} x_{smwdbr} \geq 1 \quad \forall\, s \in S, m \in M \tag{31}$$

4.3.7.3 Constraint to promote stability of the MSS

As mentioned before, it is of interest of the hospital to keep a stable MSS, meaning an MSS that does not change much from week-to-week and from month-to-month. Change means to change the specialty that is allocated to a certain slot ($mwdbr$) to another or to none.

Week-to-week

The required stability is measured by the number of changes that can occur from a week to another, given by the parameter Δ_w. To count the number of changes another variable is added to the model - y_{smwdbr}. This auxiliary variable is defined in constraints (32) and results from the difference between the values that the decision variable x_{smwdbr} takes on week one and the on the remaining weeks

$$\left| x_{smwdbr} - x_{s,m,w=1,d,b,r} \right| = y_{smwdbr} \tag{32}$$

$$s \in S, m \in M, w \in \{2, \ldots, W\}, d \in D, b \in B, r \in R$$

This expression counts the number of changes that can exist from week to week, having as reference the first week of each month. Tables 18, 19 and 20 show three schedules (for weeks 1-3). These weeks have three days each and the SS is composed of 2 ORs. The changes that the model counts are related to the first week and those changes are underlined in yellow.

Table 18 – MSS week 1

Day	Room 1	Room 2
1	General	Plastic
2	General	General
3	General	Plastic

Table 19 – MSS week 2

Day	Room 1	Room 2
1	General	General
2	General	General
3	General	Plastic

Table 20 – MSS week 3

Day	Room 1	Room 2
1	General	Plastic
2	General	General
3	Plastic	Plastic

Considering weeks 1 and 2, one can see a change on day 1 OR 2. This change is modeled by decision variable y_{smwdbr}, which results from the difference of the values that the decision variable x_{smwdbr} takes on each week, for that day and room, and for each specialty.

The specialties that are of interest in the first example (week 1 and week 2) are general surgery and plastic surgery. Equations (29), (30) and (31) exemplify how the model registers the changes for general surgery:

$$x_{general,\boldsymbol{week\ 1},day\ 1,room2} = 0 \ \wedge \ x_{general,\boldsymbol{week\ 2},day\ 1,room2} = 1 \tag{33}$$

$$\left|x_{general,\boldsymbol{week\ 2},day\ 1,room2} - x_{general,\boldsymbol{week\ 1},day\ 1,room2}\right| = y_{general,\boldsymbol{week\ 2},day\ 1,room\ 2} \tag{34}$$

$$|-1| = y_{general,\boldsymbol{week\ 2},day\ 1,room\ 2} \Leftrightarrow y_{general,\boldsymbol{week\ 2},day\ 1,room\ 2} = 1 \tag{35}$$

Constraints (32) are defined with the absolute value between the difference of the values of x_{smwdbr}, and therefore need to be linearized. This is done through constraints (36), (37) and (38):

$$x_{smwdbr} - x_{s,m,w=1,d,b,r} = y^{+}_{smwdbr} - y^{-}_{smwdbr} \tag{36}$$
$$\forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R$$

$$y^{+}_{smwdbr} + y^{-}_{smwdbr} \leq 1 \ \forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{37}$$

$$y^{+}_{smwdbr}, y^{-}_{smwdbr} \in \{0,1\} \quad \forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{38}$$

After defining y_{smwdbr}, the model restricts the number of changes on all days, shifts and rooms, from a week to another by the parameter Δ_w. This restriction is defined by constraints (39).

$$\sum_{s\in S}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}(y^{+}_{smwdbr} + y^{-}_{smwdbr}) \leq \Delta_w \qquad \forall\, m \in M, w \in \{2 \dots, W\} \tag{39}$$

Month - to - month

The MSS should adapt to the demand every month, but should not change drastically, to guarantee a certain stability to the involved stakeholders. The following constraints limit the variation of the MSS by allowing only Δ_m changes. The variable j_{smwdbr} equals 0 if any changes have occurred between month m and month 1, considered the month of reference, and equals 1 otherwise. Therefore, the summation of j_{smwdbr} should be equal to the number of changes considered reasonable.

$$\left|x_{smwdbr} - x_{s,m=1,w,d,b,r}\right| = j_{smwdbr}, m \in \{2, \dots, M\} \tag{40}$$

Constraints (40) is defined with the absolute value between the difference of the values of x_{smwdbr} , and therefore needs to be linearized. This is done through constraints (41), (42) and (43).

$$x_{smwdbr} - x_{s,m=1,w,d,b,r} = j^{+}_{smwdbr} - j^{-}_{smwdbr} \tag{41}$$
$$\forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R$$

$$j^{+}_{smwdbr} + j^{-}_{smwdbr} \leq 1 \ \ \forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{42}$$

$$j^{+}_{smwdbr}, j^{-}_{smwdbr} \in \{0,1\} \ \ \forall\, s \in S, m \in M, w \in W, d \in D, b \in B, r \in R \tag{43}$$

After defining j_{smwdbr}, the model restricts the number of changes from a month to another by the parameter Δ_m. This restriction is defined by constraints (44).

$$\sum_{s\in S}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}(j^{+}_{smwdbr} + j^{-}_{smwdbr}) \leq \Delta_m \; \forall\, m \in \{2, \dots, M\} \tag{44}$$

4.3.7.4 Restrictions for up- and downstream units

This section is the last section of Section 4.3.7 and shows the constraints related with the up- and downstream units. The constraints in this section are inspired by the papers Fügener et al. (2014) and Adan et al. (2009).

As exemplified when explaining the leveling of up- and downstream units, the allocation of a specialty to a certain slot has consequences in up- and downstream units. The above constraints constrict the allocation of slots to the various specialties to assure that every patient has a bed to stay before and after surgery. The complexity of these consequences increases due to the several paths that a patient can take, varying in the number of days and type of unit.

This section first relates the days of the month, with five days of the MSS; then will access the number of patients in each unit as consequence of a certain slots' allocation; and, finally, constraints the allocation of those slots according to the capacity and desired utilization level of the units.

4.3.7.4.1 Relation between units' calendar and MSS

In order to relate the SS with other units, a model from Fügener et al. (2014) is used as a basis to calculate the number of recovering patients on day l in the different units, coming or going to the OR on day d. This model intends to create an MSS which is organized in months and weeks of five days, in order to easier create a schedule which is similar between weeks and months. On the other hand, the units organize their schedules in days of the month without distinguishing between weeks. Figure 19 illustrates how the days of the MSS relate to the days of the month, and Figure 20 shows the relation between the units and the OR, coupled with their sets' denomination.

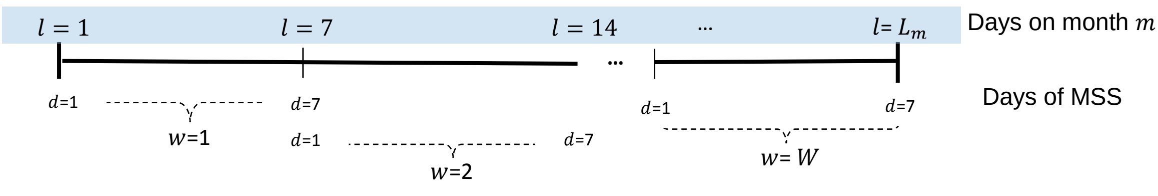


Figure 19 - Days of MSS (d) and of the month m (l)

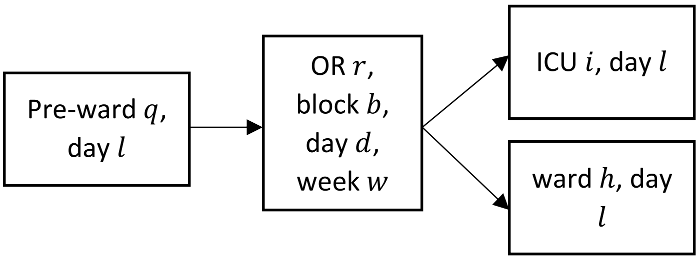


Figure 20 - Different units in perioperative care and related time sets

4.3.7.4.2 Number of patients in the up- and downstream units

In this section, it is described how the model calculates the exact number of patients on each of the units related with the SS and that result from a certain MSS.

The process is divided into three steps:

1) First, it is determined how long patients stay in the units according to their specialty;
2) then it is calculated the number of patients, of each specialty, that are in a certain day l in a certain unit according to the distribution of slots in the MSS;
3) at last, it is calculated the distribution of patients resulting from the whole MSS (merging the distribution of different slots allocated to each specialty) to calculate the occupancy levels for the pre-ward, ICU and wards.

Step 1 is based on Fügener et al. (2014) and step 3 in Adan et al. (2009). Step 2 is adapted from Fügener et al. (2014) with changes to turn the MSS no-cyclical, adding value to the literature.

Step 1

The objective is to understand how many patients a specialty generates in one slot of the MSS.

Day	Monday	Tuesday	Wednesday	Thursday	Friday
	X				
$e^z_{s,n}$	e_1	e_2	e_3	e_4	e_5

Figure 21 – Example of number of days a patient can stay in a unit

For this step one calculates for how long these patients stay in the units.

Figure 21 exemplifies this step. X is a patient from general surgery, that has surgery on Monday and according to his recovery, can stay n days on the downstream unit z (in the example until Thursday, represented by the blue arrow); e^z_{sn} indicates the probability of a patient, of specialty s, who had surgery on day one, to be on day n in unit z. Therefore, in the example, e_1 is the probability that patient X is in the unit on the day of surgery, e_2 the probability that the patient is in the unit in the day after surgery, and e_5 is the probability that the patient remains in the unit until Friday. According to the example, the patient stays at most until Thursday in the unit. Therefore, in day five the probability (e_5) to be in the unit is zero.

To calculate e^z_{sn}, the model uses a discrete empirical distribution by Fügener et al. (2014), that requires historical or estimated data for every specialty $s \in S$ as follows:

- g_s represents the probability that a patient of specialty s is admitted in the ICU immediately after surgery. $1 - g_s$ is the probability that the patient is admitted to the ward;
- $c^z_s(n)$ represents the probability that a patient from surgery of specialty s stays $n \in \{1, \dots, N^z_s\}$ days in the unit z.

To calculate $e^z_{s,n}$, the model first calculates the probability of a patient to be discharged from a unit resorting to conditional probability and represented by parameter $d^z_{s,n}$.

$$d^z_{,n} = \frac{c^z_s(n)}{\sum_{k=n}^{N^z_s} c^z_s(k)} \quad s \in S, n \in \{1, \dots, N^z_s\}, z \in Z \tag{45}$$

Expression (45) determines that the probability of a patient to be discharged from unit z on day n (d^z_{sn}) is the probability of staying $n \in \{1, \dots, N^z_s\}$ days in the unit z, represented by $c^z_s(n)$, divided by the number of days that the patient didn't stay in the unit ($\sum_{k=n}^{N^z_s} c^z_s(k)$).

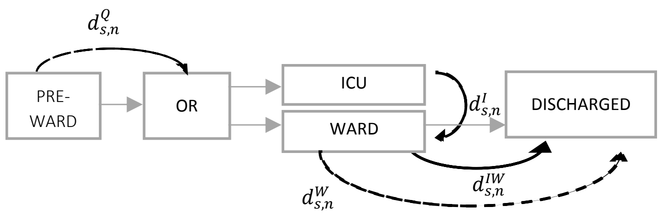


Figure 22 – Discharged probabilities

There are 4 discharged probabilities that can be computed, represented on Figure 22:

- d^Q_{sn} – discharged on day n from the pre-ward;
- d^I_{sn} – transferred from the ICU to the ward n days after surgery;
- d^W_{sn} – discharged from the ward n days after surgery;
- d^{IW}_{sn} – discharged from the ward n days after leaving the ICU;

If a patient leaves the hospital directly after staying in the ICU it is assumed that the patient stays zero days in the ward (d^{IW}_{s0}).

After computing the probability of being discharged it is possible to calculate e_{sn}^{z}, for all specialties $s \in S$ and for each day $n \in \{1, \dots, N_s^z\}$, meaning the probability of patient of specialty s who has surgery on day one is in the unit z on day n:

- e_{sn}^{Q} – probability of a patient of specialty s who has surgery on day one is in the pre-ward on day n, represented in expression (46).

$$e_{sn}^{Q} = \begin{cases} 1, \quad n = 1 \\ \left(1 - d_{s,n-1}^{Q}\right) e_{s,n-1}^{Q}, \qquad n \in \{2, \dots, N_s^Q\} \\ 0, \qquad otherwise \end{cases} \tag{46}$$

On day one the probability equals to one, as all the patient must go through the pre-ward on the day of surgery. For the following days, the probability decreases as the patient might be transferred to the OR. Therefore, from day two forward the probability equals to the probability of being in the pre-ward on the day before ($e_{s,n-1}^{Q}$) times the probability of not being discharged on the day before ($1 - d_{s,n-1}^{Q}$). The probability e_{sn}^{Q} gets smaller as the discharged probability d_{sn}^{Q} gets higher.

A similar chain of thoughts is done for the ICU, by expression (52):

$$e_{sn}^{I} = \begin{cases} g_s, \quad n = 1 \\ \left(1 - d_{s,n-1}^{I}\right) e_{s,n-1}^{I}, \qquad n \in \{2, \dots, N_s^I\} \\ 0, \qquad otherwise \end{cases} \tag{47}$$

On day 1, this probability equals g_s, i.e., the probability that the patient is directly transferred to the ICU after surgery. For the following days, the probability decreases as patients might be transferred to the ward.

To calculate e_{sn}^{W} the model differentiates between patients who were directly transferred to the ward after leaving the OR and those who were transferred via the ICU. The probability of a patient that came directly from the OR and is in the ward on day n is denoted by e_{sn}^{OW} whereas the probability that the patient is in the ward on day n after staying m days in the ICU is e_{smn}^{IW}.

$$e_{sn}^{OW} = \begin{cases} 1 - g_s, \qquad n = 1 \\ \left(1 - d_{s,n-1}^{OW}\right) e_{s,n-1}^{OW}, \qquad n \in \{2, \dots, N_s^{OW}\} \\ 0, \qquad otherwise \end{cases} \tag{48}$$

$$e_{smn}^{IW} = \begin{cases} \left(1 - d_{s,0}^{IW}\right) d_{sm}^{I} e_{sm}^{I}, \qquad m \in \{1 \dots N_s^I\}, n = m + 1 \\ \left(1 - d_{s,n-m-1}^{IW}\right) e_{s,m,n-1}^{IW}, \qquad m \in \{1 \dots N_s^I\}, n \in \{m + 2, \dots, m + N_s^{IW}\} \\ 0, \qquad otherwise \end{cases} \tag{49}$$

The calculation of e_{sn}^{OW}, in expression (48), is analogous to e_{sn}^{I}. On day 1, this probability equals $1 - g_s$, i.e., the probability that the patient is directly transferred to the ward after surgery. For the following days, the probability decreases as patients might be transferred to the ward.

To calculate e_{smn}^{IW}, in expression (49), the different transfer times from the ICU to the ward are considered. The probability of staying one day in the ward after m days in the ICU.

After staying m days in the ICU ($n = m + 1$), e_{smn}^{IW} equals the product of

(a) the probability $\left(1 - d_{s,0}^{IW}\right)$ that the patient does not leave the hospital immediately;

(b) the probability $d_{,m}^{I}$ that he is transferred to the ward on day m;

(c) the probability e_{sm}^{I} that the patient is in the ICU on day m.

If the patient stays more than one day in the ward:

(a) the probability $\left(1 - d_{s,n-m-1}^{IW}\right)$ that the patient is not discharged on the day before, which is n, the day of the month, minus m, the number of days the patient was on the ICU, minus 1, to go to the day before.

(b) the probability ($e_{s,m,n-1}^{IW}$) that the patient was in the ward on the day before ($n - 1$), knowing that she/he is m days in the ICU.

Therefore, the probability e_{sn}^{W} that a patient is in the ward on day n is calculated, in expression (50), by adding the probability e_{sn}^{OW} that the patient came directly from the OR ($n = m + N_s^{IW} = 0 + 1 = 1$) and the probabilities e_{smn}^{IW} that s/he stays m days in the ICU before going to the ward, for all possible number of days $m < n$.

$$e_{sn}^{W} = \begin{cases} e_{s,1}^{OW}, & n = 1 \\ e_{sn}^{OW} + \sum_{m=1}^{n-1} e_{smn}^{IW}, & n \in \{2, \dots, N_s^{W}\} \\ 0, & otherwise \end{cases} \tag{50}$$

Step 2

After determining how long a patient can stay in a unit, the model relates variable x_{smwdbr} with the probability e_{sn}^{z} in constraints 51).

$$F_{sl}^{z} = \sum_{b \in B} \sum_{r \in R} \lambda_s \left(\sum_{k=0}^{N_s - 1} x_{s,m,l-k,b,r} \;\; e_{s,k+1} \right) \forall\, s \in S, m \in M, z \in Z, l \in \{N_s^{z}, \dots, L_m\} \tag{51}$$

F_{sl}^{z} represents the distribution, on the ℓth day of a month, of the number of recovering patients of specialty s in the unit z, which results from the allocation of slots N_s^{z} days before the ℓth day.

An example is given to better explain constraints 51):

Example

A specialty s knows, from historical data, the maximum number of days (N_s^{z}) that a patient can stay in the unit z. Let's state $N_s^{z} = 6$.

Given N_s^{z} it is possible to know how many patients are in the unit z on day n. For example,

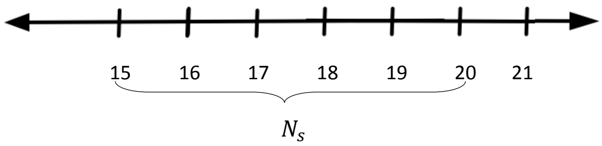


Figure 23 – Axis of days l

looking for the axis on Figure 23, how many patients are in unit z on day 20? There are the patients who stays in the unit 6 days from the day of surgery, meaning the patients that are operated on the 15th, the patients who are operated on day 20 and go directly to the unit, and the patients who are operated in the other days and stay more than one day and less than six days. If one reduce constraints 51) to expression (52) , where $x_{s,m,l-k,br}$ stands for the slot allocated to specialty s on month m on day $l-k$ on shift b on room r, and $e^{z}_{s,k+1}$ stands for the probability of a patient of specialty s is in the unit z on day $k+1$, the number of patients in unit z is equal to expression (51). Index k is used to go forward in the recursive expressions.

$$\sum_{k=0}^{l-1} x_{s,m,l-k,b,r} \;\; e^{z}_{s,k+1} \tag{52}$$

$$\begin{aligned} F^{z}_{s,20} = {} & x_{s,m,w,15,b,r} * e_{s,6} + x_{s,m,w,16,b,r} * e_{s,5} + x_{s,m,w,17,b,r} * e_{s,4} + x_{s,m,w,18,b,r} * e_{s,3} \\ & + x_{s,m,w,19,b,r} * e_{s,2} + x_{s,m,w,20,b,r} * e_{s,1} \end{aligned} \tag{53}$$

End of example

The full expression, in constraints 51), sums all the slots of those days, between l and $l - N^{z}_{s} + 1$ - in the example between 20 and 20-6+1=15 (meaning the combination of shits b and ORs r) and multiply by the average number of patients that a specialty can operate in a slot (λ_s). In this way, it is possible to calculate the number of patients of specialty s in the unit z on day l. Again, as we are dealing with a strategic-tactical problem, the average number of operated patients (λ_s) can be used.

Moreover, the constraints must be coherent with the domain of the sets of the variable x_{smwdbr}, meaning that l, must be converted into a certain day d in a certain week w. This conversion is given by equations (54) and (55).

$$week = w = \left\lceil \frac{l-k}{7} \right\rceil \tag{54}$$

$$day = d = (l-k) - \left\lfloor \frac{l-k}{7} \right\rfloor 7 + 1, \qquad \forall\, d \neq 6, 7 \tag{55}$$

After the conversion of l into days d and weeks w we can update constraints (51) to constraints (56) and (57), where constraints (56) is for instance where $\mathrm{l} > N^{z}_{s}$ and constraints (57) for $\mathrm{l} < N^{z}_{s}$:

$$F^{z}_{sl} = \sum_{b \in B} \sum_{r \in R} \lambda_s \left(\sum_{k=0}^{N_s - 1} x_{sm\mu\tau br} \;\; e_{s,k+1} \right) \forall\, s \in S, m \in M, z \in Z, l \in \; \{N^{z}_{s}, \dots, L_m\} \tag{56}$$

$$F^{z}_{sl} = \sum_{b \in B} \sum_{r \in R} \lambda_s \left(\sum_{k=0}^{l-1} x_{sm\mu\tau br} \;\; e_{s,k+1} \right) \forall\, s \in S, m \in M, z \in Z, l \in \; \{1, \dots, N^{z}_{s}\} \tag{57}$$

$$\mu = w = \left\lceil \frac{l-k}{7} \right\rceil \quad (58)$$

$$\tau = d = (l-k) - \left\lfloor \frac{l-k}{7} \right\rfloor 7, \qquad \forall\, d \neq 6,7 \quad (59)$$

Step 3

Until now, step one calculated for how long a patient can stay in a unit and step two computed the number of patients in a certain day and week for each unit z for each specialty. The third step merges the distribution of different slots allocated to each specialty, creating a single distribution for the pre-ward, ICU and wards.

- Number of patients on the pre-ward on day l:

$$\bar{F}_l^Q = \sum_{s \in S} F_{sl}^Q \quad \forall\, s \in S, l \in L_m \quad (60)$$

- Number of patients on the ICU on day l

$$\bar{F}_l^I = \sum_{s \in S} F_{sl}^I \quad \forall\, s \in S, l \in L_m \quad (61)$$

- Number of patients on the ward h on day l

$$\bar{F}_{hl}^W = \sum_{s \in S_h} F_{sl}^W \quad \forall\, s \in S, l \in L_m, h \in H \quad (62)$$

The model differentiates between multiple wards $h \in H$. Each specialty s corresponds to one specific ward, whereas each ward may accommodate more than one specialty. The set of specialties accommodated by ward h is denoted by S_h.

4.3.7.4.3 Balance the under and overutilization

Now that it is possible to know the distribution of recovering patients in the pre-ward, ICU and in the h wards, the model can restrict the distribution of patients to the capacity and target utilization of each pre-ward, ICU and ward. Considering that:

- $C_{z\ell},\ z \in Z = \{Q, I, H\}$ represents the available capacity of unit z on day l;
- $U_{z\ell},\ z \in Z = \{Q, I, H\}$ represents the target utilization of unit z on day l;
- $UU_{z\ell}$ is the decision variable that represents the under-utilization of unit z on day l considering the target $U_{z\ell}$;
- $OU_{z\ell}$ is the decision variable that represents the over-utilization of unit z on day l considering the target $U_{z\ell}$.

The number of patients in the unit z should be in accordance with the target utilization defined for it:

$$U_{z\ell} - UU_{z\ell} \leq \bar{F}_l^z \leq U_{z\ell} + OU_{z\ell}, \qquad z \in \{Q, I, H\}, \ell \in L_m \tag{63}$$

As represented by constraints (63), the number of patients in each unit z, modeled by the parameter $\bar{F}_l^z$, is between its target utilization $U_{z,\ell}$ plus the allowed over-utilization $OU_{z,\ell}$ and its target utilization $U_{z,\ell}$ minus the allowed under-utilization $U_{z,\ell}$. For each unit z, the available capacity should not be exceeded, so constraints (64) restricts the decision value to the unit capacity minus the unit target utilization:

$$U_{z\ell} + OU_{z\ell} \leq \; C_{z\ell} \;\; , z \in \{Q, I, H\}, \ell \in L_m \tag{64}$$

The objective is to minimize the weighted sum of expected under and overutilization. This objective is represented in constraints (65),

$$\sum_{z \in R} w_z \sum_{\ell=1}^{\mathcal{L}} (UU_{z\ell} + OU_{z\ell}), \tag{65}$$

Where the weight $w_z$for unit z is defined in constraints (66).

$$w_z = \frac{u_z}{\sum_{\ell=1}^{L} U_{z\ell}}, \tag{66}$$

where u_z is some nonnegative number such that the normalized weights sum up to 1. The weight represents the importance of the unit according to the stakeholders.

Updating the objective function:

$$\begin{aligned} \max \alpha_1 \sum_{s \in S} \sum_{m \epsilon M} \sum_{w \in W} \sum_{d \in D} \sum_{b \in B} \sum_{r \in R} \left(\frac{\sum_{i \in I} k_{isdb}}{|i|} + \frac{\sum_{a \in A} k_{adb}}{|a|} \right) x_{smwdbr} - \alpha_2 \sum_{s \in S} (t_{sm}^- + t_{sm}^+)/t_{sm} \\ - \alpha_3 \sum_{z \in Z} w_z \sum_{l \in L} (UU_{z\ell} + UO_{z\ell}) \end{aligned} \tag{67}$$

4.4 Conclusions

Chapter 4 presents a mathematical model to create a new MSS which aims to improves the effectiveness and efficiency of SS. This model assembles four objectives suggested by the case study and by the literature: to maximize the number of allocated slots, which is a common objective in papers which optimize the MSS; to maximize surgeons and anesthesiologists preferences, based on Penn et al. (2017); to match supply and demand - based on Agnetis et al. (2012) and to level the utilization of up- and downstream units, based on Adan et al. (2009) and Fügener et al. (2014). The developed model contributes to the literature by integrating all the objectives and modeling a non-cyclical MSS. In the cited papers the MSS is modeled as weekly cyclical schedule, implying the adaptation of all models to constraints for a non-cyclical approach. This non-cyclicity allows a flexible adaptation of the surgical supply (capacity) to the demand from month to month and from year to year.

Along with the objective 6 the model is composed by four groups of constraints: operational constraints (10), (11), (13) - (19); constraints to balance supply and demand, (20), (26)-(28); constraints to promote stability to the MSS (37) - (39), (42) - (44) and constraints for up- and downstream units, (56), (57), (60) - (64).

The model expects to guarantee the maximum utilization of the allocated slots by including availability of surgeons and anesthesiologists on each shift, day, week and month, reducing the number of canceled slots, and to reduce the waiting list by allocating the slots according to the shares of the waiting list.

5. Computational Results

This chapter presents and discusses the results obtained by using the model proposed in the previous chapter with data from the case study.

The model is implemented using the software General Algebraic Modeling System (GAMS). GAMS "is a high-level modeling system for mathematical programming and optimization, that consists of a language compiler and a stable of integrated high-performance solvers, tailored for complex, large scale modeling applications, that allows the user to build large maintainable models that can be adapted quickly to new situations" (GAMS website, 2016). Nevertheless, GAMS showed some limitations to implement constraints (56) and (57). Thus, the implementation of the model includes only the first two objectives: maximization of the allocated slots and its aggregated preferences, and the minimization of the deviation from the target - computed with the percentage of the waiting list that each specialty holds. This smaller implementation is not only related with the software limitations but also with a minor interest from the hospital to implement the third objective (to level the utilization of up- and downstream units).

All the tests are performed on an Intel® Core™ i5-7200U CPU @ 2.50GHz processor with the Windows 10 operating system.

This chapter characterizes the instances in Section 5.1. Section 5.2 presents the normalization of the objective function and Section 5.3 validates and discusses the quality of the results. Section 5.4 makes an analysis of the trade-off between the two objectives and Section 5.5 compares the results with the current data of the case study. Section 5.6 underlines the main conclusions.

5.1 Instances Characteristics

The MILP model is tested with data from the hospital in study. Appendices 3 and 4 summarize the sets and parameters that are used in the computational tests.

5.2 Normalization of the objective function

Objective function (68) must be normalized as the objectives have different orders of magnitude.

$$\max \alpha_1 \sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}\left(\frac{\sum_{i\in I} k_{isdb}}{|i|}+\frac{\sum_{a\in A} k_{adb}}{|a|}\right)x_{smwdbr} - \alpha_2 \sum_{s\in S}(t_{sm}^{-}+t_{sm}^{+})/t_{sm} \qquad (68)$$

To normalize the objective function, it is used a known technique which consists of three steps. First, the maximum and minimum value of each of the objectives are calculated. To this end each objective is optimized individually to find the maximum value of the optimized objective and the minimum value of the excluded objective. Then each objective is subtracted by its minimum value and divided by the difference between the maximum and minimum values, as generally represented in expression (69). Finally, the normalized terms are summed up to a single objective. The new objective is dimensionless.

$$\frac{f(x) - f^{min}}{f^{max} - f^{min}} \tag{69}$$

In this case, it is not possible to optimize the two objectives individually as the second objective depends on the first. Therefore, each objective function is individually optimized by giving a weight close to one to the objective to be optimized and close to zero to the other objective. To simplify the description, objective two is analyzed as a negative objective. Meaning that the new objective (t_2) is equal to the symmetric of the second objective (z_2): $t_2 = -z_2$. The new objective function is:

$$\max \ \frac{z_1 - z_1^{min}}{z_1^{max} - z_1^{min}} + \frac{t_2 - t_2^{min}}{t_2^{max} - t_2^{min}} \tag{70}$$

With:

$$z_1 = \sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}\left(\frac{\sum_{i\in I} k_{isdb}}{|i|} + \frac{\sum_{a\in A} k_{adb}}{|a|}\right) x_{smwdbr} \tag{71}$$

$$t_2 = -\sum_{s\in S}(t_{sm}^{-} + t_{sm}^{+})/t_{sm} \tag{72}$$

Table 21 shows the weights (α_1, α_2) given to the two objectives and the respective values.

Table 21 – Normalization weights and individual optimum value

	α_1	α_2	*Optimum value*	*Minimum value*	*Domain range*
Objective 1(z_1)	0,9999	0,0001	4104,689	3621,286	483,4
Objective 2(t_2)	0,0001	0,9999	-30,317	-69,848	39,531

As shown in Table 21, the minimum value for objective 1 is 3621,286 and for objective 2 is -69,848, and differences between the maximum and the minimum are 483,4 and 39,531, respectively, resulting in objective function (73):

$$\max \alpha_1 \frac{\sum_{s\in S}\sum_{m\in M}\sum_{w\in W}\sum_{d\in D}\sum_{b\in B}\sum_{r\in R}\left(\frac{\sum_{i\in I} k_{isdb}}{|i|} + \frac{\sum_{a\in A} k_{adb}}{|a|}\right) x_{smwdbr} - 3621{,}286}{483{,}4} + \alpha_2 \frac{\sum_{s\in S}(t_{sm}^{-} + t_{sm}^{+})/t_{sm} + 69{,}848}{39{,}531} \tag{73}$$

The next sections validate the model and present some results.

5.3 Validation

This section intends to validate restrictions and objectives related with:

- Preferences;
- Maximization of the allocation of the slots (maximization of x_{smwdbr});
- Minimization of the deviations from the target;
- Stability of the MSS with the parameters Δ_m and Δ_w, along with a sensitivity analysis.

5.3.1 Preferences

One objective of the model presented in Chapter 4, is to maximize the stakeholders' preferences, meaning to allocate the specialties where surgeons are more used to or would prefer in the future. The preferences were collected by the use of questionnaires and informal meetings. Unfortunately, the collection of preferences of all the 43 surgeons is not completed. Therefore, it was necessary to create a reasonable metric to evaluate preferences which were not collected during the collection of data. Table 22 resumes the followed principle. It is known, from the conducted interviews, that surgeons prefer to operate during the morning. This is related with the probability of delay in surgeries, and therefore to be preferable to extend the surgery to the afternoon than to the night.

Table 22 – Score of each slot according to the current MSS

	Score
Slot where the surgeon currently operates	5
Morning slot, where the surgeon does not operate	3
Afternoon slot, where the surgeon does not operate	1

Furthermore, the model does not aim to completely change the current MSS, since it is of interest to maintain current staff routines as much as possible. Therefore, it is assumed that the current slots are the most preferred ones and thus it is given the maximum score to the slots where the surgeon is currently working (5), 3 to morning slots, as is a general preference, and 1 to afternoon slots. The model allocates the slots according to aggregated preferences of each specialty for each slot, allocating the specialties with a higher score to the corresponding slots. According to this criterion, Tables 23 and 24 show the aggregated preferences of each specialty by day and shift, while Figures 24 and 25 illustrate the difference of the MSS with and without the maximization of the aggregated preferences, respectively.

The model allocates specialties to slots according to their aggregated preferences for each slot. For example, the Monday morning slot is allocated to urology, which has a score preference of four (the greatest score for that slot). On Tuesday morning the slot is allocated to general surgery (with the greatest score, 3,57). Ophthalmology, although having a dedicated OR, can also have their preferences accomplished, having morning slots, instead of afternoon slots. All these examples can be seen in Figure 25, were the MSS takes into consideration the preferences, but not in Figure 24.

Table 23 – Aggregated preferences for morning slots

Morning Slots	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**
General S.	3,14	3,57	3	3,43	3,57
Plastic S.	3	3	5	3	3
Pediatric S.	3	3	5	3	3
Stomatology	3	3	3	3	5
Ophthalmology	3,4	3,4	3,6	3,6	3,0
Orthopedics	3,4	3,4	3,4	3,4	3,4
ORL	3	3	3	3	3
Urology	4	3	3	4	3

DAY	1	2	4	5
MON	Plastic	General	Orthopedics	Ophthalmology
	-	-	-	Ophthalmology
TUE	Urology	General	Orthopedics	Ophthalmology
	General	-	-	-
WED	Pediatric	General	Urology	Ophthalmology
	ORL	-	Plastic	-
THU	General	General	General	-
	General	-	ORL	-
FRI	Stomatology	-	-	Ophthalmology
	-	-	-	-

Figure 24– MSS without aggregated preferences

DAY	1	2	4	5
MON	Urology	Plastic	Orthopedics	Ophthalmology
	-	-	-	-
TUE	General	General	General	Ophthalmology
	Plastic	-	-	-
WED	Pediatric	General	Orthopedics	Ophthalmology
	-	ORL	-	-
THU	Urology	General	General	Ophthalmology
	ORL	-	-	-
FRI	General	General	Stomatology	Ophthalmology
	-	-	-	-

Figure 25 – MSS with aggregated preferences

Table 24 - Aggregated preferences for afternoon slots

Afternoon Slots	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**
General S.	1,86	2,14	1	1	1
Plastic S.	1	5	1	1	1
Pediatric S.	1	1	1	1	1
Stomatology	1	1	1	1	1
Ophthalmology	1	1,4	1	1,2	1
Orthopedics	1	1	1	1	1
ORL	1	1	3	5	1
Urology	1	1	1	1	1

5.3.2 Target

The model attempts to allocate slots according to the demand of each specialty. To access the relation between the demand and the number of allocated slots a target is computed giving the number of slots that each specialty should achieve each month.

To validate this objective one can change the weights of each objective (α_1 *and* α_2) to two unequal values in order to first push the model to maximize the number of slots and then to minimize the deviation of the allocated slots from the target. This technique is usually done with weights between 1 and 0, where the sum of the two given weights is equal to one. The next validations follow this technique by setting the two weights, α_1 *and* α_2, to 0,1 and 0,9.

Tables 25 and 26 highlight the results when the weights α_1 and α_2 are set to 0,9 and 0,1, respectively, and then the reverse. Analyzing both tables, one can see that many specialties do not present any changes from one run to the other. This is due to restrictions on HESE's workforce. As the specialties cannot reach their target, the model looks up, in both cases, to the maximization of the allocated slots, resulting in the maximum capacities of the specialties in terms of workforce. However, in the allocation of slots to specialty stomatology, it is possible to catch the differences. This specialty has a very low target, allowing the model to allocate more slots than the specialty needs. In Table 25 the model gives more importance to maximize the number of slots allocated, resulting in the maximum allocation to stomatology which corresponds to 4 slots, one each week. Table 26 shows the results when it is more important to minimize the deviation from the slots, allocating only one slot for stomatology. The minimization of the deviations can also be seen by the relative distance from the target shown in Tables 27 and 28. The highest difference is again in specialty stomatology.

Table 25 – Distribution of the slots for a higher weight to "maximizing of the number of allocated slots" (α_1=0,9 and α_2=0,1)

SLOTS

Specialty/ Month	1	2	3	4	5	6	7	8	9	10	11	12
General Surgery	32	32	32	32	32	32	32	32	32	32	32	32
Plastic Surgery	8	8	8	8	8	8	8	8	8	8	8	8
Pediatric Surgery	4	4	4	4	4	4	4	4	4	4	4	4
Stomatology	4	4	4	4	4	4	4	4	4	4	4	4
Ophthalmology	20	20	20	20	20	20	20	20	20	20	20	20
Orthopedics	8	8	8	8	8	8	8	8	8	8	8	8
ORL	8	8	8	8	8	8	8	8	8	8	8	8
Urology	8	8	8	8	8	8	8	8	8	8	8	8
Total	92	92	92	92	92	92	92	92	92	92	92	92

Table 26 – Distribution of the slots for a higher weight to "minimizing the deviations from the target" (α_1=0,1 and α_2=0,9)

SLOTS

Specialty/ Month	1	2	3	4	5	6	7	8	9	10	11	12
General Surgery	32	32	32	32	32	32	32	32	32	32	32	32
Plastic Surgery	8	8	8	8	8	8	8	8	8	8	8	8
Pediatric Surgery	4	4	3	3	4	3	3	3	3	3	3	3
Stomatology	1	1	1	1	1	1	1	1	1	1	1	1
Ophthalmology	20	20	20	20	20	20	20	20	20	20	20	20
Orthopedics	8	8	8	8	8	8	8	8	8	8	8	8
ORL	8	8	8	8	8	8	8	8	8	8	8	8
Urology	8	8	8	8	8	8	8	8	8	8	8	8
Total	89	89	88	88	89	88	88	88	88	88	88	88

Table 27 – Relative distance from the target for a higher weight to "maximizing of the number of allocated slots" (α_1=0,9 and α_2=0,1)

Target Deviation	1	2	3	4
General	0,58	0,45	0,46	0,42
Plastic	0,43	0,33	0,33	0,33
Pediatric	0	0	0,33	0,33
Stomatology	3	3	3	3
Ophthalmology	0,35	0,2	0,23	0,31
Orthopedics	0,8	0,75	0,75	0,76
ORL	0,38	0,2	0,27	0,27
Urology	0,58	0,47	0,5	0,5
Total	**6,14**	**5,43**	**5,88**	**5,93**

Table 28 - Relative distance from the target for a higher weight to "minimizing the deviations from the target" (α_1=0,1 and α_2=0,9)

Target Deviation	1	2	3	4
General	0,58	0,47	0,45	0,42
Plastic	0,42	0,33	0,33	0,33
Pediatric	0,25	0,00	0,33	0,33
Stomatology	0	0	0	0
Ophthalmology	0,35	0,2	0,23	0,31
Orthopedics	0,8	0,75	0,75	0,76
ORL	0,38	0,2	0,27	0,27
Urology	0,58	0,47	0,5	0,5
Total	**2,18**	**1,95**	**2,42**	**2,51**

5.3.3 Stability of the MSS with the parameters Δ_m and Δ_w

he general idea of this model is to create an MSS with few changes from the current MSS as much as possible but better adjusting capacity to surgical demand. However, it is important to guarantee that the MSS is stable along the month and along the year to promote a better organization of the SS and of the surgeons' agendas.

This section intends first to validate the constraints that ensure the weekly and monthly stability of the MSS and then to perform a sensitivity analysis, to understand the effect of implying more or less stability to the hospital. Theoretically, a more flexible MSS implies a better match between surgical supply and demand, since it allows changes on the number of allocated slots from month to month. On the other hand, a more restricted MSS has more difficulties to fit the demand but allows a more stable schedule, preferred by the medical staff. This analysis is therefore relevant to understand the trade-off between stability and the match of supply and demand. This sensitivity analysis follows this structure: first, the weekly stability is analyzed to perceive the value of each change over a month. Then, after the perception of good values for Δ_w, a sensitivity analysis is done for pairs of parameters Δ_w and Δ_m, with parameter Δ_w fixed. This second analysis aims to understand, when fixing the number of changes over the month, how closer can the supply be from the demand when allowing more changes in between weeks or months.

The first test is done varying only the parameter that sets the number of changes along the week, Δ_w, ignoring the constraints related to the monthly stability, Δ_m. The validation of these constraints can be done by setting Δ_w equal to a constant n and verifying that the sum of auxiliary variables y^+_{smwdbr} and y^-_{smwdbr}, which count the number of changes, is lower or equal to constant n. Table 29 shows the number of changes when setting Δ_w to 0, and Table 30 when setting Δ_w to 3. In both cases, it is possible to see that the sum of the auxiliary variables never surpasses the value of n.

Table 29 - Number of changes from week 1 to week w when Δ_w= 0

Month/ week	1	2	(…)	11	12
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0

Table 30 – Number of changes from week 1 to week w when Δ_w=3

Month/ week	1	2	3	4	5	6	7	8	9	10	11	12
2	2	2	2	2	3	2	3	3	2	2	2	2
3	2	3	3	3	2	0	0	1	3	3	3	0
4	3	0	0	2	0	3	0	3	2	2	2	3

It is also possible to validate these constraints by visualizing the MSS, in Appendix 5, and see that there are no changes from a week to another.

The second validation is related with the number of changes from a month to another month. As previously, the validation is done by setting parameters Δ_w and Δ_m to 0 and then assuring that both variables y_{smwdbr} and j_{smwdbr} are equal to zero, implying no changes from week to week and from month to month.

The same can be done by setting parameters to values different than zero and observe that the number of changes is lower or equal to the value of the parameters (Example with $\Delta_w = 2$ and $\Delta_m = 30$ in Appendix 13 and 14).

<u>Sensitivity Analysis</u>

After validating the constraints that promote stability to the MSS, a sensitivity analysis is proposed to understand which values can be of interest to the hospital in terms of number changes from week to week and from month to month.

The first sensibility analysis is done for the parameter Δ_w. Parameter Δ_m is set to 0 and Δ_w to 0, 1, 2, 3, 4 and 6. With Figures 26 and 27 one can observe that the MSS benefits a lot when Δ_w is greater than zero but, on the other hand, there is no significant impacts when allowing more than one change. The large impact from zero changes to one change is related with the low demand of stomatology, which requires only one slot per month. The MSS benefits when allocating only one slot to stomatology meaning to have one week different from the others.

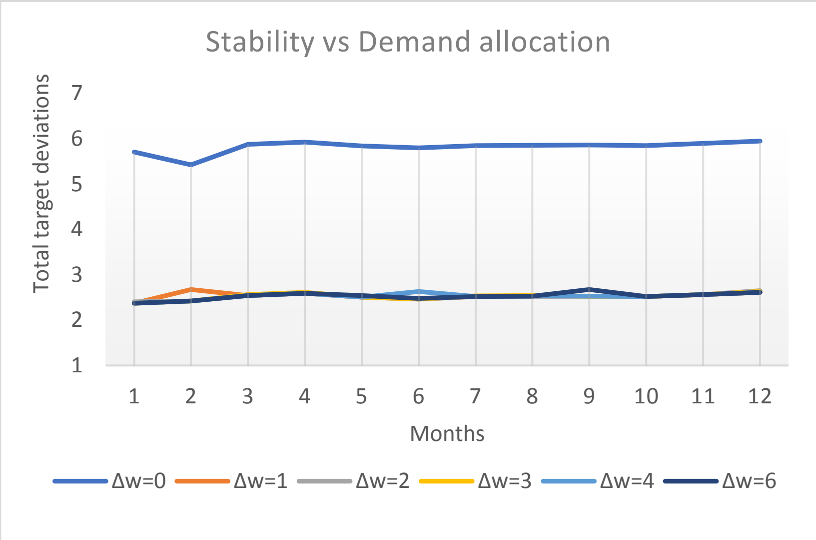


Figure 27 - Total deviations from the target for each Δ_w

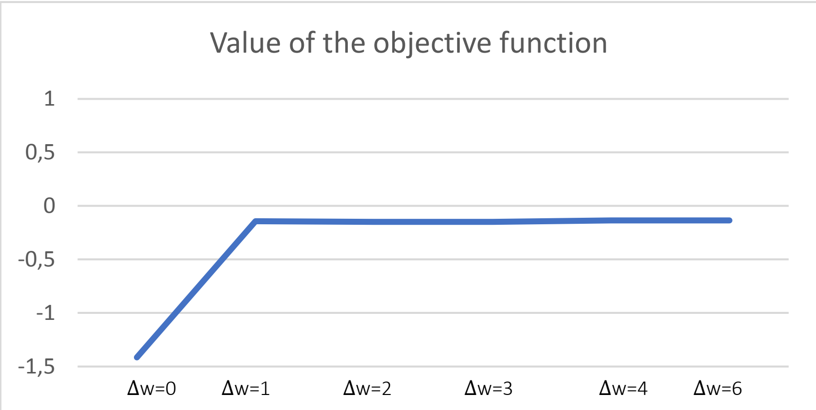


Figure 26 – Value of the objective function for each Δ_w

For sensitivity analysis of parameter Δ_m, one can observe that the data behaves in the same way than with the parameter Δ_w. The benefits are high when parameter Δ_w is greater than zero, but no considerable impact is seen with changes in parameter Δ_m. The explanation for these results is the high-level constraints in terms of workforce (staff shortage). The workforce is always working on its maximum capacity, therefore no changes can be observed. Figures 28 and 29 depict the variation of the objective function and of the values that measure the deviation from the target when changing parameter Δ_m.

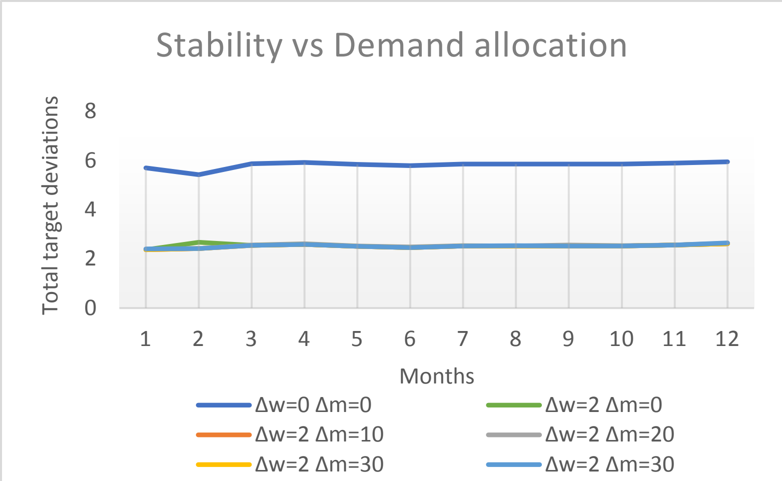


Figure 29 - Total deviations from the target for each pair Δ_w Δ_m

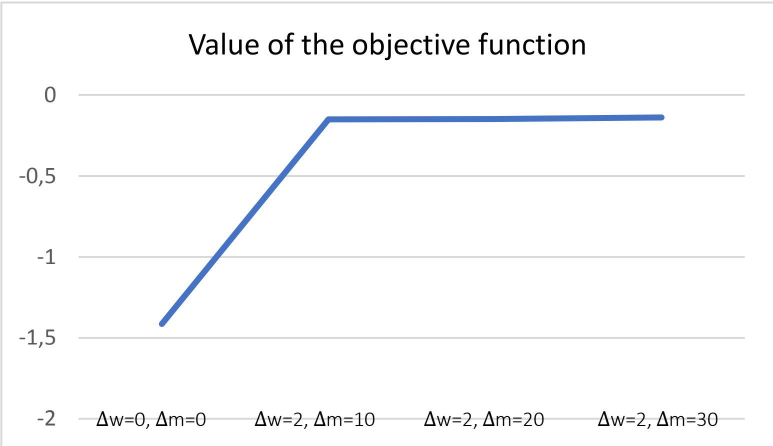


Figure 28 - Value of the objective function for each pair Δ_w Δ_m

5.4 Analysis of the multi-objective model

The Pareto front of a multi-objective optimization model is a set of nondominated solutions, which are solutions where no objective can be improved without sacrificing at least one other objective. Two conflicting objectives are considering in this model. Thus, we are dealing with a multi-objective programming model where the concept of optimality is replaced by the concept of nondominated solutions. Therefore, in the computational experiments, the weights of the two objectives α_1 and α_2 vary between 1 and 0 and sum 1. Figure 30 shows values of the objective function when varying the two weights. X-axis represents the values of objective 1 (z_1) and y-axis the values of objective 2 ($t_2 = -z_2$). Table 31 details the values for each weight (α_1 and α_2) and the corresponding values for objectives 1 and 2 ($z_1$and t_2, respectively). Furthermore, Table 31 shows that different combinations of the weights give similar results in terms of relative gaps and running time.

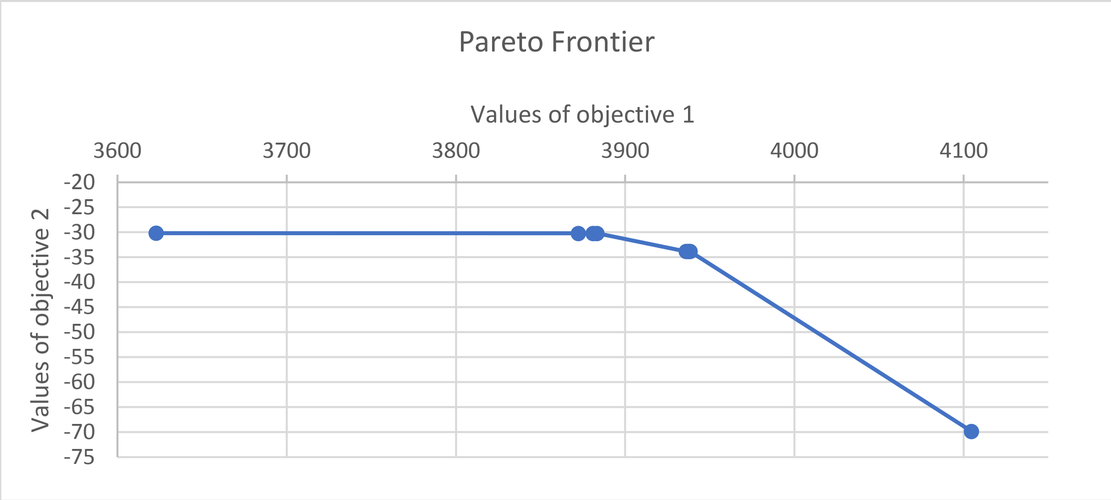


Table 31 – Values for objective 1 and 2 for different values of α_1 and α_2, respective execution time and relative gap

α_1	α_2	Objective value	Relative Gap	Running Time (seconds)	Objective 1 (z_1)	Objective 2(t_2)
0,85	0,15	0,3199	0%	0,500	4104,686	-69,848
0,75	0,25	-0,133	0%	0,391	4104,686	-69,848
0,70	0,30	30,82	0,310%	0,485	3938,400	-33,848
0,60	0,40	-0,66	1,403%	0,489	3937,657	-33,848
0,50	0,50	-0,99	0,959%	0,391	3936,114	-33,848
0,25	0,75	-1,76	0,189%	0,375	3883,40	-30,199
0,15	0,85	-2,070	0,150%	0,406	3880,971	-30,197
0,05	0,95	-2,378	0,095%	1,109	3872,400	-30,198
0,00	1,00	-2,53	0%	0,422	3622,943	-30,181

5.5 Comparison of the proposed MSS with the current MSS

After validating the model with data from the hospital it is necessary to compare the results with the current MSS. HESE's MSS has been nearly the same for the last 30 years, with the same

Figure 30 – Pareto frontier of objective 1 and 2

schedule, planning and organization. Although the MSS hasn't changed, the workforce and the demand is constantly changing. This results in a bad allocation of the resources as the schedule does not follow the patients' needs and of the needs and preferences of the medical staff. This unfitted allocation means the allocation of a slot to a specialty, and later the unuse of this slot by the allocated specialty. This happens due to shortage in anesthesiologists, surgeons and nurses, due to delays in surgeries or patients no-shows. This model is not capable of improving surgeries delays or patients no-shows but it can reduce the shortages, as it allocates the specialties to slots according to workforce availability and surgical demand.

The hospital data shows:

- the number of surgeons and anesthesiologists varied during 2017;
- there are last minute changes, on the specialty which uses the slot, that sometimes are not recorded;
- some surgeries had exceptions in terms of number of surgeons in the OR during the surgical intervention (some operations occurred with only one surgeon).

These facts can compromise the comparison of the results. However, it is possible to conclude that the OR needs a tool to help in allocating the available resources. Tables 32 and 33 show the number of slots, in 2017, which are allocated to the specialties (Table 32) and the number of slots which are in fact occupied (Table 33). In some specialties, the no utilization of the slots reaches 50% of the allocated slots, and stomatology is the only specialty that used all its allocated slots. This results in waste of resources since the staff which is ready to operate on that day could be allocated to other activities. As the model takes into consideration the number of resources in each month, week and day, the results should be compared with Table 33, as reflects the real occupation of the slots.

Table 32 – Number of allocated slots in 2017

Specialty/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Surgery	40	34	40	27	32	35	32	13	25	33	28	20
Plastic Surgery	9	7	9	6	8	6	4	2	4	7	5	3
Pediatric Surgery	4	4	5	4	5	4	3	1	3	4	3	3
Stomatology	1	1	1	1	0	1	1	0	1	1	1	0
Ophthalmology	26	22	27	14	23	21	14	3	17	25	19	14
Orthopedics	20	19	21	13	16	13	15	8	12	21	19	10
ORL	8	8	10	4	7	5	5	2	5	7	5	2
Urology	9	8	9	8	7	5	6	3	2	7	5	1

Table 33 – Number of occupied slots in 2017

Specialty/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Surgery	28	25	29	27	32	35	32	13	25	25	16	15
Plastic Surgery	6	7	7	6	8	6	4	2	4	5	4	0
Pediatric Surgery	4	4	3	4	5	4	3	1	3	4	1	3
Stomatology	1	1	1	1	0	1	1	0	1	1	1	0
Ophthalmology	20	22	22	14	23	21	14	3	17	23	15	6
Orthopedics	18	15	17	13	16	13	15	8	12	18	12	7
ORL	3	6	7	4	7	5	5	2	5	7	3	1
Urology	8	7	7	8	7	5	6	3	2	7	3	1
Total	88	87	93	77	98	90	80	32	69	90	55	33

Table 34 shows one of the obtained solutions in order to compare the two MSS.

Table 34 – Obtained MSS

Specialty/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Surgery	32	32	32	32	32	32	32	32	32	32	32	32
Plastic Surgery	8	8	8	8	8	8	8	8	8	8	8	8
Pediatric Surgery	3	4	3	3	4	3	4	3	3	3	4	4
Stomatology	1	1	1	1	1	1	1	1	1	1	1	1
Ophthalmology	20	20	20	20	20	20	20	20	20	20	20	20
Orthopedics	8	8	8	8	8	8	8	8	8	8	8	8
ORL	8	8	8	8	8	8	8	8	8	8	8	8
Urology	8	8	8	8	8	8	8	8	8	8	8	8
Total	88	89	88	88	89	88	89	88	88	88	88	88

Looking at the month of January it is possible to conclude that with the same number of allocated slots (88), the model suggests another distribution among the specialties. The biggest differences are in general surgery and orthopedics – the model increases the number of slots in general surgery and decreases the number of allocated slots to orthopedics, in order to better match supply and demand. The differences in terms of number of operated patients are depicted in Table 35. This table suggests that supply is better suited to the demand in model's suggestion. This table suggests that surgical supply is better suited to the demand in the case of the solution proposed by the model. The difference between the percentage of the supplied demand of general surgery and orthopedics is higher in HESE's distribution of the operating room time $(10{,}50\% - 6{,}30\% = 4{,}25; 7{,}20\% - 4{,}70\% = 2{,}5\%)$.

In the other months, it is clear that HESE has some difficulties in maintaining the normal schedule, having a lot of fluctuation in the number of allocated slots, reaching, sometimes, better numbers than the allocation made by the model. These fluctuations are more pronounced in some specialties as general surgery that reaches a difference of 10 slots.

Table 35 – Comparison of the distribution of operating room time between the current MSS and model's suggestion

Indices	MSS	Specialty	
		General Surgery	Orthopedics
Number of slots	**HESE**	28	18
	Model	32	8
Number of operated patients	**HESE**	$28 \times \lambda_s = 28 \times 2 = 56$	$18 \times \lambda_s = 18 \times 3 = 54$
	Model	$32 \times \lambda_s = 32 \times 2 = 64$	$8 \times \lambda_s = 8 \times 3 = 24$
Demand		$888\ patients$	$514\ patients$
Percentage of the demand	**HESE**	$\frac{56}{888} = 6{,}30\%$	$\frac{54}{514} = 10{,}50\%$
	Model	$\frac{64}{888} = 7{,}20\%$	$\frac{24}{514} = 4{,}70\%$

This section shows that the model cannot allocate much more slots than the ones that are now being allocated but suggests a reallocation of the slots among the specialties. This reallocation can lead to changes in the workforce of each specialty. As consequence, the next section analyses the current HESE's workforce and the distribution that the model suggests.

5.5.1 Workforce Analysis

An interesting analysis is to understand how much the hospital would improve in terms of allocated slots if the workforce increased. The comparison is always made in terms of allocated slots, as this work deals with the strategic-tactical decision level.

How does the model allocate the specialties if we do not have into consideration the human resources? By ignoring the constraints in terms of human resources, and only considering space constraints, one could depict what should be the proportionality in number of surgeons between specialties.

This analysis is made varying the parameters that guarantee stability. Tables 36 and 37 present the number of surgeons that HESE's could have to fill all the available slots. Table 35 presents the number of surgeons, variable over the year, to better reach the demand. Table 36 does not allow changes over the year, suggesting a constant number of surgeons for the whole year. The numbers suggested by the model can also be used to calculate the proportionality of required surgeons between the specialties. As the model suggests a proportionality of the workforce, HESE can maintain the same number of surgeons but changing the distribution of them as depicted in Table 38.

Table 36 – suggested distribution of the surgeons with $\Delta_m = 0$

Specialty		Actual	Prop.
General Surgery	20	14	29%
Plastic Surgery	4	2	6%
Pediatric Surgery	2	2	3%
Stomatology	2	2	3%
Ophthalmology	12	10	17%
Orthopedics	16	5	23%
ORL	6	4	9%
Urology	8	4	11%
Total	80	43	

Table 37- suggested distribution of the surgeons to fill all the slots of the MSS $\Delta_m = 20$

Specialty	Max	Min	Actual
General Surgery	24	20	14
Plastic Surgery	4	2	2
Pediatric Surgery	2	2	2
Stomatology	2	2	2
Ophthalmology	14	12	10
Orthopedics	16	14	5
ORL	6	6	4
Urology	8	8	4
Total	86	78	43

Table 38 – suggested distribution of surgeons maintaining the total number of surgeons

Specialty	Actual	Sugg.
General Surgery	14	12
Plastic Surgery	2	2
Pediatric Surgery	2	2
Stomatology	2	2
Ophthalmology	10	7
Orthopedics	5	10
ORL	4	4
Urology	4	5
Total	43	44

5.6 Conclusions

This section validates and discusses the results obtained by using the proposed model in the previous chapter, maximizing the objective function composed by the first two objectives: maximize the number of allocated slots and their associated aggregated preferences and minimize the difference between the number of allocated slots per specialty s and its target t_s. It is possible to conclude that this model can be used as a tool for flexible resource allocation (i.e. operating room time allocation among the specialties) according to the variability in surgical demand and availability of staff (tactical decision) and to perform sensitive analysis to understand the consequences of variations in strategic decisions (e.g. staff capacity dimensioning). Due to shortages in anesthesiologists, surgeons and nurses, some allocated slots are left empty decreasing the efficiency and effectiveness of the SS. The model is able to allocate specialties to slots considering the availability of the clinical staff for each month, week and day allowing a better allocation over the year. Furthermore, it is possible to conclude that the model suggests another distribution of the slots, allocating more slots to the specialties with higher surgical demand. The model allows the hospital to better understand its demand and how should the slots be allocated. Since it considers demand and clinical staff availability, this model can compute in seconds the MSS for the next month if any changes in demand or workforce happen, allowing a better decision making on the part of the SS management. Furthermore, with the last section of this chapter, this model helps to understand how should be the hospital workforce, helping on asking for greater investment from the state.

Conclusions and future work

Hospitals depend on their SS as this unit represents more than 40% of hospitals costs and profits and are usually considered in the literature as the engine of the organization (Beliën & Demeulemeester, 2007; Blake & Donald, 2002). As analyzed in the literature review, the complexity of this unit is not only related with planning of different surgeries with different patients within the same physical and scarce space but also with the large amount of other up and downstream services that it compromises.

In this work, the case study challenges were analyzed and studied with tools suggested by the literature and with the experience of the involved stakeholders. Based on the collected data and on the existing literature, this work develops a multi-objective mixed-integer programming model that captures the case study needs by structuring the planning of SS and by supporting the hospital understudy on the strategic-tactical decision making. The model constructs a new MSS which aims to be more effective and efficient on the allocation of HESE's resources. Efficiency is one of the major objectives since HESE is a small hospital with low financial resources, that needs to be efficient in other to handle its demand.

Furthermore, this work contributes to the literature by integrating objectives which according to this work literature review have never been studied together. These objectives promote an MSS which gathers the maximization of the allocated slots with an allocation directed towards a better match between supply and demand, meaning an allocation based on the percentage of the surgical waiting list. The model uses one year of planning horizon, which allows a more fitted allocation of the slots to the demand. To accomplish this adjustment, the model develops a non-cyclical MSS not very common in the literature. The non-cyclicity allows the incorporation of the staff availability in all weeks and months, allowing a projection of the effects of staff shortages or vacations. Moreover, for a better implementation of the new MSS, this model embodies objectives as the maximization of the stakeholders' preferences and the stability of the SS master schedule.

All in all, this work proposes a model to better allocate operating room time among the surgical specialties, considering HESE's workforce, SS space and the surgical demand. To evaluate the developed model comparisons are made on the number of allocated slots. Results showed that the model cannot allocate a bigger number of slots than HESE, in turn, suggests a different distribution of slots. This different distribution improves the matching between supply and demand, not by increasing the total number of operated patients but, by allocating more slots to those specialties with larger waiting lists. Moreover, this model potentially improves the efficiency of the SS by including the availability of surgeons and anesthesiologists in every month, week, day and shift, helping in predicting future shortages, and consequently avoiding empty allocated slots.

Results allow to conclude that the workforce greatly restricts a higher match of the demand. For this reason, another analysis is made on the distribution of surgeons by the specialties, suggesting another distribution with the same number of surgeons and for future larger workforces.

Some interesting points are left to future work.

One of the major challenges of this study is to match supply and demand. The developed tool allows to plan the SS activities with one year in advance, suggesting a variation on the number of slots allocated to each specialty. This variation changes surgeons' agenda and the number of hours each one dedicates to the SS. An interesting study would be to adjust and analyze the trade-off between the number of hours a surgeon spends in the operating room and in consultations. Another open point is the assessment of the preferences. It would be interesting to change the aggregated preferences to singular preferences, maximizing each anesthesiologist and surgeon preference and not of the entire specialty. Finally, the last objective, to level the utilization of up- and downstream resources, hasn't been implemented due to software restrictions. Despite the limited interest of the hospital on this topic, the validation and implementation of this objective could lead to new perspectives on the planning of HESE's SS.

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Appendices

Appendix 1 – Objectives, models and approaches of the papers reviewed

Table 39 - Objectives, models and approaches of the papers under review, ordered by year of publication

Article	Objective	Model	Approach		Simulation	Scenario Analysis
			Heuristic	Exact		
Blake & Donald (2002)	Divide equitably the OR time in the different SG	IP	Improvement Heuristic	-	-	-
Blake et al. (2002)	Minimize the weighted average under supply of OR hours	IP	Improvement Heuristic	-	-	-
Sciomachen et al. (2005)	Maximize utilization rate, throughput and minimize overruns	Simulation Model	Improvement Heuristic	-	X	X
Beliën & Demeulemeester (2007)	Leveling of wards/ beds occupancy	IP	Improvement Heuristics	Dynamic programming-	-	-
Santibáñez et al. (2007)	Leveling of wards/ beds occupancy	IP	-	MIP	-	X
Van Oostrum et al. (2008)	Minimize required OR capacity and hospital beds	ILP	-	Column Generation	-	-
Zhang et al. (2009)	Minimize inpatients' length of stay waiting for their surgery	IP	-	MIP	X	X
Adan et al. (2009)	Maximize the resource utilization	MILP	-	Goal Programming	-	-
Agnetis et al. (2012)	Evaluate long-term policies in MSS planning.	IP	-	-	X	X
Day et al. (2012)	Maintain a high utilization of capacity with a modified block scheduling strategy	MILP	-	Column Generation	X	X

Article	Objective	Model	Approach		Simulation	Scenario Analysis
			Heuristic	Exact		
Mannino et al. (2012)	1. Balancing patient queue lengths among different specialties 2. Minimize resort overtime	MILP	Light Robust Approach	MILP	-	X
Vansteenkiste et al. (2012)	Allocate OR block time among SGs to turn acceptable the waiting time after the need for surgery is established	Due Time Model	-	Constructive Algorithm	-	X
Holte & Mannino (2013)	Distribute the excess ORs to different surgeons to minimize queue cost in health-care	MIP	-	Row and Column Generation	-	X
Hosseini & Taaffe (2014)	Balance over and under times and minimize the cost of over-utilized time and under-utilized time	LP	-	Constructive Algorithm,	-	X
Fügener et al. (2014)	To minimize downstream costs by leveling bed demand and reducing weekend bed requests	LP	1.Branch-and-bound 2.Simulated annealing 3.Incremental improvement heuristic (IIC)	Analytical Procedure	-	-
Cappanera et al. (2014)	Maximize the number of scheduled surgeries	MIP	-	Dynamic programming	DES	X
Choi & Wilhelm (2014)	Minimizing total expected costs due to penalties for any patients who are not accommodated and for under or over usage of OR capacity	Stochastic programming	Improvement Heuristic Analytical Procedure	Integer Programming	-	X

Article	Objective	Model	Approach		Simulation	Scenario Analysis
			Heuristic	Exact		
Fügener (2015)	Maximize hospital reveneu	IP	-	-	-	X
Malik et al. (2015)	To minimize the number of patients waiting for an elective surgery and the associated costs	Bi-objective mathematical formulation	Non-dominated sorting genetic algorithm (NSGA-II)	-	-	X
Collins et al. (2017)	To distribute a new block time	Decision-making Approach	-	-	-	-
Penn et al. (2017)	Smooth bed usage, give surgeons slots they prefer, have all-day slots and repeat assignments weekly	MILP	-	MIP	-	-
Dellaert & Jeunet (2017)	To minimize over and underutilization of several resources compared with their target level of utilization.	MIP	Search Technique	-	X	-
Guido & Conforti (2017)	Take into account trade-offs among underutilization of OR capacity, balanced distribution of OR time among surgeon groups, minimization of surgeries' waiting times and over- time working hours.	Multi-objective integer linear programming	Genetic Algorithm	-	-	-
Siqueira et al. (2018)	1.To design a periodic surgery allocation schedule; 2. Long term plan for a recovery ward utilization, assuring the performance of all surgeries in a timely manner	MILP	-	-	-	X

Appendix 2 – Other characteristics of the papers reviewed

Table 40 - Main characteristics of the papers under review, ordered by year of publication

Article	Case study	Non-/ elective patients	In/out patients	MSS T. horizon	Up/ down streams	LoS	OR for emergency	STKH	Uncertainty	Data
John T. Blake & Donald (2002)	CA	Both	Both	Fixed	-	-	X	X	-	App
Blake et al. (2002)	CA	Elective	Both	1 month	-	-	-	X	-	App
Sciomachen et al.(2005)	IT	Elective	NM	1 week	-	-	-	-	Arr; Dur	Real
Santibáñez et al. (2007)	CA	Elective	NM	4 weeks	X	-	X	-	-	Real
Beliën & Demeulemeester (2007)	-	Elective	Inpatient	1 week	X	X	-	-	Arr; Dur	Theo
Van Oostrum et al. (2008)	NL	Elective	NM	1 week	X	-	X	X	Dur	Real
Zhang et al.(2009)	US	Both	Both	NM	X	X	X	-	Arr; Dur	Real
Adan et al. (2009)	NL	Elective	Inpatient	4 weeks	X	X	-	X	Dur	Real
Agnetis et al. (2012)	IT	Elective	NM	Dynamic	-	-	X	X	-	App
Day et al. (2012)	US	Elective	Inpatient	2 weeks	-	-	-	X	Arr; Du	App
Mannino et al. (2012)	NO	Elective	NM	1 month	-	-	-	X	-	Real
Vansteenkiste et al. (2012)	BE	Elective	Both	NM	-	-	-	X	-	Real
Holte & Mannino (2013)	NO	NM	NM	1 to 8 weeks	-	-	-	-	-	Real
Hosseini & Taaffe (2014)	US	Elective	NM	NM	-	-	-	-	-	Real
Fügener et al. (2014)	NL	Elective	Inpatient	2 weeks	X	X	-	-	Other	Real
Cappanera et al. (2014)	IT	Elective	Inpatient	2 weeks	X	X	X	-	Dur, Other	Real
Choi & Wilhelm (2014)	-	NM	NM	6 to 12 months	-	-	-	-	Arr; Dur;	Theo

Article	Case study	Non-/ elective patients	In/out patients	MSS T. horizon	Up/ down streams	LoS	OR for emergency	STKH	Uncertainty	Data
Fügener (2015)	DE	Both	Inpatient	Changea ble	X	X	-	-	LoS	Real
Malik et al. (2015)	EU	Both	Both	12 months	X	X	-	X	-	Real
Collins et al. (2017)	US	Elective	Both	NM	X	-	-	X	-	Real
Penn, et al. (2017)	NM	NM	NM	Changea ble	X	-	-	X	-	Real
Dellaert & Jeunet, (2017)	NL	Elective	Inpatient	28 days	X	X	-	X	-	Real
Guido & Conforti, (2017)	IT	Elective	NM	1 week	-	-	X	-	-	Real
Siqueira et al. (2018)	IT	Elective	NM	1 week to 1 year	X	-	X	X	-	Real

Case Study – refers to the country of the case study. The country acronyms are the official ones.
http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Country_codes
STKH – Inclusion of the stakeholders on the process of decision
Uncertainty: Dur – Duration in one or more units; Arr – Arrival to the SS
Data: App - Applied in practice; Real - Based on real data; Theo - Based on theoretical data
NM – Not mentioned - Information not mentioned or not clear

Appendix 3 – Summary of the sets

Table 41 – Summary of the sets

SETS	CARDINALITY	COMMENTS	
$\boldsymbol{D}$	1 to 5	From Monday to Friday	
$\boldsymbol{W_m}$	1 to 5	Only the months of January, April, August and October have 5 weeks	
$\boldsymbol{M}$	1 to 12	From January to December of 2017	
$\boldsymbol{R}$	1,2,4 and 5	OR 3 is not included as it is reserved for the emergency service	
$\boldsymbol{B}$	m and a	m stands for morning shifts and a stands for afternoon shifts	
$\boldsymbol{S}$	8	General Surgery, Plastic Surgery, Pediatric Surgery, Stomatology, Ophthalmology, Orthopedics, ORL, Urology	
$\boldsymbol{I}$	Distribution of the surgeons per specialty	General Surgery	14 surgeons
		Plastic Surgery	2 surgeons
		Pediatric Surgery	2 surgeons
		Stomatology	2 surgeons
		Ophthalmology	10 surgeons
		Orthopedics	5 surgeons
		ORL	4 surgeons
		Urology	4 surgeons
$\boldsymbol{A}$	10		

Appendix 4 - Summary of the parameters

Table 42 – Summary of the parameters

PARAMETERS	CARDINALITY		COMMENTS
$slots_m$	200 or 160		Depending on the number of weeks that each month has. 200 for 5 weeks, 160 for 4 weeks
asd_s	General Surgery	2,151	The average duration is gathered with the monitoring of the surgeries in 2017 which includes the hour of beginning and end of each surgery. From this monitoring is possible to compute the duration of each surgery and then compute an average
	Plastic Surgery	1,348	
	Pediatric Surgery	0,660	
	Stomatology	1,122	
	Ophthalmology	0,917	
	Orthopedics	1,906	
	ORL	1,184	
	Urology	2,055	
λ_s	General Surgery	2,06	This numbers are also extrapolated from the monitoring of the surgeries by collecting the number of patients that each specialty can operate in one slot
	Plastic Surgery	2,07	
	Pediatric Surgery	4,23	
	Stomatology	2	
	Ophthalmology	7,24	
	Orthopedics	1,5	
	ORL	2,36	
	Urology	1,66	
P_{sm}	Appendix 6		The demand per specialty and per month is equal to the waiting list of 2017
t_{sm}	$t_{sm} = \frac{P_{sm} \times ast_s}{\sum_s (P_{sm} \times ast_s)} \times slots$;		Computed with GAMS with the previous data
a_{ismwdb}	Sample in Appendix 7		Obtained through meetings with surgeons and with surgeons' schedulers
a_{amwdb}	Sample in Appendix 8		Obtained through a meeting with the head nurse
d_{sd}	Sample in Appendix 9		Parameter stem from a_{ismwdb}
da_d	Sample in Appendix 10		Parameter stem from a_{amwdb}
k_{isdb}	Sample in Appendix 11		Parameter obtained through meetings, questionnaires and assumptions
ww_{is}	Sample in Appendix 12		Parameter obtained through meetings with the head of each specialty
ww_a	Sample in Appendix 12		Parameter obtained through meetings with the head nurse
$\Delta_w, \Delta_m, \alpha_{1,2,3}$	Chapter 5		These parameters are discussed in Chapter 5

Appendix 5 – MSS for $\Delta_w = 0$

Week 1

Dia	1	2	3	4	5
SEG	Urology	Plastic		Orthopedics	Ophthalmology
	-	-		-	-
TER	General	General		General	Ophthalmology
	Plastic	-		-	-
QUA	Pediatric	General		Orthopedics	Ophthalmology
	-	-		ORL	-
QUI	Urology	General		General	Ophthalmology
	ORL	-		-	-
SEX	General	General		Stomatology	Ophthalmology
	-	-		-	-

Week 2

Dia	1	2	3	4	5
SEG	Urology	Plastic		Orthopedics	Ophthalmology
	-	-		-	-
TER	General	General		General	Ophthalmology
	Plastic	-		-	-
QUA	Pediatric	General		Orthopedics	Ophthalmology
	-	-		ORL	-
QUI	Urology	General		General	Ophthalmology
	ORL	-		-	-
SEX	General	General		Stomatology	Ophthalmology
	-	-		-	-

Week 3

Dia	1	2	3	4	5
SEG	Urology	Plastic		Orthopedics	Ophthalmology
	-	-		-	-
TER	General	General		General	Ophthalmology
	Plastic	-		-	-
QUA	Pediatric	General		Orthopedics	Ophthalmology
	-	-		ORL	-
QUI	Urology	General		General	Ophthalmology
	ORL	-		-	-
SEX	General	General		Stomatology	Ophthalmology
	-	-		-	-

Week 4

Dia	1	2	3	4	5
SEG	Urology	Plastic		Orthopedics	Ophthalmology
	-	-		-	-
TER	General	General		General	Ophthalmology
	Plastic	-		-	-
QUA	Pediatric	General		Orthopedics	Ophthalmology
	-	-		ORL	-
QUI	Urology	General		General	Ophthalmology
	ORL	-		-	-
SEX	General	General		Stomatology	Ophthalmology
	-	-		-	-

Figure 31 – MSS for m=1 when $\Delta_w = 0$

Appendix 6 – Demand 2017

Table 43 – Demand per specialty and month in 2017

Specialty/ Month	1	2	3	4	5	6	7	8	9	10	11	12
General Surgery	888	858	830	803	842	871	891	845	884	924	848	812
Plastic Surgery	254	267	259	280	280	260	273	262	254	278	253	241
Pediatric Surgery	161	162	143	155	149	145	134	133	128	130	131	132
Stomatology	25	26	28	34	30	27	29	27	30	27	26	27
Ophthalmology	825	825	862	997	808	794	878	847	875	956	857	865
Orthopedics	514	508	505	551	584	589	590	573	571	577	523	478
ORL	260	267	281	290	329	328	328	313	337	353	343	332
Urology	230	221	229	247	250	243	256	243	245	249	250	230

Appendix 7 – Surgeons availability

Table 44 – Sample of data for parameter a_{isdb} which represents the availability of each surgeon of specialty s on day d, shift b

Specialty	*Surgeon*	*Shift*	*Day*				
			1	2	3	4	5
General Surgery	SR	m	0	1	0	1	1
General Surgery	SR	a	0	1	1	1	0
General Surgery	MS	m	1	1	1	1	1
General Surgery	MS	a	0	1	0	0	0
General Surgery	RS	m	1	1	1	1	1

General Surgery	RS	a	0	1	1	0	1

Appendix 8 – Anesthesiologist availability

Table 45 - Sample of data for parameter a_{adb}which represents the availability of anesthesiologist on day d shift b

Anesthesiologist	*Shift*	*Day*				
		1	2	3	4	5
C	m	1	0	1	1	0
C	a	0	0	0	1	0
TE	m	1	1	1	0	1
TE	a	0	0	1	0	0

Appendix 9 – Number of available surgeons on day d

Table 46 - Sample of data for parameter d_{sd} which represents the number of surgeons of specialty s available on day d

Day/ Specialty	*1*	*2*	*3*	*4*	*5*
General Surgery	13	13	14	13	11
Plastic Surgery	2	2	2	0	0
Pediatric Surgery	0	0	2	0	0
Stomatology	2	2	1	2	2
Ophthalmology	10	9	10	9	9
Orthopedics	2	2	3	3	1
ORL	1	3	4	4	2
Urology	3	4	3	4	5

Appendix 10 – Number of available anesthesiologists on day d

Table 47 - Sample of data for parameter dad_d which represents the number of anesthesiologists available on day d

Day	**1**	**2**	**3**	**4**	**5**
$\boldsymbol{dad_d}$	9	10	10	10	7

Appendix 11 - Surgeons Preferences

Table 48 - Sample of data for parameter k_{isdb} which represents the preference of a surgeon of specialty s to work on day d shift b

Specialty	*Surgeon*	*Shift*	*Day*				
			1	**2**	**3**	**4**	**5**
Geral	SR	m	3	5	3	3	3
Geral	SR	a	1	1	1	1	1
Geral	MS	m	3	3	3	3	3
Geral	MS	a	1	5	1	1	1

Appendix 12 – Number of visits per week to the SS

Table 49 - Sample of data for parameter ww_i which represents the number of times a surgeon can occupy a slot

Specialty	Surgeon	ww_i
Geral	RF	1
Geral	RCS	1
Geral	AS	2
Geral	JJ	1

Table 50- Sample of data for parameter ww_a which represents the number of times a anesthesiologist can occupy a slot

Anesthesiologist	ww_a
C	4
TE	5
CR	5
DU	4

Appendix 13 – Number of changes for $\Delta_w = 2$

Table 51 – Number of changes per month between week 1 and week w (2,3,4) when setting Δ_w to 2

Week/ Month	*2*	*3*	*4*
1	*1*	*2*	*1*
2	*1*	*2*	*2*
3	*2*	*2*	*2*
4	*2*	*2*	*2*
5	*2*	*2*	*2*
6	*2*	*2*	*2*
7	*2*	*2*	*2*
8	*2*	*2*	*2*
9	*2*	*2*	*2*
10	*2*	*2*	*2*
11	*2*	*2*	*2*
12	*2*	*2*	*2*

Appendix 14 - Number of changes for $\Delta_m = 30$

Table 52 - Number of changes between month 1 and month m (2, (…), 12) when setting Δ_m to 30

Month	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Number of changes	*11*	*20*	*12*	*10*	*4*	*4*	*4*	*4*	*20*	*4*	*4*