Operating Room Planning and Scheduling in the Scope of Scheduling Literature

Maria de Henriques Lebre da Silva Pinto

Dissertation to obtain the Master of Science Degree in

Industrial Engineering and Management

Supervisor: Prof. Daniel Rebelo dos Santos

Examination Committee:

Chairperson: Prof. Mónica Duarte Correia de Oliveira

Supervisor: Prof. Daniel Rebelo dos Santos

Member of the Committee: Prof. Ana Sara Silva Rodrigues da Costa

November 2021

Acknowledgments

First of all, I would like to thank my family for all the support throughout my life and academic path. Especially my parents and my sisters for their affection, understanding, and encouragement, without which none of this would have been possible.

To my supervisor, Dr Daniel Rebelo dos Santos, I would like to thank you for having trusted me for this project, for the availability shown and for all the guidance and knowledge shared with me in these last months that made this master's thesis possible.

Last but not least, a special thank you to all my friends, who have accompanied me through this journey, and for helping me grow and always being there.

Abstract

The increasing demand for health care alongside the ageing population has resulted in growing waiting lists for elective surgery. In Portugal, approximately 32% of patients enrolled in the surgery waiting list in 2020 exceeded the maximum guaranteed response time. Operating Room (OR) Planning and Scheduling problems, namely, the Master Surgery Scheduling (MSS) and Elective Case Scheduling (ECS), are crucial to tackle these issues and improve the quality of services provided to the overall population. Nevertheless, analysing the literature, it is possible to observe that only a few studies attempt to place these problems in the general scheduling literature. Thus, this dissertation's objective is to position the OR Scheduling problems in the scheduling literature. An overview of scheduling problems, such as Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare, is provided. Characteristics present in these problems were included in a descriptive and percentage analysis to visualize in which ones are those features present or not. In the MSS and ECS problems, the characteristics emphasized are patient prioritization, staff preferences and uncertainty. Patient preferences, clustering methods, and fairness aspects stand out as the characteristics that are barely mentioned in the setting of OR scheduling and are widely studied in other scheduling categories. Concluding, for the MSS and ECS, there are multiple opportunities to invest in further research and take advantage of the knowledge already existing in other scheduling categories to improve performance measures, for example, waiting time, quality of service, and patient satisfaction.

Keywords: Operating Room Planning and Scheduling, Master Surgery Scheduling, Elective Case Scheduling, Scheduling

Resumo

A crescente procura de cuidados de saúde, juntamente com o envelhecimento da população, resultou em listas de espera acrescidas para cirurgia eletiva. Em Portugal, no ano de 2020, a percentagem de pacientes inscritos na lista de espera para cirurgia onde o tempo máximo de resposta garantido foi excedido, foi aproximadamente 32%. Os problemas de Planeamento do Bloco Operatório (BO), nomeadamente, *Master Surgery Scheduling* (MSS) e *Elective Case Scheduling* (ECS), são cruciais para enfrentar estes problemas e melhorar a qualidade dos serviços prestados. No entanto, é possível observar que apenas alguns estudos tentam posicionar estes problemas na literatura geral de escalonamento. Assim, o objetivo desta dissertação é posicionar os problemas do BO nessa literatura. É fornecida uma visão geral dos problemas de escalonamento, tais como Escalonamento Instrucional, Atribuição de Cama, Colheita de Sangue, Agendamento de Consultas, e Cuidados de Saúde ao Domicílio. As características presentes nos problemas foram incluídas numa análise descritiva e percentual para visualizar em quais estão presentes. Nos problemas de MSS e ECS, as características enfatizadas são priorização do paciente, preferências do pessoal e incerteza. Preferências dos pacientes, métodos de agregação, e aspetos de equidade destacam-se como as características que mal são mencionadas no contexto do BO e que são amplamente estudadas noutras categorias de escalonamento. Concluindo, para o MSS e ECS, existem oportunidades para investir em mais investigação e tirar partido do conhecimento já existente noutros problemas de escalonamento para melhorar medidas de desempenho, por exemplo, tempo de espera, qualidade de serviço e satisfação do paciente.

Palavras-chave: Planeamento do Bloco Operatório, *Master Surgery Scheduling*, *Elective Case Scheduling*, Escalonamento

Table of Contents

List of Figures

List of Tables

List of Acronyms

ACSS - Administração Central do Sistema de Saúde (Health System Central Administration)

CP - Constraint Programming

ECS - Elective Case Scheduling

ETP - Exam Timetabling Problem

FCFS - First-Come-First-Served

FIFO - First In, First Out

ICU - Intensive Care Unit

KPI - Key Performance Indicator

MGRT - Maximum Guaranteed Response Time

MILP - Mixed-Integer Linear Programming

MINLP - Mixed-Integer Non-Linear Programming

MIP - Mixed-Integer Programming

MMBJS - Multi-Mode Blocking Job Shop

MSS - Master Surgery Scheduling

OECD - Organization for Economic Cooperation and Development

OR - Operating Room

PACU - Postanesthesia Care Unit

PHU - Preoperative Holding Unit

PM - Performance Measure

SAP - Supervisor Assignment Problem

SIGIC - Sistema Integrado de Gestão para Inscritos na Cirurgia (Integrated System for the Management of Registered Patients for Surgery

SIGLIC - Sistema Integrado de Gestão das Listas de Inscritos para Cirurgias (Integrated System for the Management of Patient Lists Queued for Surgery)

SNS - Serviço Nacional De Saúde (Portuguese National Health System)

SWL - Surgery Waiting Lists

1. Introduction

The first chapter of this dissertation contextualizes the problem and explains the motivation for this study (Section 1.1). In Section 1.2, the research objectives are presented. This chapter ends in Section 1.3, where the document structure is listed.

1.1 Overview

The demand for healthcare, due to the aging population, is gradually growing and waiting times for elective surgeries are a pivotal concern in several countries due to creating dissatisfaction for patients. According to the Organization for Economic Cooperation and Development (OECD), in Portugal, waiting times from specialist assessment to treatment in the past decade for different types of elective surgical procedures have been increasing, with some (e.g. cataract surgery) nearly doubling from 28% in 2010 to 58.9% in 2018 (OECD, 2021). Hence, operating room planning is a crucial activity to tackle these problems and improve the services provided to the overall population.

The Operating Room (OR) is the unit within a hospital or a medical centre which requires the most planning and funding as it utilizes the majority of human resources, as well as indispensable and expensive equipment. This way, surgical activity has a substantial impact in the hospitals and its planning is necessary to improve the efficiency of the OR. In order to reduce the respective waiting lists and maximize resource utilization, effective scheduling strategies must be put into practice. The problem of Operating Room Planning and Scheduling is often divided into three levels, such as the strategical level (long-term decisions), the tactical level (medium-term decisions), and the operational level (short-term decisions). Each one of these levels corresponds to a scheduling problem, respectively, Case Mix Planning, Master Surgery Scheduling (MSS), and Elective Case Scheduling (ECS) (Proença, 2010).

The MSS problem is characterized by the development of a cyclic schedule (e.g. monthly) that is responsible for defining and assigning the number of available operating rooms to different medical disciplines, as well as providing information on OR opening hours, and priorities of surgeons and specialties (Beliën & Demeulemeester, 2007). Taking into consideration the developed schedule, the ECS problem establishes the specific date and the exact time of each surgery. Additionally, the allocation of the OR resources is determined (Zhu, Fan, Yang, Pei, & Pardalos, 2018). Both these problems are of utmost importance to the flow and proper functioning of the OR. However, there have not been many attempts to position the MSS and ECS problems in the general scheduling literature. Positioning them in a broader scheduling setting and studying possible knowledge transfers will bring advantages to the OR planning and scheduling.

The literature regarding the Operating Theatre and the problems associated with this matter is somewhat extensive and has been growing over the past few years. Several classification schemes have been proposed due to the increased interest in this area. Throughout this dissertation, a structured and detail-oriented approach is followed, which consists of a literature review organized into four descriptive fields, namely, patient characteristics α, delineation of the decision β, uncertainty incorporation γ, and performance measures δ (Cardoen, Demeulemeester, & Beliën, 2010a).

Several scheduling problems can be found in the literature that properly reflect numerous and diverse factors, such as patient waiting times and resource utilization, depending on the nature of the industry the problem is inserted in. Within this dissertation, scheduling problems with restricted capacity and limited resources will be addressed in a literature review. These problems are divided into five categories, specifically, Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare.

Multiple characteristics and performance measures common in both literature reviews will be highlighted with the objective of situating the Master Surgery Scheduling and Elective Case Scheduling problems in the scope of certain general scheduling problems. Among the highlighted characteristics are Patient Preferences, Patient Prioritization, Workload Balance, Fairness, Clustering, and Uncertainty. The analysis of these features allows identifying which scheduling problems are most closely related to the OR Scheduling and Planning problems and facilitate the discussion of whether knowledge transfer between them is possible or not.

1.2 Research Objectives

This dissertation has as principal aim to position the master surgery scheduling and elective case scheduling problems in the general scheduling literature by identifying the problems that are most closely related and clearly stating the differences and similarities. The lack of comparison between different models and problems in the operating room planning and scheduling and general scheduling contexts and works of literature motivates this research dissertation and justifies its objective. Thus, the main objectives of this dissertation are:

- Describe and provide an overview of the concept of OR Planning, and particularly, the MSS and ECS problems, to familiarize the reader with the importance and challenges of these problems to the good performance of the OR. Furthermore, the problem under study in this work is defined;
- Search and evaluate the existing literature on Operating Room Planning and Scheduling, more specifically, the MSS and ECS problems, to compose a literature review. The main features of each problem are identified, according to the chosen classification scheme based on Cardoen, Demeulemeester, & Beliën (2010a);
- Elaborate a literature review on different scheduling problems and identify the problems that are most closely related closest to the MSS and ECS problems. State the differences and similarities between these problems and analyse possible knowledge transfers between the problems on general scheduling and the MSS and ECS problems.

1.3 Document Structure

The structure used in this dissertation is divided into eight stages, each corresponding to one chapter:

Chapter 1 – Introduction: The first chapter of this document contextualizes the problem and explains the motivation for this study. The principal objectives for the research work are defined and the respective structure is presented.

Chapter 2 – Problem Definition: The second chapter explains the concepts of OR planning, the MSS, and the ECS problems, while simultaneously proving their importance to the proper functioning of the operating theatre and to the reduction of the surgery waiting lists (SWL). The chapter concludes with the definition of the problem being studied.

Chapter 3 – Literature Review: In this chapter, a detailed literature review following a classification scheme of four descriptive fields, namely, patient characteristics, delineation of the decision, uncertainty, and performance measures (PM), is presented.

Chapter 4 – Research Methodology: This chapter outlines the four stages of the proposed research methodology.

Chapter 5 – Scheduling Problems Review: Similarly to Chapter 3, a comprehensive literature review of different scheduling and assignment problems, which take into consideration multiple criteria and deal with capacity and resources limitations, is presented.

Chapter 6 – Positioning the MSS and ECS Problems: To position the MSS and ECS problems in the review of different scheduling problems, multiple features and performance measures, prevalent in both Chapter 3 and 5 reviews, will be highlighted through a qualitative and percentage analysis to determine in which problems are those features present or not, and in the case that they are, where are they most common.

Chapter 7 – Discussion of Possible Knowledge Transfer: In this chapter, the differences and similarities between the MSS and ECS and general scheduling problems are clearly stated. Thus, it is possible to clearly visualize the lack of research covering certain aspects in a specific scheduling group and in which other groups that same aspect is thoroughly contemplated. This allows a better understanding of whether knowledge transfer between the different scheduling categories is possible or not.

Chapter 8 – Conclusions and Future Work: This chapter ends this dissertation and concludes with the most relevant findings and conclusions. Additionally, future work and research opportunities are presented.

2. Problem Definition

This chapter provides an overview description and definition of the problem under study. In Section 2.1, Operating Room Planning is characterized and the importance of such activity is demonstrated, with an example of how it is employed in Portugal. Thereafter, in Section 2.2, the definition and scopes of the scheduling problems, such as the Master Surgery Scheduling and the Elective Case Scheduling problems, present in the Operating Room Planning are explored. Finally, the last two sections present the problem definition and the main conclusions, respectively Sections 2.3 and 2.4.

2.1 Operating Room Planning

Health care demand is gradually increasing and waiting times for elective surgeries are a longstanding issue present in several countries. Operating room planning is a crucial activity to tackle these problems and improve the services provided to the overall population. In this section, the history and definition of OR planning (Subsection 2.1.1) and its scope (Subsection 2.1.2) are explained. In addition, the surgery waiting list management program in Portugal, also known as SIGIC, and the success it has had in efficiently managing resources and cost are highlighted (Subsection 2.1.3).

2.1.1 History and Definition

The concept of operating room did not exist when the first surgeries started being performed, such as the first recorded execution of Trephination, a surgical procedure where a hole is drilled into the skull using only fundamental surgical tools, circa 8000 BC in Egypt (Sampol, 2018). The first operating rooms were created in the early 18th century, based on the famous dissection theatres in Padua, Bologna, and other Italian cities. Other leading European countries, in particular Germany, France, Austria, England, and the United States of America followed the same model and designed their own operating theatres, which had as the main purpose to serve as an operating setting as well as a teaching environment (Optimus ISE AG, 2021). During the 1900s the evolution of the operating room accelerated, embracing trends regarding the sterility of the site and the affordability of surgery by utilizing disposable products. Nowadays, an operating room is focused on having an elevated rotation of patients and is centred around high technology, for example real-time monitoring systems and robotic surgical machines (Sampol, 2018).

An operating room can be simply defined as a facility within a hospital or clinic that is equipped for performing surgical procedures (Shield Jr., 2018). Other names for OR present in the respective literature are Operating Theatre and Surgical Centre, with both terms having the same meaning. Subsequently, operating room planning is the activity of finding the balance between demand and supply when it concerns surgery scheduling, for example capacity planning (Lopes, 2012). As stated in many literature, the good performance and high efficiency of the operating room have a pivotal role regarding the improvement of the hospitals' welfare standards and the quality of the service provided to the patients. The particular reason for this circumstance is the OR being both the main cost and revenue source of a hospital (Zhu, Fan, Yang, Pei, & Pardalos, 2018). Within the literature, it is readily apparent that the operating room is the facility which requires the most funding as it utilizes the majority of human resources and indispensable equipment is needed. More specifically, surgical operations constitute more than 60% of hospital admissions (Fügener, Schiffels, & Kolisch, 2017). This way, the effort put in by the hospital managers towards the improvement of the OR performance is considerably high. Different scheduling techniques and planning strategies must be studied to afterward be exercised in view of the influence they have over OR functioning.

2.1.2 Scope

The literature generally states that operating room planning is a process comprised of three phases (Cardoen, Demeulemeester, & Beliën, 2010b). The three phases are as follows: Case Mix Planning, Master Surgery Scheduling, and Elective Case Scheduling (Proença, 2010).

The “Case Mix Planning” phase is where the strategical decisions are made and is allocated to each surgical specialty their respective OR time. Furthermore, this OR time is assigned according to the weight distribution estimation each specialty has, depending also on the priority a hospital has given to it. The weight estimation is usually pondered through the number of registered patients on the surgery waiting list and the number of surgeons a specific specialty has (Lopes, 2012).

Secondly, the level that concerns tactical decisions is denominated “Master Surgery Scheduling”. In this stage, for each combination of OR and day, a schedule is composed that lists every surgical procedure to be performed (Oostrum, et al., 2008). This term and its definition will be explained in further detail in Section 2.2.

Lastly, the “Elective Case Scheduling” phase consists of assigning details regarding the performance of elective surgeries, chosen from the hospital waiting list, such as, for example, an intervention date, along with a starting time and an operating room (Marques, Captivo, & Pato, 2015). The literature on this level is often divided into two procedures, namely, Advance Scheduling, i.e., the process of fixing a surgery date for a patient, and Allocation Scheduling, i.e., determining the operating room and the starting time of the procedure on the specific day of surgery (Magerlein & Martin, 1978).

2.1.3 SIGIC

The SIGIC, Sistema Integrado de Gestão para Inscritos na Cirurgia (Integrated System for the Management of Registered Patients for Surgery), was established in June 2004, within the scope of special programs for fighting the long waiting lists for surgery in Portugal. Up to that point, there was no reliable source of information regarding the dimension of patients registered for surgical procedures or how long they had to wait. Consequently, SIGIC started to regulate all surgical activities and cover every step involved in the management of its users, since their enrolment in the program up until after the surgery is performed. This program resulted in the creation of a centralized and structured system as an attempt to reduce waiting lists and relieve the pressure on the National Health System of Portugal (SNS).

The main goals of SIGIC are to reduce the waiting times, to guarantee equal access to every user, to promote the overall efficiency of the system through the management of the List of Registrants for Surgery and the allocated resources, and finally, to assure the quality and transparency of information (SNS, Portuguese National Health System, 2016). In order to achieve such goals and centralize the desired information, SIGLIC, Sistema Integrado de Gestão das Listas de Inscritos para Cirurgias (Integrated System for the Management of Patient Lists Queued for Surgery) was created. This type of system enabled the extraction of statistical data and indicators which then allow for the management control of programmed surgical activities (Ministério da Saúde, 2015). According to the SNS, the information mentioned above is obligatorily registered and transferred to SIGLIC.

The SIGIC system follows a certain order of priority, which allows to determine the maximum guaranteed response time (MGRT) accordingly to each level. This level of priority is attributed depending on the clinical urgency of the treatment in question of the patient's clinical situation. By way of explanation, patients whose operation is considered extremely urgent will have a higher level of priority, while those with a lower urgency stand on the last rated level (SIGA SNS, 2018). These levels are summarized in Table *1*.

Table 1. Clinical Priority Level and MRGT

Priority Level	**MGRT**
Level 4	3 days
Level 3	15 days
Level 2	60 days Oncologic Disease: 45 days
Level 1	270 days Oncologic Disease: 60 days

Ever since the implementation of SIGIC, it was possible to extract sufficient data indicating the system was successful in improving the efficiency of the operating room management in Portugal. From 2015 to 2019, there was a continuous increase in the number of entries of patients for surgery waiting lists, rising from 662,642 in 2015 to 724,324 in 2019, corresponding to an increase of 9.3%. Moreover, the number of patients at the end of each year who still remained in the surgery waiting list decreased 0.6%, reaching a total of 242,949 patients. Another demand indicator is the 90-percentile that had an increment of about 17.0% in the period of time mentioned, from 9.3 to 13.3 months. Lastly, and possibly the most important indicator, is the percentage of registered patients that exceed the MGRT. This indicator has multiple variations throughout the considered years (SNS, 2019). These data are summarized in Table 2. This observed stabilization over this period of time can be justified by the continuous work of SIGIC, as well as other initiatives implemented, such as strengthening the openness of institutions to meet certain health needs and increasing the pressure on the productive capacity of institutions, as a result of the combination of more complex cases (Unidade Central de Gestão de Inscritos para Cirurgia, 2015). Thus, one can conclude that operating room planning and the systems introduced with the purpose of optimizing its efficiency and the quality of services are essential to guarantee the best performance possible and relieve the pressure on hospital beds, and generally, on SNS.

Table 2. Demand Indicators from 2015 to 2019 *(SNS, 2019)*

Indicators	**2015**	**2016**	**2017**	**2018**	**2019**	**Δ 2015/2019**	**Δ 2018/2019**
No. of entries of patients in the SWL	662,642	670,913	699,132	706,103	724,324	9.3%	2.6%
No. of remaining patients in the SWL	197,401	210,906	231,250	244,501	242,949	23.1%	-0.6%
90-percentile of the SWL (months)	9.3	10.3	9.7	11.4	13.3	43.0%	17.0%
% of registered patients that exceed the MGRT	28.7%	28.4%	32.3%	30.0%	32.1%	11.8%	7.0%

However, in 2020, it is observed a regression concerning the waiting times and an interruption on the efforts made by the SNS in the previous years (Figure 1). Since 2014, the number of patients enrolled in the surgery waiting list within MGRT has been gradually increasing. Nonetheless, in 2020, that number decreases drastically to where it was approximately in 2014, as a consequence of the pandemic. The current health situation strongly emphasizes how important it is to invest in operating room planning and its relevant scheduling problems.

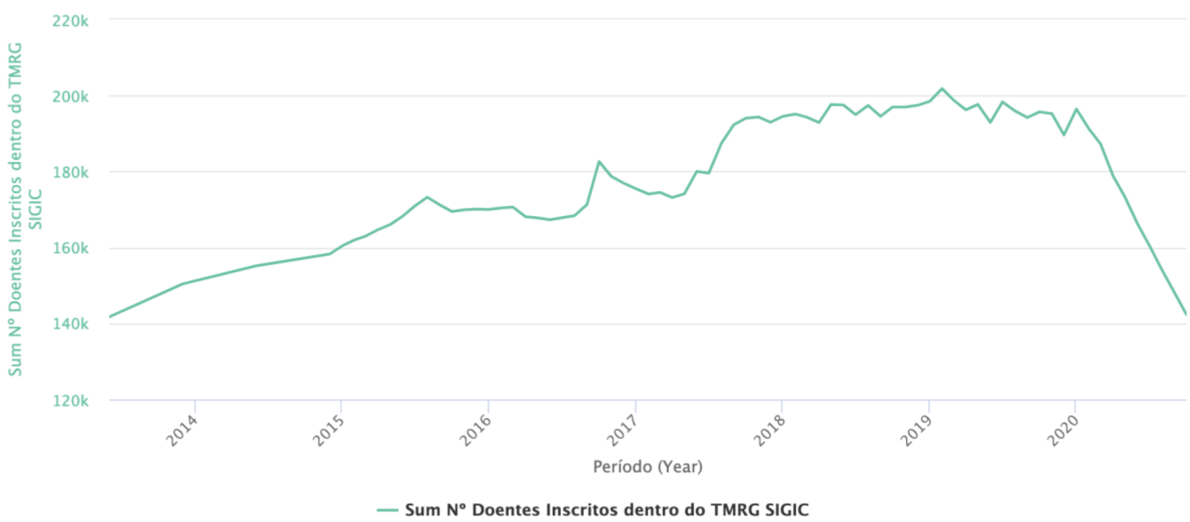

Figure 1. Number of patients enrolled within MGRT *(ACSS, 2021)*

2.2 Scheduling Problems in Operating Room Planning

For the proper functioning of the OR, effective scheduling strategies must be implemented. Subsection 2.2.1 presents the concept of the Master Surgery Scheduling Problem and the different strategies to be adopted. Subsection 2.2.2. is similar to the previous one but instead introduces the Elective Case Scheduling Problem. In Subsection 2.2.3, the importance of positioning these problems in the general scheduling context is explained.

2.2.1 Master Surgery Scheduling

In order for surgeries to be scheduled and performed efficiently, and subsequently reduce the respective waiting lists and maximize resources utilization, a master surgery schedule must be first developed. This schedule is a cyclic schedule (e.g. monthly) that attributes different medical disciplines to available ORs, which facilitates the decisions later made at the operational level (Bovim, Christiansen, Gullhav, Range, & Hellemo, 2020). The concept of the Master Surgery Scheduling Problem is explored in Subsection 2.2.1.1 and the different scheduling strategies practiced are introduced in Subsection 2.2.1.2.

2.2.1.1 Definition

One of the phases included in operating room planning is the Master Surgery Scheduling. The main purpose of this phase is the development of a master timetable, one that will serve as a baseline example for the scheduling of surgical procedures (Proença, 2010). An example of what a baseline schedule could be is presented in Table 3. Integrated into the tactical level of hospital management, in other words, the intermediate level when it comes to decision making, the problem it deals with is regarding cyclic OR schedules. Such schedules follow a monthly or quarterly time scale (Zhu, Fan, Yang, Pei, & Pardalos, 2018). In the literature, the concept of Master Surgery Scheduling is defined in several ways; to give an example: a master surgery schedule is a cyclic timetable that determines the number and type of operating rooms that are available at a specific period for each surgical specialty or group. This schedule is also responsible for specifying the hours that rooms will be open and the surgeons or specialties which should be given priority at an operating room (Beliën & Demeulemeester, 2007).

Throughout the year, the master schedule can be adjusted as a consequence of changes regarding the number of available rooms, OR opening hours or surgical teams. These changes are usually associated with seasonal demand fluctuations and adjustments made at the strategic level (Barros, 2016). Developing a master surgery schedule is of extreme importance in the scheduling process, since the MSS determines the surgical workload distribution. Hence, it presents a major influence on time and resource allocation, which then facilitates the decisions made at the operational level.

Table 3. Master Surgery Schedule Example *(Gomes, 2015)*

	Monday Morning	**Monday Afternoon**	**Tuesday Morning**	**Tuesday Afternoon**
Room 1	Specialty A	-	Specialty E	Specialty D
Room 2	Specialty B	Specialty B	Specialty B	Specialty B
Room n	Specialty C	Specialty A	-	Specialty C

2.2.1.2. Scheduling Strategies

In the literature, the OR planning and scheduling problems are typically organized into three different strategies, them being: the block strategy, the open strategy, and the modified block strategy (Chaabane, Meskens, Guinet, & Laurent, 2008).

In the block strategy, the operating room planning consists of pre-allocating the OR capacity to different surgeons, groups of surgeons, and surgical specialties. As the name indicates, the capacity of OR is divided into blocks, where each block will have a specific duration. The pre-allocation of resources and the surgeons' preferences have an impact when establishing this strategy. Furthermore, a plethora of European hospitals employs the block strategy. This actively demonstrates that surgeons have a preference for centralized blocks of work instead of dispersed cases throughout the day. Nevertheless, if a surgeon does not have any cases or work planned for a specific OR on a certain day and the OR was already allocated to that surgeon, it is not possible for another specialty or surgeon to book or perform surgical procedures for that operating room slot (Zhu, Fan, Yang, Pei, & Pardalos, 2018). This disadvantage contributes to the overall inefficiency of the operating room and, consequently, to the performance of a hospital.

Secondly, the open strategy is characterized by having no pre-allocation of the OR capacity, as opposed to the block strategy, therefore being considered more flexible. This approach follows the concept of first-come-first-served, where an empty OR is filled up and surgical activities are performed according to the order of arrival (Chaabane, Meskens, Guinet, & Laurent, 2008). Moreover, no surgeon or surgical specialty has a priority over another, and two different specialties can be present in the OR at the same time, becoming necessary to distinguish between dedicated rooms and multi-purpose rooms (Meskens, Duvivier, & Hanset, 2013). However, as an expected outcome of the application of this strategy, the OR capacity utilization rate is higher than in the block strategy. On the other hand, due to its lenient organization with stochastic operation time, the waiting periods tend to be longer and delays are more frequent. As mentioned before, surgeons prefer to have their workload centralized, therefore, the open strategy is not as popular within the operating room setting. The drawbacks presented for this strategy, along with the evolution of OR planning, have conducted it to be less utilized throughout the years (Zhu, Fan, Yang, Pei, & Pardalos, 2018).

Lastly, the modified block scheduling strategy is a mixture of the block and the open strategies. Following this combination, the OR capacity is divided and pre-allocated to surgeons and surgical specialties, exactly as in the block strategy, while allowing for a booked slot to be fulfilled by another procedure in the case it was not going to be utilized, such policy is not existent in the block approach. By modifying both strategies, it becomes possible to increase the utilization rate of the OR, as well as, reducing the waiting time for patients. Moreover, this strategy allows, such as in the block schedule, to maintain the difficulty level of constructing a schedule and centralizing the surgeons' daily caseload (Zhu, Fan, Yang, Pei, & Pardalos, 2018).

The decision of implementing one of these three scheduling strategies is made by the OR management team of each specific hospital and can depend on whether the hospital is public or private and on the organization of the operating room, for example, if surgical specialties or surgeons are assigned to a specific room (Chaabane, Meskens, Guinet, & Laurent, 2008).

2.2.2 Elective Case Scheduling

Based on the previously discussed Master Surgery Scheduling Problem and the cyclic schedule derived from it, decisions to be made at the patient level are studied through the Elective Case Scheduling Problem, also known as Surgical Case Scheduling or Elective Patient Scheduling. This problem is included in the last phase concerning the decisions of OR planning and scheduling. Furthermore, this phase is incorporated in the operational level, meaning that it involves decisions whose aim is to support short-term goals, such as maximizing the surgical suites utilization and, in consequence, increasing the efficiency of the hospitals' operating theatre (Marques, Captivo, & Pato, 2012). Subsequently, a specific OR, a day, and a starting time are given to a certain surgery included in the waiting list.

The literature on Elective Case Scheduling and operational level decision making often divides this phase into two stages, namely, the advance scheduling and the allocation scheduling problem. The former is also addressed in the literature as intervention assignment or surgical case assignment, and its main objective is to determine the specific date of each surgery over a planning horizon of multiple days. On the other hand, the latter, otherwise known as intervention scheduling, is the problem where the exact starting time of the procedure and the allocation of the OR resources are determined. Although rare, in addition to these two phases, some researchers study the two problems simultaneously with the goal of maximizing the OR utilization and the allocation of resources, such as nurses, surgeons, equipment, and operation time (Zhu, Fan, Yang, Pei, & Pardalos, 2018).

The principal aim of the ECS problem is to schedule the surgical procedures, based on the previously defined MSS, such that the workload is evenly distributed, resources are available and correctly allocated, and lastly, the proposed schedule for each day is practical and contributes to the proper functioning of the OR.

2.2.3 Positioning the Operating Room Problems in the Scheduling Literature

As mentioned in the previous sections, the MSS and ECS problems result from important planning phases that can have an immense impact on the flow of an operating room, as well as on the scheduling of resources and patients. Literature regarding these problems and on improving the flow of patients, reducing the OR costs, with uncertainty consideration and other capacity constraints, is somewhat extensive and it has been present throughout the years (Beliën & Demeulemeester, 2007; Litvak & Long, 2000; Min & Yih, 2010; Bovim, Christiansen, Gullhav, Range, & Hellemo, 2020). However, there have been only a very small number of papers and studies attempting to place these problems in the general scheduling literature. Considering how vast the literature on general scheduling problems is and the dimension of different settings and applications, it would be expected that more studies would introduce and compare them to the health care context, specifically the operating room management setting.

Some studies have been conducted where either an MSS or an ECS problem is formulated as a setting studied in the scheduling theory. For example, Fügener, Hans, Kolisch, Kortbeek, & Vanberkel (2014) resort to a general assignment problem model, with the intent of minimizing downstream costs for a given master surgery schedule. One of the most studied problems in the general scheduling domain and that is relatively successfully used in healthcare is the job shop problem (Pham & Klinkert, 2008). The authors of both studies mentioned recognize the importance and practicability of using general scheduling problems and adapting them to other scenarios, and as in their case to surgical scheduling. Thus, one can conclude that positioning the MSS and ECS problems in a broader scheduling environment and study possible transfers of knowledge can only bring advantages to the OR planning and scheduling.

2.3 Problem Definition

Inside hospitals or medical centres, the operating theatre is the facility that causes the most impact. More concretely, it is responsible for generating the majority of the funding for the hospitals, and, at the same time, it is a particularly expensive facility, constituting most of their costs. Effective scheduling strategies are crucial to the good performance of the OR and the utilization of different types of resources, for example surgeons, nurses, rooms, and medical equipment. Subsequently, these also influence the speed of access and the possibility to meet the demand for health care, which has been increasing in modern days.

The Master Surgery Scheduling and the Elective Case Scheduling problems are at the centre of attention when it comes to the operating room planning and scheduling environment. The decisions involved in both these problems have a direct impact on the delineation of the strategies and schedules of the overall setting of a medical facility. The MSS consists of a cyclic timetable with information about the number and type of operating rooms available and assigned to a specific time and medical specialty, in other words, it determines the workload distribution, whereas the ECS is responsible for the matching and scheduling of patients in the waiting list and resources, that is short-term decisions. The tasks in question are of a multidimensional and complex character. Within the framework of these problems, several stakeholders and other factors are present, hence, maintaining and improving the efficiency of an OR, minimizing the waiting lists while simultaneously meeting the requirements for patient satisfaction becomes an extremely difficult process.

This dissertation aims to position the Master Surgery Scheduling and the Elective Case Scheduling problems in the general scheduling literature. The objective is to provide an overview of the general scheduling problems and identify the ones that are most closely related to both decision phases mentioned in the operating room planning. Thereafter, the differences, as well as the similarities between the various problems and their settings must be clearly stated. This analysis should then lead to the discussion of whether it is possible, or not, to transfer knowledge between the general scheduling problems and the master surgery scheduling and elective case scheduling problems. Since these problems are mostly defined in the context of health care, there is a need to place them in a broader context and take advantage of the existing dimension of the literature regarding general scheduling problems.

2.4 Conclusions

Throughout the past years, due to the ageing population and the increased demand for healthcare, the number of patients on the waiting lists for surgery has been growing. As a response, special programs have been implemented to help fight the long waiting list in Portugal, namely, SIGIC. Although these programs have been successful in reducing the waiting times, there is still a considerable number of patients enrolled in the surgery waiting lists whose maximum guaranteed response time was exceeded. In 2019, over 232,500 enrolled patients, which corresponds to approximately 30%, had a waiting time that surpassed the MGRT (SNS, 2019). Thus, it is still necessary to improve the OR flow and efficiency in order to provide a better quality of service to the patients.

The Operating Room Planning and Scheduling problem, particularly, the MSS and ECS problems, study strategies that influence several performance measures of the OR, such as the patient waiting time, the OR utilization, and the levelling of resources. Consequently, these measures impact the sustainable and well-ordered functioning of the operating theatre. Considering the importance of the problems mentioned, the focus of this dissertation is to position them in the general scheduling literature and analyze possible knowledge transfers.

A literature review is developed in the next chapter. As previously mentioned in this chapter, this dissertation considers the problems of Operating Room Planning, specifically, the Master Surgery Scheduling and the Elective Case Scheduling. For this reason, the literature review elaborated will be focusing on the existing studies and papers regarding both these problems and organizing them into different descriptive fields.

3. Literature Review

This chapter presents a detailed overview of the existing literature on OR planning and scheduling. Due to the problem defined in Chapter 2, this literature review is more focused on the tactical and operational levels, corresponding to the MSS and ECS problems, respectively. This literature review follows a classification scheme, based on Cardoen, Demeulemeester, & Beliën (2010a), of four descriptive fields, namely, patient characteristics (Section 3.1.1), delineation of the decision (Section 3.1.2), uncertainty (Section 3.1.3), and performance measures (Section 3.1.4). Finally, Section 3.2 concludes this chapter with the main conclusions and findings.

3.1 Classification Scheme

Literature regarding the Operating Theatre and subjects related to this matter has been growing over the last few decades. This stems from an increased interest of researchers as well as hospitals and medical associated facilities to improve efficiency in the operating room and its utilization rate, and, subsequently, the number of patients in the respective waiting lists. Also, as a consequence of this interest, multiple classification schemes or approaches arose. Some authors prefer to classify their articles based on the three hierarchical decision levels, mentioned in the previous section: strategic level, tactical level, and operational level. However, depending on the setting considered, these levels can be seen as vague and interrelated (Samudra, et al., 2016). In response to this interpretation and to overcome the ambiguities remaining, other researchers proposed a more structured and detail-oriented approach. This approach consists of a review of the literature divided into descriptive fields, those being: patient characteristics, performance measures, decision delineation, research methodology, uncertainty, and lastly, applicability research. Be that as it may, some found that scheme not brief enough, and therefore, proposed the building of a scheme that studies the literature from only four different perspectives, as presented in Figure 2: patient characteristics α, delineation of the decision β, uncertainty incorporation γ, and performance measures δ (Cardoen, Demeulemeester, & Beliën, 2010a). The classification scheme including the latter descriptive fields will be followed throughout this literature review.

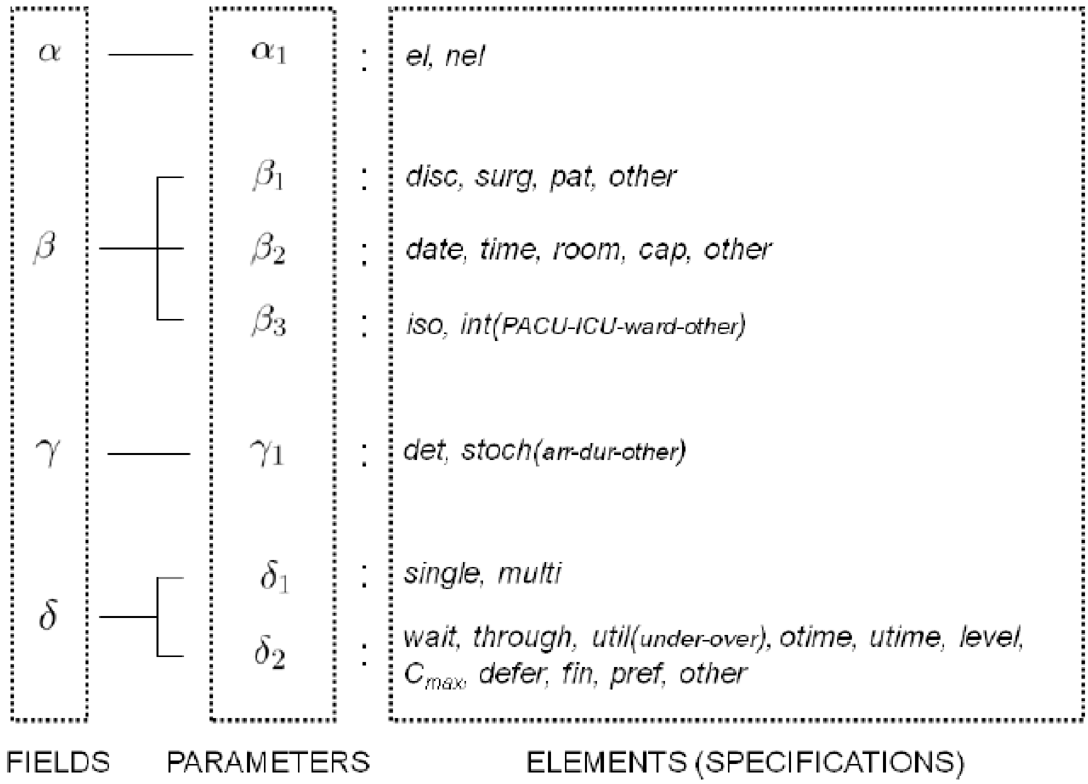

Figure 2. Overview of the Fields, Parameters, Elements that constitute a classification scheme for OR planning and scheduling *(Cardoen, Demeulemeester, & Beliën, 2010a)*

3.1.1 Patient Characteristics

In the literature of operating room planning and scheduling, the field α consists of identifying the different types of patients that are considered for this problem. Specifically, the field is usually divided into two main groups, namely, elective patients (el) or non-elective patients (nel). A patient is integrated into the elective class if it does not have to be treated immediately, in other words, its surgery can be planned in advance to then be done in the future. The latter class includes patients whose surgery is not planned and hence it should be performed as soon as possible. Additionally, many researchers distinguish between urgent non-elective patients (i.e. patients whose surgery can be postponed for a short time) and emergency non-elective patients (i.e. surgery needs to be performed as soon as possible). Moreover, some studies differentiate between inpatients and outpatients. Hospitalized patients who require an overnight stay are considered inpatients, while on the contrary, outpatients leave the hospital the same day of their arrival (Samudra, et al., 2016). Conventionally, surgical procedures performed on outpatients are shorter and have a more stable duration, due to being predominantly routine and only slightly invasive procedures, as opposed to inpatients' surgeries. In this way, specific rooms may be allocated to exclusive use for procedures concerning outpatients (Ramos, 2018). Be that as it may, as a consequence of the increment in the usage of these procedures in the past decades, distinguishing between main (i.e. ORs utilized for major inpatient procedures), and elective rooms is becoming somewhat indifferent with a lot of outpatients being treated in the main operating rooms. However, elective rooms are still, generally, reserved by hospitals for the use of outpatients cases (Blake & Donald, 2002).

Concerning the Master Surgery Scheduling problem, Beliën, Demeulemeester, & Cardoen (2008) developed a decision support system that relies on mixed-integer programming techniques. Furthermore, it involves the solution of multi-objective linear and quadratic optimization problems, in addition to being on a simulated annealing metaheuristic. In this paper, the authors only account for elective cases, with the justification for this simplification being that it is not possible to plan non-elective cases beforehand. Therefore, considering non-elective patients would significantly increase the amount of uncertainty and variability in bed occupancy. Moreover, it is also stated in their study that a significant part of the variance can be controlled by applying practical and logical scheduling strategies to this type of cases. Moosavi & Ebrahimnejad (2020) also study the operating room planning problem at a tactical level and consider elective and emergency patients. To construct the MSS, the authors propose a multi-objective mathematical programming model. Additionally, the authors introduce a new strategy named complete opening policy for the management of which ORs to open or close.

Pham & Klinkert (2008) propose a new elective case scheduling based on the Job Shop scheduling problem. The authors model their optimization problem using a multi-mode blocking job shop (MMBJS). The MMBJS is formulated as a mixed-integer linear programming (MILP), where the objective function minimizes performance criteria, such as the makespan while simultaneously forcing the surgical operation to be scheduled as early as possible, by minimizing the sum of all starting times. In their study, the authors consider both elective and non-elective patients, being also included in these groups the terms of inpatient, outpatient, urgent and emergent. In this case, a surgical activity (job) is considered as a sequence of procedures (operations) to be executed according to the hospital resources, namely, personnel (surgeons and nurses) and facilities, such as ORs, preoperative holding unit (PHU) beds. Moreover, between the processing of two consecutive activities, it is specified a maximum allowed waiting time and priorities rules are also established to prevent conflicts over the needed resources. Additionally, the authors state that any emergency case should be scheduled for a prompt surgery within two hours after its arrival, with a possible consequence of delaying or bumping (i.e. remove a certain patient/case to accommodate a new one) some elective cases in case of incompatible modes. These emergency cases are modelled into the MMBJS as the job insertion problem. Kamran, Karimi, & Dellaert (2018) consider the advance scheduling problem and target both elective and non-elective, both urgency and emergency, patients. The available OR blocks are determined through a modified block scheduling strategy. The objective proposed by the authors is the minimization of the patients' waiting time and the number of surgery days of each surgeon within the planning horizon. In their study, a variation of a two-stage stochastic programming and a two-stage chance-constrained stochastic programming are formulated. The algorithms used to solve these models generate effective solutions with reasonable computational time.

Adan & Vissers (2002) also consider both inpatients and outpatients in their study. However, outpatients are assessed as inpatients. For this purpose, these inpatients would only have a stay of one day and do not need access to special resources, such as the ICU. The authors developed an integer linear programming model with the objective of determining the number and mix of patients admitted to the hospital, for a certain specialty each day. The main aim of this research is to obtain the ideal utilization of resources and exploit the capacity of the operating rooms, the ICU, the ward, and the nursing staff. For this case, the ICU and the ward capacities are equivalent to the number of beds available for each specialty. Having this in consideration, an admission profile is generated with the ability to minimize the deviation between the realised and the target resource utilization for different specialties.

On the topic of patients characteristics, as mentioned before, the majority of the papers only focus on elective patients and disregards the non-elective patients, while, in fact, the latter class is the source, for the most part, of the uncertainty present in the problems related to operating room scheduling and planning. Cardoen, Demeulemeester, & Beliën (2010b) associate this research preference with the fact that elective cases typically generate more profit for the hospitals. Thus, in some literature, non-elective patients are either incorporated into the elective schedule, by considering a buffer capacity reserved for this type of cases, or are channelled into ORs dedicated to non-elective cases (Samudra, et al., 2016). Lamiri, Grimaud & Xie (2009) objective is to propose several stochastic optimization methods for elective case planning, in a scenario where OR capacity is shared by elective and emergency surgery, in order to minimize expected overtime cost and patients' related costs. Their planning problem is presented as an exact solution method combining the Monte Carlo sampling technique and mixed integer programming. Wullink et al. (2007) study a framework where it shows that reserving elective OR capacity for emergency surgery leads to an improvement in waiting times, a reduction in overtime work, and overall the OR utilization increased. Kroer, Foverskov, Vilhelmsen, Hansen, & Larsen (2018) investigate the planning of OR while taking into account both elective and emergency patients. However, elective operations are scheduled while still making space for accommodating potential emergency procedures. This way, the authors develop a stochastic model capable of withstanding different operations durations and unknown arrivals of emergency patients.

3.1.2 Delineation of the Decision

Among the literature, one can find several ways the authors divide the research on this descriptive field, represented by β. Some studies choose the classification of the three hierarchic classical levels: strategic, tactical, and operational. The definitions of the problems corresponding to each one of these levels vary between different authors and there are no clear boundaries dividing the three levels. Other common distinctions made when it comes to the decisions of OR scheduling problems are block and open scheduling and advance scheduling and allocation scheduling. Using these classification distinctions is somewhat vague and would make it harder to define which type of decisions are being made and what parameters are being considered (Samudra, et al., 2016).

This field concerns the type of decisions that are necessary to make in a certain operating room planning and scheduling problem. According to Cardoen, Demeulemeester, & Beliën (2010a) this field consists of three parameters and aims to respond to three questions, each corresponding to a different parameter. The first question and parameter regard the subject of decision, β_1. The authors consider four different constituents, specifically, medical disciplines (disc), surgeons (surg), patients or patient types (pat), and other subjects (other), for example, hospitals. Astaraky & Patrick (2015) present a model to contribute to the problem of allocating OR capacity, in other words, specific daily allocations, to different medical specialties. The problem presented by the authors is formulated as a Markov Decision Process model, capable of scheduling patients in a multi-class, multi-resource surgical system. The authors concluded that their model outperforms the First In First Out (FIFO) policy due to maintaining the waiting lists stable with only a slight increase in the OR overtime and in the downstream congestion, for systems with insufficient base capacity. Doulabi, Rousseau, & Pesant (2016) study the integrated OR planning and scheduling with a focus on surgeons. They take into account the surgeons' maximum daily working hours and aim to prevent the overlapping of surgeries performed by the same surgeon. The problem is developed using a branch-and-price-and-cut algorithm capable of addressing several types of settings. As conclusion, the authors state that their model outperforms a compact mathematical formulation present in the literature. Durán, Rey, & Wolff (2017) develop and compare two optimization models (i.e. two integer linear programming models) and two algorithms (i.e. a feasibility model and a constructive algorithm) for scheduling interventions over a defined period to satisfy patient priority criteria. Within the feasibility model, a general assignment problem is also solved to determine which patients can be assigned or not. The authors stated that the number of patients that can be treated is directly impacted by the scheduling of surgical interventions, and justify this as the motivation for their study. The proposed techniques show an improvement in OR utilization rates ranging from 10 to 15% over the manual techniques currently used. Other subjects, for example, hospitals, are also the subject of decision (Litvak & Long, 2000).

Type of decision, β_2, is the second parameter in this descriptive field and the question trying to be answered is what type of decision is addressed. The decisions that have to be taken are regarding the assignment of a date (date), a time indication (time), an operating room (room), capacity (cap), as well as other decisions (other) which may contemplate the pairing of patients with specific surgeons. Molina-Pariente, Hans, Framinan, & Gomez-Cia (2015) study the operating room planning problem and have an objective of assigning an intervention date and an OR to a set of surgeries on the waiting list. To reach their objective, a set of different kinds of heuristics is presented and then compared to other existing heuristics found in the literature. The proposed method shows an improvement on several key performance indicators, for example, the number of surgeries scheduled and the resource utilization. Li, Gupta, & Potthoff (2016) address the rescheduling problem, which includes decisions regarding the starting times of surgeries. In their study, the authors attempt to reduce OR staffing costs besides improving OR utilization. The problem is formulated as a variant of the bin-packing and results show that rescheduling saves significant OR costs of staffing. Koppka, Wiesche, Schacht, & Werners (2018) propose and evaluate an optimization model that tactically distributes the total available operating time over the different OR with the aim of improving the overall performance. The authors reach the conclusion that Key Performance Indicators (KPI) such as overtime and utilization can be significantly influenced by optimal operating hours for ORs. Penn, Potts, & Harper (2017) address the MSS problem and develop a model that assists in the creation of master theatre timetables. The capacity of ORs is studied along with the maximum number of beds required and the number of surgeons available.

Several other factors are also taken into consideration for the development of the timetables. The conclusion reached by the authors in this paper is that it is possible, for medium size hospitals, to solve a mixed-integer programming (MIP) problem of finding master surgical timetables in a reasonable amount of time.

Degree of integration, β_3, is the third and last parameter present in the field of Delineation of the Decision. This parameter seeks to answer the extent to which the operating room is studied. In other words, are others facilities present in an operating room setting integrated into the problem or not? The problem can either study the OR in an isolated setting (iso) or in an integrated way (int) (Augusto, Xie, & Perdomo, 2010). In the latter case, both upstream and downstream facilities can be considered. Furthermore, the authors differentiate between these facilities: postanesthesia care unit (PACU), intensive care unit (ICU) (Hamid, Hamid, Musavi, & Azadeh, 2019), and hospital wards (wards) (Ansarifar, Tavakkoli-Moghaddam, Akhavizadegan, & Amin, 2018). Agnetis et al. (2014) study the OR planning problem in an isolated setting, focusing only on determining the MSS on a weekly basis, by assigning the different surgical specialties to the available sessions. Following this, surgeries are allocated to each session, and patients are selected from the waiting list respecting variables, such as the surgery duration, waiting time, and priority class of the procedure. This decomposition approach is then compared to an integrated one, where it is concluded that the former finds satisfactory results and shows notable savings in computation time. When it comes to studying the problem in an integrated setting, Latorre-Núñez et al. (2016) address the surgery scheduling problem while simultaneously considering the PACU and resources required by surgery and for recovery. The authors propose a MILP model, a constraint programming (CP) model, and a metaheuristic. These methods are capable of addressing all the stages of the problem at once and, subsequently, reduce the space for bottlenecks.

The same authors that indicate the three parameters propose, in a different paper, a two-dimensional classification of planning and scheduling decisions, which provides further detail on the exact type of decision being made. The parameters explained above are respected and included in this classification, making it more appropriate than other classifications presented previously (Cardoen, Demeulemeester, & Beliën, 2010b).

Samudra et al. (2016) state that disregarding and, therefore, not integrating into the problem the upstream and downstream facilities when one is trying to improve the OR schedule and performance may actually worsen the efficiency of those related facilities. Some papers already work within the integrated frameword. For example, based on the MSS, Vanberkel et al. (2011) describe an approach to determine the workload for downstream units, in specific, the ward occupancy and the patient admission and discharge distributions. Additionally, the number of patients in their recovery stage is also accounted for each day. The authors consider that this workload of downstream units can be described as a function of the MSS. Hence, the model presented in this study allows the managers of the downstream departments to aggregate their associated tasks with recovering surgical patients. It is concluded that upcoming capacity and resource conflicts can be anticipated or even eliminated beforehand, if an MSS where a relationship between the downstream facilities and the OR can exist, is applied. Hsu, Matta, & Lee (2003) in their study aim to schedule patients and minimize the number of

PACU nurses at an ambulatory surgical centre. Since it is a sequencing problem the decisions being made are at the patient and time level. This patient scheduling problem is formulated as a new variant of the no-wait, two-stage process shop scheduling problem. The first stage consists of the OR and its surgeons as the main resources, whereas the second stage is the PACU and its respective nurses. The authors propose a heuristic approach that solves the two problems in a synergetic way.

3.1.3 Uncertainty Incorporation

The field of uncertainty incorporation, γ, deals with one of the major problems associated with operating room scheduling and planning, and, by consequence, with the activity of developing precise and detailed schedules. The environment where surgery scheduling is placed is considered to have several factors contributing to consistent uncertainty. This uncertainty, more often than not, causes deviations between what was planned and what ended up being performed (Sperandio, Gomes, Borges, Brito, & Almada-Lobo, 2014). As explained before, an important portion of the variability and variance in a hospital environment can be controlled by implementing well-thought-out scheduling strategies, despite non-elective cases being the source of the majority of this uncertainty. Litvak & Long (2000) also place emphasis on this framework. Moreover, the authors differentiate between different kinds of variability, for example, “natural” and “artificial”. Natural variability derives from the uncertainty deep-rooted in the healthcare systems and is random by nature, therefore, multiple operation research methodologies and models, such as the queuing theory can be employed. On the other hand, artificial variability, for example, extreme variation in daily bed occupancy, is generated by negligent management and inefficient schedule strategies and is non-random.

Furthermore, in the literature, problems concerning uncertainty can be classified either as deterministic (det) or stochastic (stoch), based on the approach the authors used to incorporate uncertainty. Deterministic planning and scheduling approaches ignore uncertainty or variability. Contrarily to this, stochastic approaches explicitly try to incorporate it (Cardoen, Demeulemeester, & Beliën, 2010b). Recently, studies where stochasticity is frequently taken into account have been increasing in the literature. Atighehchian, Sepehri, & Shadpour (2015) aim to minimize idle and over time of ORs and optimize the scheduling of surgeries with uncertain durations. The authors propose a two-stage stochastic model solved using an L-shaped algorithm. Xiaoa, Jaarsveld, Dong, & Klundert (2016) analyse the stochastic operating room scheduling problems and study the improvements attainable by the scheduled cancelations to accommodate to the large demand while avoiding the consequences of excessive overwork time.

In the literature, the majority of the papers take into account one of two different types of stochasticity in the form of uncertainty, namely, duration uncertainty (dur) and arrival uncertainty (arr). Additionally, some papers consider other kinds of uncertainty (other), such as resources and care requirement (Zhu, Fan, Yang, Pei, & Pardalos, 2018). Duration uncertainty is associated with the deviations between the actual and the planned duration of activities related to the surgical process. The reason for the duration of a surgical activity to be so uncertain is due to several factors, including the patient disease and condition and the professional ability of the surgeon (Litvak & Long, 2000). In Denton, Miller, Balasubramanian, & Huschka (2010), the authors present stochastic optimization models for the assignment of surgeries, specifically, the multi-OR allocation problem under uncertainty. This paper aims to minimize the costs of OR overtime and OR opening. Other authors propose robust optimization methods for the Advanced Scheduling Problem when it comes to block scheduling (Addis, Carello, & Tànfani, 2014). In this paper, a robust optimization model is proposed with uncertain surgery durations, where the objective of the problem is to minimize a measure of the waiting time of the patients. The robust methods do not assume that probability distributions are known, stating that uncertain data is placed in a presumed uncertainty set, as well as guaranteeing the feasibility of the solution for some variations of the considered parameters (Bram L. Gorissen, 2015). Beliën & Demeulemeester (2007) propose stochastic models, a MIP approach, and a metaheuristics approach, for building a master surgery schedule with levelled resulting bed occupancy, intending to minimize the expected shortage of beds. In this study, the length of stay of each patient is considered uncertain, following a multi-nomial distribution. In another study, Denton, Viapiano, & Vogl (2007) develop a stochastic optimization model that hedges against the uncertainty in surgery durations. The study shows that a simple sequencing rule based on surgery duration variance can be used to generate substantial reductions in total surgeon and OR team waiting, OR idling, and overtime costs. Considering that surgery durations are uncertain, Khaniyev, Kayış, & Güllü (2020) aim to determine the starting and finishing time of a certain surgery included in a sequence of non-identical procedures. The objective of the authors is to minimize the weighted sum of expected patient waiting times, room idle time, and overtime. To do this, a set of simple-to-use different heuristics is proposed, along with a hybrid one.

Arrival uncertainty is also very present in the literature. This uncertainty can concern several scenarios, for instance, the unexpected arrival of either outpatients or emergency patients, or the late arrival of surgeons for the beginning of a surgical activity. Min & Yih (2010) address the elective case scheduling problem where patients with different priorities are scheduled in a surgical facility with a definitive capacity. The authors suggest a stochastic dynamic programming model to assign a certain patient from the waiting list to a schedule period. In their study, it is concluded that considering patient priority results in significant differences in the surgery schedule when compared to one that does not consider it. Different management policies also contribute to arrival uncertainty, as well as surgery duration. This happens as a consequence of these policies affecting the patient waiting times, cancelations, and the utilization of OR time (Persson & Persson, 2010). Soudi, Heydari, & Mazdeh (2019) formulate a weekly scheduling of an integrated surgical procedure as a hybrid flow shop scheduling problem, with capacity constraints on ward beds and ORs. Furthermore, the authors consider the arrival uncertainty of emergency patients and the impact it has on the elective schedule. The proposed approach is divided into two phases: predictive and reactive. Through the computational results, the approach's efficiency is shown.

Finally, resource uncertainty and care requirement uncertainty are addressed as well in some studies. Cardoen, Demeulemeester, & Beliën (2010b) state that both these terms appear often in the same scenario. The arrival of an emergency patient may require a specific surgeon and operating room, resulting in a disruption in the resources available for elective surgeries, and therefore causing delays and cancelations. Hooshmand, MirHassani, & Akhavein (2017) study the MSS problem and intend to develop a cyclic allocation table in which blocks are assigned to surgeons. The authors consider the number of available beds in hospitalization units, as well as the length of stay of patients to be uncertain and their objective is to minimize the expected bed shortage in the ICU and wards. The method propose is a two-stage stochastic model, solved through a sample average approximation where the results obtained converge to a real optimum.

3.1.4 Performance Measures

The final field in the classification scheme being followed regards the performance measures, δ. These measures serve as a way to evaluate the operating room planning and scheduling problems and procedures. The problems in question can address single (single) or multiple (multi) objectives, in other words, if the problem has one single criterion or multiple criteria incorporated to assess its possible solutions. Furthermore, a single problem can have incorporated various types of performance criteria. Cardoen, Demeulemeester, & Beliën (2010a) distinguish between the main performance measures: waiting time (wait), throughput (through), utilization (util), overtime (otime), undertime (utime), levelling (level), makespan (C_{max}), deferrals or refusals (defer), financial measures (fin), preferences (pref), and others (other). It should be noted that some authors relate underutilization to undertime and overutilization to overtime in the same measure (utilization) and therefore, do not make the separation between utilization, overtime, and undertime (Samudra, et al., 2016). The authors justify this choice on the fact that several papers do not specify which view is applied.

Depending on the interests and expectations of each stakeholder, different priorities will be taken into consideration and therefore different performance measures will be evaluated. Due to the variety in stakeholders and their objectives, in the literature researchers, more often than not, opt to include more than one criterion in their studies to try and adapt to real-life problem settings. These settings may have multiple objectives, such as minimizing the patient waiting times (Khaniyev, Kayış, & Güllü, 2020), maximizing the OR utilization (Ansarifar, Tavakkoli-Moghaddam, Akhavizadegan, & Amin, 2018), minimizing the overtime (Moosavi & Ebrahimnejad, 2020), minimizing the makespan (Latorre-Núñez, et al., 2016), and levelling the utilization of different resources, for example, the up and downstream units of the OR (Fügener, Hans, Kolisch, Kortbeek, & Vanberkel, 2014).

As explained previously in Section 2.1.2., waiting lists are increasing due to the situation related to the Covid-19 pandemic, since many standard procedures have been delayed or cancelled, and as a consequence, waiting times for patients are also growing. The reduction of waiting times for both patients and surgeons is a popular objective among several papers, due to the impact this measure has on the efficiency and service quality provided by medical facilities. Creemers, Beliën, & Lambrecht (2012) present a model for assigning server time slots to different classes of patients over a variety of medical disciplines. Their study aims to minimize the total expected waiting time of a particular class of patients. The optimal allocation scheme is found by using the output of the bulk service queueing system as the input of the optimization model. Another approach to assess the patient waiting time is proposed by Aringhieri, Landa, Soriano, Tànfani, & Testi (2015b). The authors suggest a two-level metaheuristic method to study the joint problems of OR planning and advance scheduling, in other words, the tactical and operational scheduling problems. In their model, the objective is to optimize both patient and hospital utilities by reducing the waiting time costs as well as the production costs corresponding to the number of weekend stay beds required by the surgery planning. Kamran, Karimi, Dellaert, & Demeulemeeste (2019) also have the objective of minimizing the patient waiting time, along with the number of cancelations, the block overtime, and the number of surgeon's surgery days within the planning horizon. The authors consider a modified block scheduling policy and a reserved slack policy to deal with the arrival of emergency patients. The problem is formulated as a stochastic mixed integer programming model, which in addition to the other assumptions described, allows for efficient solutions.

A performance measure deeply connected to the waiting time, but not as studied in the literature, is throughput, a quantitative measure that indicates the number of patients that passes through the operating room (VanBerkel & Blake, 2007). Liang, Guo, & Fung (2015) propose a scene-based combination with three simple scheduling rules, namely, First-Come-First-Served (FCFS), shortest processing time, and earliest due date, to optimize surgery scheduling performance, that is, maximize patient throughput and minimize waiting time.

Another common objective is the minimization of overtime. When overtime happens in an OR it can have diverse consequences from the dissatisfaction of the surgical staff to the cancelation of other surgeries and disturbance of the OR schedule. This could also implicate higher costs for the hospital, as it would have to pay for more working hours (Samudra, et al., 2016). Ozkarahan (1995) proposes an expert hospital decision support system for resource scheduling. The mathematical model presented is similar to a job shop scheduling model and is capable of minimizing overtime and maximizing room utilization in a multiple OR setting, while sequencing the loaded cases respecting priority rules. Another study related to minimizing overtime is (Dexter & Traub, 2002). In their study, for elective case scheduling, a strategy for scheduling a new case into an unfulfilled OR is analysed. Earliest Start Time and Latest Start Time are the two-patient scheduling rules used by the authors. They conclude that Earliest Start Time maximizes OR efficiency when a service has nearly filled its regular schedule hours of OR time, in other words, it helps with the reduction of overtime. On the other hand, Latest Start Time is concluded to work better when balancing workload among services. Zhang, Dridi, & Moudni (2019) study the elective case scheduling problem with consideration of ORs and downstream units. The authors develop a two-level optimization model to minimize the overtime and the costs associated with it, and the number of open ORs. Other authors also have as objective the minimization of overtime, for example (Moosavi & Ebrahimnejad, 2020; Astaraky & Patrick, 2015; Meskens, Duvivier, & Hanset, 2013).

The levelling of resources is a matter very present in the literature. One understands levelling of resources as the development of OR schedules that lead to smooth resource occupancies without peaks (Cardoen, Demeulemeester, & Beliën, 2010b). The operating room is not the only resource taken into consideration, the levelling of resources such as bed occupancy, and utilization of the down and upstream facilities is also studied. The reason for this is that these resources and units influence the operating room itself. If a downstream unit, for instance the ICU, is suffering from overcapacity, it blocks the flow of patients coming from the OR, and as a result, impacts other surgical activities. Oostrum, et al. (2008) address the MSS problem as a proposal to deal with the demand fluctuations of surgical wards and ICU, caused by poor scheduling decisions in the OR. A column generation approach is proposed to solve the mathematical model, which has as objectives the levelling of the requirements for hospital beds in the wards and the ICU, as well as the maximization of the OR utilization. Another study that considers the MSS problem in which the block OR time is assigned to different surgical activities is Fügener, Hans, Kolisch, Kortbeek, & Vanberkel (2014). The authors concentrate on the effect an MSS has on the flow of patients to downstream inpatient care units. In their study, a generic model to minimize the downstream costs and level the demand distribution for downstream resources using a general assignment problem is presented. The conclusion reached is that when designing tactical OR schedules and there is a consideration for the downstream units, there is potential to save costs and improve quality and efficiency regarding the staff and the resources. Aringhieri, Landa, & Tànfani (2015a) study the problem of having to schedule elective surgery patients into a series of available OR blocks. The authors aim is to level the post-surgery ward bed occupancies during the days, in order to alleviate and smooth the respective workload, and subsequently, improve the quality of the services provided to the patients. To reach this goal, a Variable Neighbourhood Search is exploited. This provides a general solution framework, which can be easily adapted to different settings and problems.

3.2 Conclusions

In this chapter, an overview of the existing literature on Operating Room Planning and Scheduling problems, specifically, the Master Surgery Scheduling and the Elective Case Scheduling problems, is provided. This literature review follows a classification scheme, where the several manuscripts present are explored according to different descriptive fields. The four proposed perspectives are patient characteristics α, delineation of the decision β, uncertainty incorporation γ, and performance measures δ. The following of this scheme allows an organized and detail-oriented review of the characteristics of the addressed papers.

Even though there is a significant number of papers where non-elective patients are considered, the majority still only concern elective patients. However, in recent years, more authors are integrating non-elective planning into their studies. Regarding the delineation of the decision, most of the researchers deal with decisions made at the patient level, whether it be for the assignment of a date (i.e. advance scheduling), a time, and a room (allocation scheduling). Apart from these assignment levels, the capacity allocation for a given day of the week is dealt with frequently as well. The discipline and surgeon levels are also quite addressed in the literature. Additionally, there is a balance between manuscripts studying the Operating Room Planning and Scheduling problems in an isolated and integrated way. In the latter case, the authors mainly focus on the downstream units (i.e. PACU, ward, ICU). One of the main problems studied and associated with the OR planning context is uncertainty, with the majority of papers taking into consideration some type of uncertainty. These types include duration uncertainty, which has had a continuous growth in interest in the past few years, arrival uncertainty, or other types, such as resource uncertainty. For this reason, authors often opt for stochastic approaches instead of deterministic ones, which ignore uncertainty. Performance measures (PM) are a common approach used to evaluate the functioning of the OR. The most frequently used PMs are overtime and patient waiting time. However, depending on the interest of the stakeholders involved in the problem, multiple measures are frequently measured alongside each other.

Despite the fact that each paper studies different problems, offers new perspectives and presents multiple methodologies and solutions, only a few authors adapt general scheduling models to solve the MSS and ECS problems. Furthermore, the majority of the papers that integrate those models focus mostly on the Job Shop and Flow Shop. Given how extensive the literature on scheduling problems is, a bigger effort should be made to introduce and apply them to the health care setting, particularly, to the Operating Room Planning and Scheduling context.

4. Research Methodology

The main objective of this research work is to position Operating Room Scheduling and Planning problems, namely, the Master Surgery Scheduling and Elective Case Scheduling problems, in the scope of the general scheduling literature. In this chapter, the proposed methodology to meet this objective is listed.

Stage 1. Literature Review of Scheduling Problems

In this stage, a literature review of scheduling problems, in general, will be provided. Similar to Stage 2 and Chapter 3 of this document, the aim of this stage is to acquire a deeper understanding of the existing research and studied applications relevant to scheduling problems.

For this review, several steps were followed in order to collect and select relevant literature. One of the conditions for this collection was that only studies written in English were considered. Secondly, to be eligible for consideration, the studies had to be published in peer-reviewed journals. Consequently, expertly curated databases, such as Web of Science, Scopus, and Science Direct, were used as a basis for the search in collecting papers and proceedings. Within these databases, to limit and refine the search to relevant papers, several keywords were provided to the search engine. These keywords were defined taking into account characteristics present in the MSS and ECS problems. In the frameworks of these problems, resource allocation, timetables development, and patient prioritization are among the principal activities performed to guarantee the proper performance of the OR and maximize its efficacy. For this reason, combinations of keywords, such as “Scheduling”, “Healthcare”, “Resource Allocation”, “Prioritization”, “Assignment Problems” were applied to search different articles. With this first level of keywords, it becomes possible to start constructing groups of different scheduling problems, that is, classifying these problems depending on the focused features and strategies used. The scheduling problems collected were then grouped into the categories of Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare. Afterwards, a new search was performed using the name of these categories as keywords to finalize the selection of relevant papers to be included in this literature review and considered for the next stages of the methodology.

Stage 2. Positioning the Master Surgery Scheduling and Elective Case Scheduling Problems

This stage has as the main purpose to position the OR Scheduling and Planning problems in the review and classification of the general scheduling problems provided in the previous stage. In order to understand this position, a descriptive analysis is performed, where the scope of the different scheduling problems is compared to the MSS and ECS problems. This comparison is performed using multiple features and performance measures present not only in the categories mentioned above but in the OR problems as well. Within the characteristics present in the problems included in both literature reviews the selected ones to be analysed were Patient Preferences, Patient Prioritization, Workload Balance, Fairness, Clustering, Staff Preferences, and, lastly, Uncertainty.

Stage 3. Identification of the Problems Most Closely Related

With the two previous stages completed and taking in consideration an overview of the features and settings of the multiple examples of the MSS and ECS problems analysed, it becomes possible to identify which are the scheduling problems that are most closely related with both of them. In order to perform the intended identification, a percentage analysis of the different characteristics in each scheduling category, including every paper covered in the literature reviews of Chapters 3 and 5, is performed. This allows to better understand and visualize the possible similarities and the differences between general scheduling problems and the OR planning and scheduling problems studied in this dissertation.

Stage 4. Discussion of Possible Knowledge Transfer

This is the final step of the research methodology for this dissertation work. By addressing the existing research gaps in the OR planning problems and analysing the differences and similarities between both matters, one can conclude how often and what characteristics have been explored in the various categories and recognize if there are studies significantly covering the ones that are not contemplated in the OR scheduling setting. Hence, it is possible to discuss whether or not knowledge transfer between the problems defined and addressed in the previous stage, namely, the general scheduling problems, and the MSS and ECS, is feasible.

The research methodology is summarized in Figure 3, where the objective and methods applied in each stage are stated.

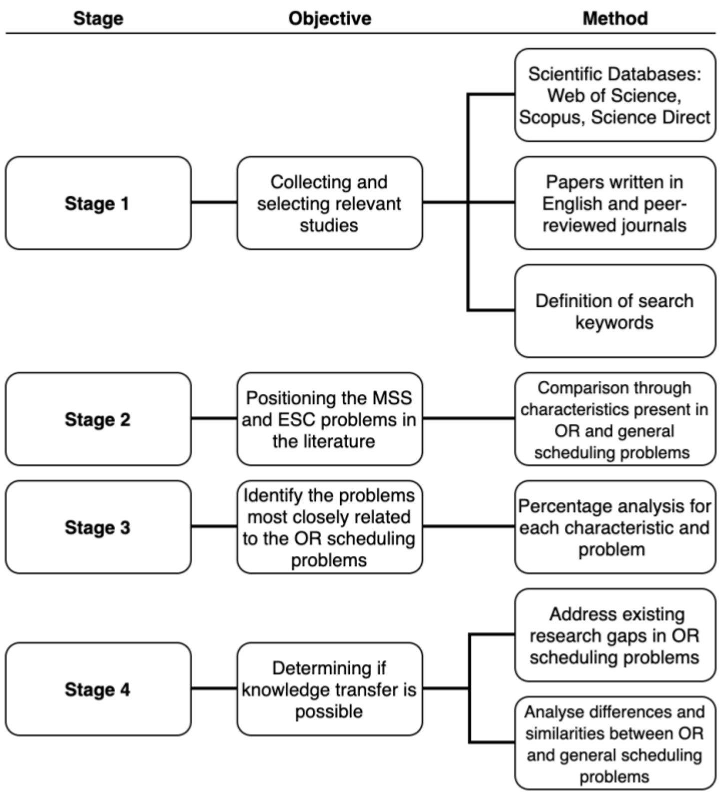

Figure 3. Research methodology, objective, and methods (adapted from *Barbosa-Póvoa, Silva, & Carvalho (2017)*)

5. Scheduling Problems Review

This chapter provides an overview of the existing literature regarding different scheduling and assignment problems. In Section 5.1, the problems included in this review are divided into five categories, depending on which subject is addressed, namely, Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare. Finally, in Section 5.2, the main findings conclude this chapter.

5.1 History and Definition

The concept of scheduling is not one that has recently appeared, being traced back as over as 3000 years. The Giza Pyramid Complex, a project that started circa 2550 B.C, and the Liverpool Road Station, built in 1830, are two examples to prove that the science of 'scheduling' has been in use for as long as we can remember (Weaver, 2006). Scheduling can be described as the decision-making process to establish when, where and with which resources to provide a combination of services and to produce a set of products (Güler, Geçici, Köroğlu, & Becit, 2021). The decisions involved in this process are mainly aimed at optimizing one or more objectives, such as decreasing waiting times, increasing efficiency, maximizing resources utilization, minimizing inventory and processing costs, along with others.

Among the literature, one can find several scheduling problems, that consider multiple and diverse criteria, depending on the type of industry the problem is inserted in. For instance, if the industry considered is manufacturing, the job completion time and the number of units produced are two of the most important criteria. On the other hand, in the healthcare sector, patient waiting times and resource utilization may be more relevant. Throughout the following review, different scheduling problems, that deal with limited capacity and resources, that are divided into five categories, specifically, Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare, will be presented.

5.1.1 Instructional Scheduling

Since the activity of scheduling is present in multiple sectors globally, the academic setting, as expected is no exception. The large scale scheduling problems in higher institutions, such as universities can be denominated as instructional scheduling. This involves the development of a course schedule, in other words, the booking of a free time slot for both students and lecturers, as well as the assignment of suitable classrooms, while taking into consideration the different types of classes taught and the existing courses in each institution. Adding to the complexity of this scheduling problem is also the number of students and teachers that are part of a university. This way, a well-rounded course schedule will lead to an optimization of the allocation of resources in addition to the efficient use of the available infrastructures.

Shen-min Lv (2018) studies the wide-ranging and complex scheduling problems in institutions of higher learning and proposes an optimization plan. The Memetic algorithm is used to solve the proposed optimal scheduling scheme. The author concludes that this algorithm effectively improves the quality of class scheduling, as well as the efficiency of calculation, proving that it can be used to solve high-dimensional and dynamic problems. Gunawan, Ng, & Ong (2008) address a timetabling problem, more concretely, the assignment of teachers to the courses and course sections at the university level. The authors formulate the problem as a mathematical programming model and propose a genetic algorithm with two types of crossover to solve it. Firstly, the teachers are allocated to the courses and the number of courses to be assigned to each teacher is determined. Afterwards, the teachers' workload is balanced by scheduling them to the course sections. To evaluate the model's efficiency, computational experiments are made against real data sets. Results show that the proposed algorithm presents better solutions than manually allocation and scheduling. The aforementioned authors address the same problem, however, two different algorithms, based on simulated annealing and tabu search algorithms, are proposed in this study. The computational results show that the algorithms also give better solutions than the manual allocation made by the university (Gunawan & Ng, 2011). Phillips, Waterer, Ehrgott, & Ryan (2015) propose an integer programming method to address the class assignment problem. Thus, a novel pattern-based formulation, which generalizes existing models is introduced. The authors validate the model through the computational results based on experiments previously made in a university.

Another problem present in higher education is the master thesis defense scheduling problem. Typically, a master student is associated with one supervisor and, when the time comes to defend the thesis, a jury is formed, usually composed of the dissertation supervisor and two other reviewers. Thus, for each student defense, an available room and suitable time slot must be determined. Huynh, Pham, & Pham (2012) study the master thesis defense scheduling problem in Vietnamese universities and provide a formulation for the problem based on realistic requirements. The authors propose a genetic algorithm to solve the problem and are able to show its feasibility. Fiarni, Gunawan, Ricky, Maharani, & Kurniawan (2015) focus on the scheduling of thesis and projects presentations. The researchers present a practical method for modelling and solving a dynamic resource allocation using a forward chaining heuristic approach. The product of this method is an automated set of presentation schedule alternatives that take into consideration every constraint. The system proposed in this study increases resource utilization and helps the facility to book the presentations in an easier process.

Furthermore, there are papers studying the scheduling of exams in universities. Güler, Geçici, Köroğlu, & Becit (2021) address the exam timetabling problem (ETP) and the supervisor assignment problem (SAP) in a university. The authors propose MIP models for both the ETP and the SAP. In order to find the optimal solution for the ETP within a reasonable time a decomposition technique is utilized. Concluding, an average end-user is able to prepare a complete timetable in less than two minutes, using a web based decision support system. Goli, Tirkolaee, Mahdavi, & Zamani (2019) objective is to determine the best exam scheduling within a reasonable computational time. This way, a genetic algorithm along with a firefly algorithm are developed. The effectiveness of both algorithms is proved through computational tests, which results show that flexible solutions are achieved with either one of the algorithms.

5.1.2 Bed Assignment

As previously mentioned in Chapter 3, beds are one of the most important resources hospitals and medical centres possess. If this particular resource is lacking, for example in a downstream unit, the flow of patients coming from that unit is blocked, and as a result, other surgical activities are impacted. Additionally, as a consequence of the increased demand for health care, the request for hospital beds grows as well. For this reason, an efficient management and assignment of beds is essential to minimize the number of internal movements within a unit and to maximize the bed usage, improving the overall performance of a hospital and the quality of care delivered. With that being said, the bed assignment problem consists of managing a set of beds with specific characteristics and assigning them to a set of patients with certain requirements compatible with those features (Taramasco, et al., 2019). For instance, whether is it an emergency or elective patient and the different medical and surgical disciplines.

Several authors study the bed assignment problem with the objective of improving the quality of the service provided to patients, as well as its efficiency. Guido, Groccia, & Conforti (2018) focus on the problem of assigning elective patients to beds by considering multiple requirements, those being, the clinical conditions and personal preferences of the patient, the bed availability in departments, the length of stay, among others. The authors develop combinatorial optimization models to support the decisions being made. These models are solved through a matheuristic solution, and the results obtained exhibit an impressive performance for all the benchmark instances. In another study, Heydar et al. (2021) focus on emergency and elective patients who have had surgery, that is, random patient arrivals and departures. A Markov chain is constructed to model the problem in question, where the states correspond to the number of patients in each type of ward, and which class of patient arrived or if there was a departure. The problem is formulated as a stochastic dynamic program which is proven to be an effective method to solve the patient-to-bed assignment problem, even in large scale scenarios. Conforti, Guido, Mirabelli, & Solina (2018) also recognize the importance of efficient use of healthcare resources and address the similarity between the bed assignment problem and the problems present in the manufacturing environment. The patients correspond to jobs with a processing time (length of stay), a start date, a due date, and the necessity of being assigned to an equipped machine (room/bed). In their paper, the authors focus on elective patients and formulate an optimization model to support the decision-making in bed management in an automated way, stating that it is a general model to enable a greater number of applications. The model developed achieves several results, including the increase in efficiency, productivity, and patient satisfaction.

Taramasco et al. (2019) aim is to find the patient-to-bed assignment that minimizes the weighted sum of the unsatisfied constraints, those being the constraints that in real-life problems are violated. For example, if the maximum risk is assumed for a patient, a critical bed must be assigned. In the case that no critical bed is available, a normal bed will be equipped as a critical bed. An autonomous bat algorithm is presented to which is then used to solve problems with data from multiple hospitals in order to validate the proposal. The authors show that their approach is capable of efficient results with decreased solution times.

Thomas et al. (2013) formulate the bed assignment problem as a mixed-integer goal-programming model, allowing the accommodation of multiple goals of different hospitals, such as the assurance that a patient is not assigned to a bed occupied by a clinically discharged patient. The model developed shows improved productivity, visibility of bed assignments throughout the hospital, and a consistent decision-making process. Moreover, these improvements have an impact on the performance and environment of the hospital. Finally, Lei, Na, Xin, & Fan (2014) study the bed planning problem, centered in a gynecological ward. The authors propose a MIP model, where the patient's length of stay is considered determined, that is, once the patient is admited the bed will be assigned for a fixed period of time. Furthermore, a stochastic model is also proposed in which the length of stay is to be described. A comparison is made between the models, showing that the stochastic model is able to guarantee a better solution, generating better bed planning arrangements with lower potential schedule conflict costs.

5.1.3 Blood Collection

Blood is a crucial component used in multiple medical interventions, and consequently having a major role in the health care systems worldwide. Being only produced by humans, blood is a limited resource. Moreover, it cannot be stored for long periods of time due to its short shelf life, which means the time between donation and utilization is bounded. The Blood Donation system is responsible for providing suitable amounts of blood units to supply the demand from hospitals and transfusion centres. Within the Blood Donation supply chain, the first and most important step is blood collection. The number of donations has to be great enough not only to provide reliable blood units, and therefore meet demand requests, but also to maintain the throughput of the Blood Donation system in the following steps. With an appointment scheduling of blood donors for efficient management of arrivals, the number of donations at the overall system can be improved (Güre, Carello, Lanzarone, & Yalçındağ, 2018).

Alfonso, Xie, & Augusto (2012) goal is to determine the optimal appointment schedules of scheduled donors in order to minimize the total waiting time of all donors in a day. Subsequently, the steady-state performances of the queueing network are used to approximate the waiting times of all patients arriving in an hourly period. The authors present a mixed-integer non-linear programming model (MINLP) to schedule appointments of plasma and platelets donors in a blood collection system. Additionally, random walk-in donors are also considered as donors in the model. Afterwards, comparisons are performed and it is possible to conclude that combining the queueing-based approximation and optimization approach is a competitive method. In another study, the same authors develop an optimization model of queue dynamics for fixed-site capacity planning and blood donors' appointment scheduling in order to improve various performance measures, such as the service level given to the donors, the system overtime, and the total waiting time of donors. The mathematical model is formulated as multi-criteria MIP and the blood collection system is simplified to a M/M/S(t) system. The authors conclude that combining a queueing-based approximation and mathematical programming approach is useful in regard to the scheduling of appointments of donors (Alfonso, Xie, & Augusto, 2015). Mobasher, Ekici, & Özener (2015) address the collection and appointment scheduling operations at the blood donation sites, calling it the Integrated Collection and Appointment Scheduling Problem. The authors' aim is to maximize the number of donated blood units that can be collected and delivered to a processing centre within the processing time limit for platelet extraction (i.e. six hours). A MILP model is proposed along with a heuristic algorithm called Integer Programming Based Algorithm. The results obtained show that the proposed heuristic provides better solutions with less computation time. Lastly, Baş, Carello, Lanzarone, & Yalçındağ (2018) consider the Blood Donation Appointment Scheduling problem, with the goal of balancing the production of the different blood types in order to provide a continuous supply of units to the blood donation system. To achieve this goal, a framework for the appointment reservation that accounts for both booked and walk-in donors. The framework consists of a MILP model to preallocate time slots of the different blood types, and a prioritization policy to assign the preallocated slots. The approach proposed is tested on a real blood collection centre, and the results show the capability of the approach to balance the production of the different blood types.

5.1.4 Appointment Scheduling

The Appointment Scheduling Problem is present in multiple service settings, such as airlines, notarial services, health care, among many others. This problem mainly arises when it is customary to serve the customers sequentially, service times are uncertain, and most commonly, when it is necessary to assign time slots for booking customers beforehand (Mittal, Schulz, & Stiller, 2012). In the health care environment, appointment scheduling is an activity with extreme importance, as it is vital to ensure the good performance of the hospital or medical centre along with patient satisfaction, the high quality of the care delivered and the high rates of resource utilization.

Xue, Li, & Xuan (2018) study the appointment system for both patients requiring conventional treatments, such as routine examinations, and patients in need of emergency care. The authors develop a joint planning and scheduling model for fixed-length diagnosis and treatment time, in which the objective is to minimize the average waiting time and overtime. The optimal schedule of patients is given through a precise neighbourhood search algorithm, where experiments show that no-show probability has a significant impact on overbooking and, consequently, on the system's performance. This way, it is suggested that is preferable to overbook in order to mitigate the influence of no-shows rather than allowing random walk-in patients. Additionally, patients who require emergency treatment should be scheduled at the beginning of the clinic cycle. Yan & Tang (2015) also study the appointment scheduling system of a clinic. Therefore, they propose a sequential appointment scheduling method to determine the optimal booking number of patients and the optimal scheduling time for each patient. To find the optimal solution, a myopic scheduling algorithm, that considers waiting time, idleness, overtime and patient's preferences, is developed. Results show the existence of an optimal solution and the number of patients seen in a day can be increased if patient choice is allowed.

Ala & Chen (2020) goal is to optimize the appointment scheduling problems in healthcare by reducing patient's waiting time and obtain patient's satisfaction. In order to so, the authors propose an integer programming model with a Tabu search approach, as well as a simulation approach. Through an analysis of the results, it is possible to conclude that the model presented is capable of significantly decreasing the operating room idle time and overtime. Zhou & Lou (2017) study the problem of outpatient appointment scheduling window considering patient no-show, with the objective of minimizing the sum cost of patient waiting time and doctor idle time. The authors develop an M/M/1/N model by applying the queuing theory. The effectiveness of the model is proved by numerical experiments and the efficiency of the appointment system is improved.

Zhou & Yue (2019) consider an appointment scheduling problem in multi-stage sequential systems, where it is necessary to determine an appointment time for each patient in the first stage to minimize the total expected weighted costs of customers' waiting times. The authors develop an L-shaped algorithm to solve the two-stage stochastic model, where it is assumed that customers' service time is random and customers arrive at the service system punctually. The conclusion reached is that the relationships among idle and waiting times in different stages can be formulated as linear equations and that the multi-stage appointment scheduling problem can be modelled as a two-stage stochastic program. The same authors address a joint sequencing and scheduling appointments problem with stochastic service times and no-shows in multi-stage service systems as well. This paper shares the same objectives as the one mentioned above. Firstly, the problem is formulated as a stochastic program and then transformed into a two-stage optimization problem. The authors propose a Benders decomposition-based algorithm with the aim of finding a near-optimal solution. Computational results show the efficiency and good performance of the algorithm and methodology (Zhou & Yue, 2021). Erdogan, Gose, & Denton (2015) also present a two-stage stochastic mixed integer program for dynamic sequencing and scheduling of appointments. In their study, the service durations and the number of customers to be served on a certain day are considered uncertain. To solve the model presented, an L-shape method is implemented. The authors conclude that the numerical experiments give insights into optimal sequencing and scheduling decisions.

Chen, Robielos, Palaña, Valencia, & Chen (2015) study the best solutions of four different appointment scheduling policies, those being constant arrival (i.e. a constant number of patients arrived at a constant time period irrespectively from the service needed), mixed patient arrival (i.e. contrary to the former policy, variable number of patient arrivals at different time intervals), three-section pattern arrival (i.e. arrivals during the day are divided into three sections, each with its own group of constraints similar to the constant arrival policy), and irregular arrival. Depending on the KPI hospital managers want to improve an appropriate appointment policy is suggested. The results obtained from the simulation tests show how useful the outcomes from these policies are to hospital managers. Lastly, Ahmed, Chou, & Shehadeh (2014) investigate the joint effects of patient appointment scheduling and selection. The Appointment Scheduling Rule is associated with patient arrivals and the Selection Rule is related to the patient assignment to multiple doctors. The simulation analysis is performed through ANOVA, whereas to determine the rule that led to the minimum patient waiting time and doctor's idle time a data envelopment analysis is applied. The experimental results show that when considering both rules simultaneously a higher efficiency is achieved, rather than considering only the Appointment Scheduling Rule.

5.1.5 Home Healthcare

By definition, home healthcare is any sort of care given to a patient at his own home instead of in a hospital or medical centre. This type of service is rapidly becoming one of the most important in the healthcare sector, due to alleviating the flow in hospitals. Moreover, the standard of living of the patients is greater, as they are able to reside in the comfort of their own homes, and unnecessary hospitalizations are avoided. Home healthcare managers provide the nurses and caregivers with an effective route and schedule to minimize total travel time and costs and deliver high quality care to the patients (Yang, Ni, & Yang, 2021).

Restrepo, Rousseau, & Vallée (2020) present a two-stage stochastic programming model for integrated staffing and scheduling in home healthcare. It is specified that first-stage decisions correspond to staff dimensioning and the allocation of caregivers to schedules, whereas second-stage decisions correlated with the temporary reallocation of caregivers to neighbour district and to contact other caregivers to work on their day off. The proposed model is tested on real-world instances and the respective results demonstrate that using flexible recourse actions minimizes the total costs while simultaneously improving the service level and resource utilization.

Yang, Ni, & Yang (2021) propose an uncertain programming model for a multi-objective home healthcare routing and scheduling problem. When formulating the model, the authors consider uncertain travel and service times, having as objective the minimization of the routing cost and the improvement of the service consistency and workload balance. To solve the model an improved multi-objective artificial bee colony metaheuristic that integrates the large neighbourhood search heuristic is applied. After computational experiments, the efficiency of the model is verified. Additionally, the authors execute a trade-off analysis where it is possible to conclude that a great improvement on the workload balance can be achieved with little deterioration in caregiver consistency.

An, Kim, Jeong, & Kim (2012) consider a scheduling problem in a home healthcare system in which nurses visit patients regularly for minor healthcare services. The authors aim to determine the visiting schedule with the objective of minimizing total travel time of the nurse over the planning horizon. Consequently, a two-phase heuristic algorithm is developed. The results obtained from computational experiments demonstrate that the heuristic algorithm gave near-optimal solutions in a reasonable amount of time and that it can be put into practice for scheduling healthcare services in home healthcare systems.

Demirbilek, Branke, & Strauss (2021) consider a problem where the decision of patient assignment must be made immediately after the request for home healthcare. Patients are then serviced on the same days and times by the same nurse. This study’s objective is to maximize the number of patients visits for a set of nurses during the planning horizon. Having this in consideration, the authors propose a new heuristic based on generating multiple scenarios that include the nurses’ current schedule and the new request for care, as well as randomly generated requests that pose as possible future demand. Through the results derived from a comparison of the proposed approach with a greedy heuristic, one can observe a significant increase in average daily visits and a decrease in daily travel times per visit for each scenario.

5.2 Conclusions

In this chapter, a research review with the purpose to provide an overview of the existing literature of various scheduling and assignment problems is presented. The problems are divided into five different categories, namely, Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare. After extensive research on scheduling problems, where numerous industries and sectors were included, ranging from manufacturing processes to transportation scheduling, the categories mentioned above were selected to perform a more detailed review and an analysis of the respective integrated problems. The reason for choosing these categories was based on certain factors, such as the number of papers and studies present in the literature for each group of problems, and most importantly, the possibility of parallelism with the Operating Room Planning and Scheduling problems, that is, the MSS and ECS problems. This possibility was assessed through the features of the problems researched. Among these features are included the scheduling of dates and time slots, the allocation of resources, the development of an optimal schedule under various objectives, such as minimization of waiting times and improvement of patient satisfaction, and lastly, the simultaneous presence of these features.

This review shows that the main characteristics in common between each problem presented are capacity constraints, limited resources, as well as time slots determination. For example, for scheduling a certain university exam, an adequate and large enough room must be determined, in addition to a suitable time slot and specific date. Moreover, there are other elements present in more than one problem, such as patient prioritization and patient’s preferences. Lastly, none of the problems introduced in this research review has adapted or compared the respective different methodologies and solutions with the Master Surgery Scheduling and Elective Case Scheduling problems. To be able to apply them to the Operating Room Planning and Scheduling context, the MSS and ECS problems must be positioned in this general scheduling review. Through this analysis, it will be possible to understand which of the most studied features in the studies of this review are present or not in the literature of the MSS and ECS problems.

6. Positioning the MSS and ECS Problems

With the objective of positioning the Master Surgery Scheduling and the Elective Case Scheduling problems in the review of certain general scheduling problems, provided in the previous chapter of this document, multiple features and performance measures prevalent in both reviews will be highlighted. In this chapter, a critical analysis will be performed to determine in which problems are those features present or not, and in the case that they are, where are they most common. Among these features are the patient preferences, patient prioritization, workload balance, clustering, fairness, staff preferences, and uncertainty. Additionally, this comparison will facilitate and contribute to the identification of the general scheduling and assignment problems that are most closely related to the MSS and ECS problems.

6.1 Patient Preferences

Patient preferences can be understood as the decisions between different options patients have to make regarding their treatment in healthcare, for example, preference for a certain surgeon. According to Gärtner et al. (2019), certain medical disciplines are more prone to preference-sensitive decisions, such as orthopaedics and oncology. The reason so is because the treatments that are performed in these specialties are burdensome, in addition to having limited benefits and potentially impacting the patient's quality of life. However, patient preferences are rarely used for determining the surgical operating time. As a matter of fact, patient preferences are not usually included in the Operating Room Planning and Scheduling problems even though taking them into consideration when planning an OR schedule increases patient satisfaction and continuance in treatments. In the MSS and ECS problems, it is more frequent to incorporate the surgeon's or the department's preferences rather than the patient's (Aggarwal, Harris, & Naylor, 2016).

On the other hand, there are multiple subjects in which patient preferences are well studied and incorporated into the respective problems. In the matter of the problems addressed in the review of Chapter 4, Bed Assignment, Appointment Scheduling and Home Healthcare are the ones that take into account patient's preferences most frequently.

In the Bed Assignment context, a patient may demonstrate preferences for the capacity of the room they will be occupying (e.g. single or double bedroom), the gender of the patients sharing the room, and the type of diagnosis which will lead to the specific type of bed. Researches include patients preferences as a set of constraints in the different models developed, giving penalties when these preferences are not met (Guido, Groccia, & Conforti, 2018; Monroy, Ramírez, Neira, Caicedo, & Sánchez, 2021; Schäfer, Walther, Hübner, & Kuhn, 2019; Schmidt, Geisler, & Spreckelsen, 2013; Dorgham, Ben-Romdhane, Nouaouri, & Krichen, 2020).

Appointment scheduling is another scenario where patient preferences are regularly involved in the decisions made in each problem. After being given a set of options from the healthcare facility, patients preferences refer to the time slot and day of the appointment and the preferred physician or medical staff. In the appointment booking problem, it is also necessary to account for different types of patients, which will have distinct preferences. Additionally, there is uncertainty regarding these preferences as they may change over time. Several studies recognize the difficultly of accommodating patients preferences with real-time responses concerning appointment requests but, nonetheless, incorporate it into their models with the objective of ensuring patient satisfaction and minimizing patient no-show probabilities (Wang & Gupta, 2011; Feldman, Liu, Topaloglu, & Ziya, 2012; Wang & Fung, 2015; Tunçalp & Örmeci, 2019; Yan, Huang, Kuo, & Tang, 2021).

Home healthcare in itself already takes patient preferences into consideration. In other words, the patient chose to receive care at home rather than staying hospitalized in a medical facility. Other choices present in this environment are mainly focused on the home visit times and the nurse assignment. Furthermore, there are studies where the priority of the preferences of the patients are considered, being assigned weights depending on the importance of each preference (Mutingi & Mbohwa, 2013; Lin, Liu, & Lin, 2019; Brennan & Strombom, 1998).

Other categories of scheduling problems, such as Instructional Scheduling and Blood Collection, do not frequently incorporate patient preferences. In the former group of scheduling problems, students are equivalent to patients, since they are the ones being served by the system, and their preference for not having scheduled more than one exam per day is somewhat considered by some researchers (Güler, Geçici, Köroğlu, & Becit, 2021). In the latter group, it is observed that patients may choose between a preferred day and period from different options (Baş, Carello, Lanzarone, & Yalçındağ, 2018).

In Figure 4 it is possible to observe how Patient Preferences are distributed in the different groups of general scheduling problems. For this analysis, it was taken into consideration every article included in the literature reviews of both Chapters 3 and 5 of this dissertation. Appointment Scheduling and Bed Assignment are two categories in which this feature is widely considered and studied, whereas, in the groups of Blood Collection and OR Planning and Scheduling Problems, it is not as thoroughly contemplated.

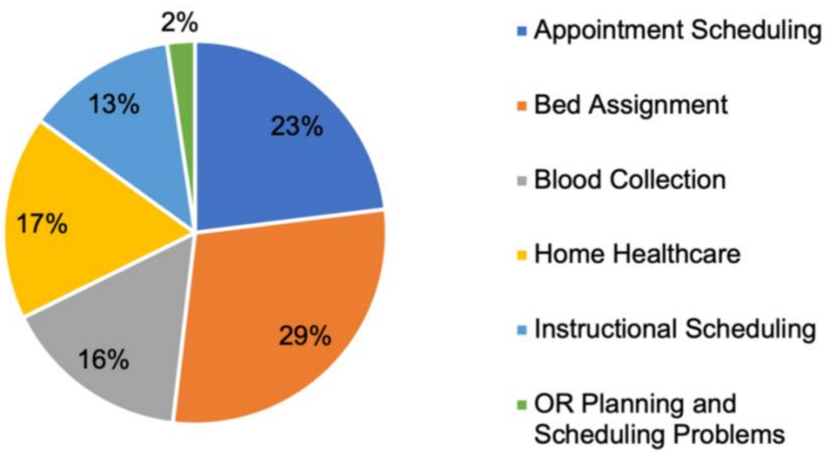

Figure 4. Distribution of Patient Preferences within the groups of scheduling problems

6.2 Patient Prioritization

When constructing a Master Surgery Schedule and, therefore, scheduling the details for several surgeries, there is a priority order of patients. For example, in Portugal, the system for scheduling surgeries and selecting patients from waiting lists follows a certain order of priority. The level of priority differs accordingly with the clinical urgency of the treatment the patient requires. This way, the Operating Room Planning and Scheduling problems, namely, the MSS and ECS problems, are well acquainted with prioritizing patients when establishing the weekly/monthly surgery schedules. Various authors state that considering patient priority results in significant differences in the surgery schedule when compared to one that does not consider it. It is reached the conclusion that not incorporating priorities regarding patients can lead to inefficient schedules and, consequently, reduce patient satisfaction (Min & Yih, 2010; Durán, Rey, & Wolff, 2017).

Similarly to Patient Preferences, in the Bed Assignment context, the prioritization of patients is a common occurrence. Patients are divided into priority groups reflecting the treatment urgency, which are then controlled to not exhaust specific resources needed for each group. For instance, patients in the highest priority group may have a longer length of stay and occupy a bed for more days than a patient with lower priority. In the literature, the factors which influence patient priority the most in the bed assignment problem are, from highest to lowest importance, treatment type, ward subspecialty, days in waiting, patient's room preference. These factors are formulated as attributes with different weights (Schmidt, Geisler, & Spreckelsen, 2013; Tsai & Lin, 2014).

In the Blood Collection problems, depending on the donation centre, different priority rules may apply to distinguish between scheduled donors and random walk-ins. In the case of those rules, scheduled donors usually have priority over the walk-in donors and, therefore, have a shorter waiting time (Alfonso, Xie, & Augusto, 2012).

Within the framework of the Appointment Booking Problem, patient prioritization is very present as well. Moreover, when booking and scheduling appointments, different priority rules are applied. Primarily, it is common practice that patients with appointments are given a higher priority than random walk-ins. However, certain walk-ins have to be treated immediately, being placed ahead of the scheduled patients. Furthermore, patients requesting appointments are scheduled depending on the type of treatment, that is, if more than one type of equipment is necessary, as well as on the probability of the patient being prompt or not. First-come-first-served is also an appointment system traditionally used, however, for more complex situations, for example, healthcare, researchers opt for other rules, such as the ones mentioned above (Tsai & Teng, 2014; Li, Li, Zhang, & Kong, 2021; Guo & Yao, 2019; Borgman, Vliegen, Boucherie, & Hans, 2018).

In the context of Home Healthcare, certain patients, those with higher priority, need to be visited before other patients. Several factors influence the priority each patient has, those being: the existence of wounds, depression, limitation in current toileting status, number of conditions, and so forth. Decision support systems developed by researchers aim to determine which patients should receive priority, having into account all the factors listed previously, to minimize rehospitalization (Topaz, Trifilio, Maloney, Bar-Bachar, & Bowles, 2018).

Patient prioritization is not a feature present in Instructional Scheduling, considering students as the patients, this being the reason why it is not featured in this subsection.

Figure 5 illustrates the presence of Patient Prioritization as a feature in the scheduling problems. As previously mentioned, in the MSS and ECS problems, researchers frequently study how different patient priority rules affect patient satisfaction and the overall performance and efficacy of the developed surgical schedules. In the Appointment Scheduling and Bed Assignment frameworks, patient prioritization is also often taken into account. On the other hand, in Instructional Scheduling, the priority of patients, which, in this case, are the students, is not a characteristic observed in the respective problems.

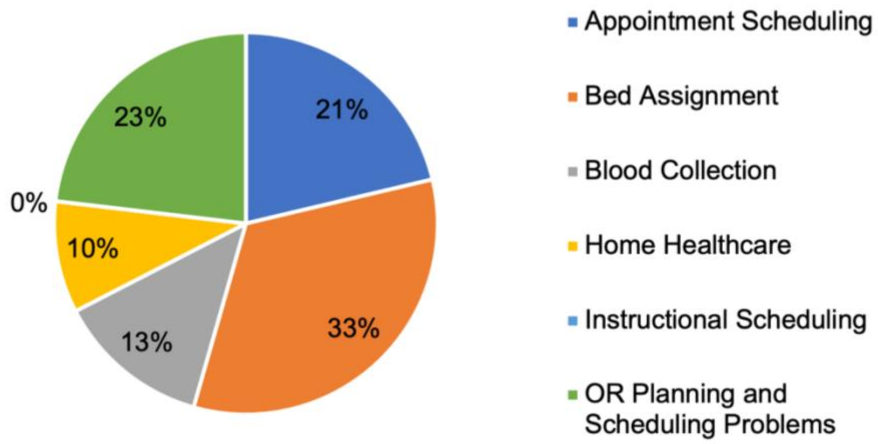

Figure 5. Distribution of Patient Prioritization within the groups of scheduling problems

6.3 Workload Balance

A well though-out master surgery scheduling is of extreme importance in the operating room scheduling process, since it is responsible for determining the workload distribution. Subsequently, it is the objective of the elective case schedule to schedule surgical procedures and ensure the even distribution of the workload, since a significant number of patients are associated with a specific surgeon and surgeons prefer to have their workload centralized instead of dispersed cases throughout the day. Within the scope of the MSS and ECS problems, workload is an element incorporated into several studies. Time and resource allocation are among the factors why workload balance has such a great significance in the surgical activities schedule. Furthermore, in the literature, workload is studied in various distinct settings. These include the downstream and upstream units, which may negatively impact the OR performance when not integrated into the MSS problem (Aringhieri, Landa, & Tànfani, 2015a; Dexter & Traub, 2002; Vanberkel, et al., 2011).

Within the framework of Instructional Scheduling, in the exam scheduling problem, the workload of multiples elements is studied depending on the perspective and objective of the researchers. Some authors focus more on balancing student's workload during exams, while others address the professors and instructors participating in the exams, whether by supervising or teaching a course. Since the task of creating an optimal exam scheduling is essentially not possible, due to the great number of students taking different courses and not the same amount of exams, as well as the requests from the faculty staff, researchers often opt for creating a balanced exam scheduling to avoid conflicts, in which each element's workload is evenly distributed (Cavdur & Kose, 2016; Khan & Sahai, 2020; Güler, Geçici, Köroğlu, & Becit, 2021).

In the context of Bed Assignment problems, researchers often include in the respective models developed constraints to limit and balance the workload of the bed-management staff since they are responsible for patient flow, patient care, and resource utilization when assigning patients to beds (Thomas, et al., 2013; Schäfer, Walther, Hübner, & Kuhn, 2019).

Workload balance is briefly introduced in the framework of Blood Collection. Some studies aim to schedule a certain number of donations spread throughout a specific time interval in order to maximise resources utilization and improve the workload balance (Mobasher, Ekici, & Özener, 2015).

When researchers address the Appointment Scheduling problem, workload balance rarely is the focal point of the study. However, balancing workload is important when it comes to improving the quality of the service provided to the patients by the medical staff, and, subsequently, to patient satisfaction. Be that as it may, workload balance is, to some extent, present in the literature of problems regarding appointment booking. This feature is usually formulated into the models developed as constraints, for example, each member of the medical staff cannot exceed a specific number of hours working continuously (Yan, Huang, Kuo, & Tang, 2021; Heshmat, Nakata, & Eltawil, 2018).

Workload balance is an extremely discussed matter in the home healthcare context. When planning routes and scheduling home visits, nurses' workload must be taken into account in order to control that the number of assignments of each nurse is not excessive and to ensure the continuity of care. Included in the workload of the caregivers may be the travel time, the time spent in the patient's home providing treatments, as well as the idle time, depending on the problem being studied. Several researchers objective is to minimize total travel time and maximize patient satisfaction while simultaneously balancing the workload of caregivers. Distinct methods applied by different authors were able to provide schedules that met every objective (Demirbilek, Branke, & Strauss, 2021; Decerle, Grunder, Hassan, & Barakat, 2018; Errarhout, Kharraja, & Corbier, 2016).

In Figure 6 it is summarized the distribution of Workload Balance throughout the different groups of general scheduling problems. OR Planning and Scheduling problems and Appointment Scheduling are the two categories with the higher concentration of problems considering workload balance. The remaining categories also incorporate this characteristic into the respective problems, however, not as frequently as the mentioned above.

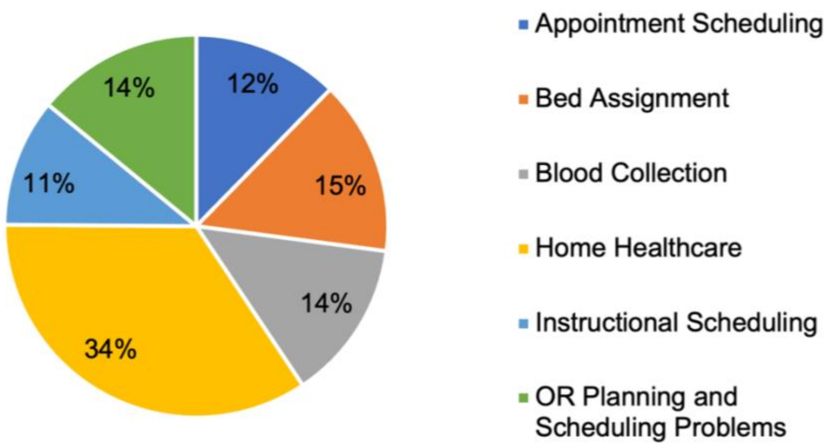

Figure 6. Distribution of Workload Balance within the groups of scheduling problems

6.4 Clustering

One understands clustering as dividing a certain number of similar things and grouping them closely together, forming clusters. For example, grouping together surgeries depending on their type or strategically combining medical departments into clusters. Within the Master Surgery Scheduling and Elective Case Scheduling problems, clustering is not very present, however, in recent years, interest has been growing. There are only a few studies where clustering methods and cluster analysis are used to maximize the benefits of a master surgery schedule, and, subsequently, reduce waiting lists and variability in resource demand for multiple surgical procedures. In these studies, the researchers cluster surgical activities mainly according to the types of surgery and surgery duration. (Oostrum, Parlevliet, Wagelmans, & Kazemier, 2011; Santoso, Sudiarso, Masruroh, & Herliansyah, 2018).

Clustering approaches are also put into practice when it comes to exam scheduling. In this setting, students are grouped into clusters depending on the similarity between the combination of subjects being taken by each student. Following this stage, an exam timetable is arranged where it is attempted to minimize the consecutive exams a student has to take in one day (To & Win, 2010).

Within the medical resource allocation domain, such as bed assignment, clustering strategies have positively contributed to its performance and efficiency. For the Bed Assignment problem, researchers often present models to merge clinical departments into clusters and afterwards, assign them to an available ward and determine the optimal number of beds in each ward. The reason so is because beds are a bottleneck resource and clustering departments reduces the probability of a patient not being able to be admitted (Hübner, Walther, & Kuhn, 2016; Essen, Houdenhoven, & Hurink, 2015).

Regarding the Appointment Scheduling problem, only a few studies incorporate clustering methods. These methods are applied to classify outpatients into different priority classes, as well as to determine the optimal number of patients to integrate a cluster. This represents the first stage of certain appointment booking problems where the main objectives are minimizing the total completion time of a treatment and the waiting times (Yousefi, Hasankhani, & Kiani, 2019; Heshmat, Nakata, & Eltawil, 2018).

Lastly, in the Home Healthcare setting, multiple clustering methodologies are proposed to deal with the staff scheduling problem. Among the studies where these methodologies are applied, clusters are formed accordingly with the type of task to be performed, the duration of the home visit, geographical location, among others. Once the clusters are formed, depending on the respective objectives of the problem, different algorithms are proposed to find an optimal or near-optimal schedule for the caregivers home visits (Quintana, Cervantes, Saez, & Isasi, 2017).

Figure 7 represents the distribution of which scheduling categories have clustering incorporated as an element in their respective problems. In the Home Healthcare, Bed Assignment, and Instructional Scheduling frameworks, clustering methods are often applied to achieve the objectives of a certain problem.

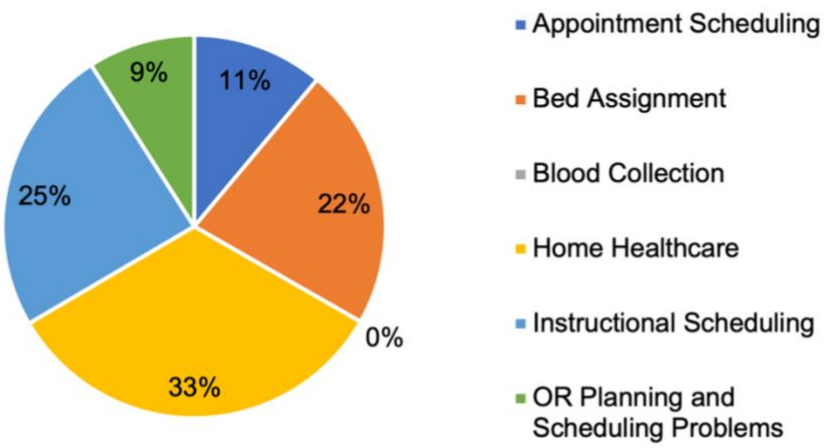

Figure 7. Distribution of Clustering within the groups of scheduling problems

6.5 Fairness

Fairness can be defined as the equality of characteristics among numerous individuals in a certain situation. Within the context of the Master Surgery Scheduling problem, fairness can be analysed through different perspectives. In the literature, some authors study fairness regarding the order that patients are treated, while others focus on fairly scheduling the nurses and other medical staff, based on their preferences (Devesse, Santos, & Toledo, 2017). Having this in consideration, fairness rarely is the main focus of the problem's objectives, being only included as constraints to improve patient's satisfaction or to avoid conflicts between staff members' schedules. Furthermore, in multiple hospitals, First Come First Served is the main scheduling rule for attending patients that incorporates a fairness perspective. However, several researchers have shown that this is not the most effective scheduling rule and often opt for combining multiple scheduling policies into one in order to meet their objectives (Liang, Guo, & Fung, 2015).

Fairness is a feature that is frequently incorporated into the problems regarding examination scheduling, mainly from the students' perspective. The motivation for this is the improvement of the students' satisfaction, as well as their well-being. Generally, when formulating their models, researchers assign penalties depending on if the student has its exams evenly spread or closer together, corresponding to small and large penalties (Muklason, Parkes, McCollum, & Ozcan, 2010).

In the problems regarding appointment scheduling, service fairness is a characteristic that has been present throughout the years. Fairness in this scenario is frequently associated with the patient waiting time and satisfaction. Multiple researchers, as a method of integrating service fairness into their model, consider it as a constraint, formulated as the standard deviation, the variance or additionally the difference between the maximum and minimum average waiting times among intervals (Yan, Tang, Jiang, & Fung, 2015; Zander & Mohring, 2016; Qi, 2016; Turkcan, Zeng, Muthuraman, & Lawley, 2011).

Within the framework of Home Healthcare problems, researchers make no distinction between workload balance and fairness (Borchani, Masmoudi, & Jarboui, 2019). Thus, they are simultaneously addressed in Subsection 6.3. Additionally, both in Bed Assignment and Blood Collection respective problems, fairness is an element that is not present, this being the reason why it is not analysed in this subsection.

In Figure 8 the distribution of Fairness throughout the different groups of scheduling problems is presented. Home Healthcare is the category in which fairness is most often considered by researchers. Appointment and Instructional Scheduling problems also integrate the fairness component, however, not as regularly. Further to previously stated, it is possible to observe that in Bed Assignment and Blood Collection problems, fairness is not a considered criterion.

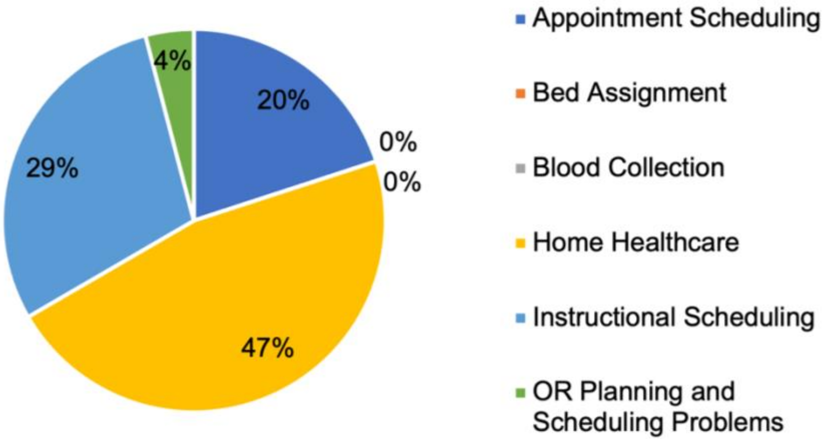

Figure 8. Distribution of Fairness within the groups of scheduling problems

6.6 Staff Preferences

For the most part, in the Master Surgery Scheduling and Elective Case Scheduling setting, the staff members included in the problems are the surgeons and the nurses. Surgeons and nurses' preferences are similar when it comes to the planning of their shifts. Both categories of staff have time slots and particular days of the week they prefer to work and additionally, they both prefer to work continuously in the same OR rather than change from one room to another in the middle of their respective shifts. Moreover, surgeons may present a preference for specific ORs where it is possible to work back-to-back, as well as for the same surgical team. Respecting and fulfilling these preferences contributes positively to staff satisfaction and improves staff retention. Therefore, staff preferences have been extensively included and studied in the Operating Room Planning and Scheduling problems (Park, Kim, Eom, & Choi, 2021; Bandi & Gupta, 2020; Jafari & Salmasi, 2015).

When scheduling exams or university classes, the teaching staff has some preferences regarding their courses and working hours, as well as the number of exams to monitor. More specifically, teachers prefer to have classes from the same course with, at least, one day apart from each other, to not overburden the students, while, simultaneously, opting for time slots where the attendance is not negatively impacted (Bedem, 2016; Hanum, Romliyah, & Bakhtiar, 2015).

As previously mentioned in this chapter, patient preferences are, for the most part, considered in the decisions in the Appointment Scheduling problem. However, staff preferences are not as regularly taken into account, as they are, for example, in elective surgery scheduling. Various rostering methodologies are applied, depending on the class of the problem, in order to distribute shifts equally between workers and to accommodate certain medical personnel preferences. Among these preferences, there are a few in respect to the time slots and days favoured to perform certain types of procedures or to have specific consults, while others regard the flexibility of the staff member to double booking and to work overtime (Ernst, Jiang, Krishnamoorthy, & Sier, 2004; Gupta & Denton, 2008).

The Home Healthcare Scheduling problem addresses the decisions involved in creating a home visit schedule for the caregivers. Staff preferences are not often prioritized in this process of decision-making. Nevertheless, some researchers integrate into their model and attempt to satisfy preferences regarding flexible work shifts and workload, full or part-time schedule, together with requests for days off (Mutingi & Mbohwa, 2014).

The literature on blood collection scheduling and bed assignment problems does not have relevant studies where staff preferences are included in the problems.

Figure 9 illustrates the presence of Staff Preferences as a feature in the scheduling problems. As previously mentioned, in the MSS and ECS problems, researchers incorporate staff preferences into their models very frequently. In the Appointment Scheduling, Bed Assignment, and Blood Collection frameworks, staff preferences are, for the most part, not taken into account. On the other hand, in Instructional Scheduling and Home Healthcare problems, fairness is frequently considered by researchers.

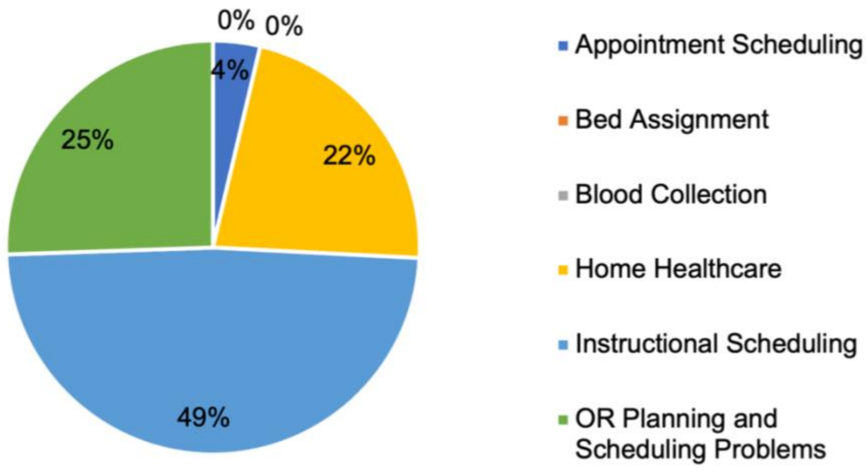

Figure 9. Distribution of Staff Preferences within the groups of scheduling problems

6.7 Uncertainty

As previously explained in Chapter 3 of this document, one of the main features studied and associated with the Master Surgery Scheduling problem is uncertainty, with the majority of papers taking into consideration some type of uncertainty, such as duration uncertainty, arrival uncertainty, and other types, for example, resource uncertainty. For this reason, authors often opt for stochastic approaches instead of deterministic ones, which ignore uncertainty.

Within the Bed Assignment context, uncertainty is also inherent and, therefore, widely studied. The respective optimization problems aiming to maximize the efficiency of bed management deal with very uncertain scenarios. Multiple researchers incorporate into their problems uncertainty largely derived from emergency patient arrivals, length of stay, treatment progression, and discharge dates. Moreover, in the literature, there are papers dealing with both static and dynamic aspects (Schäfer, Walther, Hübner, & Kuhn, 2019; Schmidt, Geisler, & Spreckelsen, 2013).

In the blood collection system, when attempting to develop an effective appointment scheduling system, researchers deal with several issues associated with uncertainty. Among those are included the scheduled donor's arrival, the blood demand coming from hospital and transfusion centers, and random walk-in donors. Predicting the latter is of extreme importance when managing and dimensioning the collection system (Güre, Carello, Lanzarone, & Yalçındağ, 2018). However, in the literature, uncertainty is not as present in problems regarding the blood collection system as in the other scheduling categories.

As expected, in the general appointment scheduling setting, uncertainty is extensively integrated into various problems as well. In which case, stochastic service times, customer no-shows, and customers with non-punctual behavior are the principal sources of uncertainty. Furthermore, some authors also consider the number of patients to be served on a specific day to be uncertain and, depending on the type of clinic, urgent care may be considered, which is inherently uncertain. This way, the majority of the papers introduce stochastic optimization models instead of deterministic ones (Zhou & Yue, 2021; Erdogan, Gose, & Denton, 2015).

Home healthcare scheduling problems are extremely associated with uncertainty-based features. In the literature, problems with stochastic settings have been increasingly more present throughout the years allowing to predict several possible future outcomes. Researchers have started to consider travel and services times as uncertain. This is mainly due to varying traffic conditions and to the physical condition of the patient and the required treatment the nurse has to give, respectively. Additionally, in certain problems, demand is also defined as uncertain to provide more robust solutions. Other uncertainties which are not very common in this context concern the availability of caregivers and the patient's preferences (Yang, Ni, & Yang, 2021; Restrepo, Rousseau, & Vallée, 2020).

Finally, Figure 10 summarizes the distribution of Uncertainty throughout the different groups of general scheduling problems. According to what was previously explained in Chapter 3, the Master Surgery and Elective Case Scheduling problems incorporate a significant amount of uncertainty-based features. Appointment Scheduling, as well as Bed Assignment and Home Healthcare are categories that also consider uncertainty in their respective problems. On the contrary, in Instructional Scheduling problems hardly any researchers regard uncertainty.

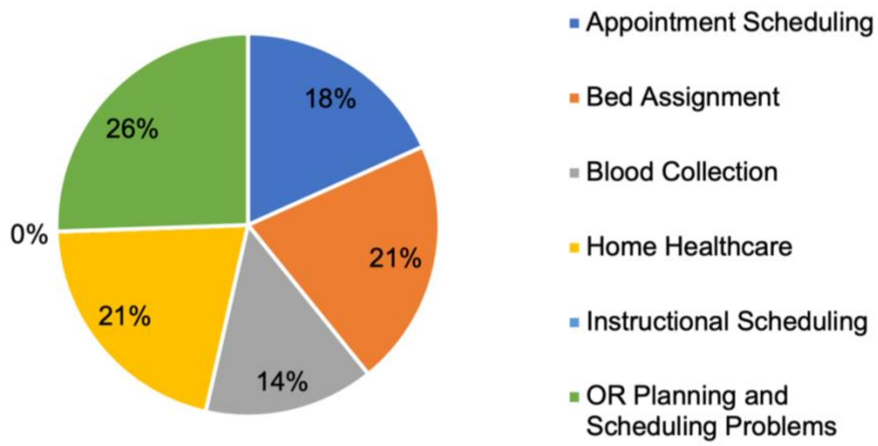

Figure 10. Distribution of Uncertainty within the groups of scheduling problems

6.8 Conclusions

For each category of problems selected, the characteristics mentioned above were included in a descriptive and percentage analysis, allowing to visualize in which problems are those features present or not, and in the case that they are, where are they most common. For this analysis, every study included in the literature reviews of Chapters 3 and 5 was included. It was possible to conclude that characteristics such as patient preference and prioritization are increasingly present in bed assignment and appointment scheduling problems. Workload balance is the prevailing criterion studied in home healthcare, with its presence being more significant than in the other scheduling categories. Additionally, clustering methods and fairness aspects are also vastly incorporated into this group of problems, as well as in instructional scheduling. In the latter category, staff preferences are taken into account, more often than not by researchers when constructing class and exams schedules. Uncertainty is represented in multiple, with emphasis on bed assignment, appointment scheduling and home healthcare. Lastly, in the MSS and ECS problems, the characteristics emphasized are patient prioritization, staff preferences and uncertainty.

7. Discussion of Possible Knowledge Transfer

The following figures presented in this chapter represent how the characteristics previously analyzed are present in the different categories of scheduling problems, and, in addition, whether or not their presence is significant. Thus, it is possible to clearly visualize the lack of research covering certain aspects in a specific scheduling group, and in which other groups that same aspect is thoroughly contemplated. This allows the identification of the similarities and differences between the multiple problems of scheduling mentioned formerly and whether knowledge transfer between the different scheduling categories is possible or not.

7.1 Research Gaps in Scheduling Problems

As demonstrated in the previous chapter, within the Master Surgery and Elective Case Scheduling problems certain characteristics are more contemplated than others. Each characteristic has a different relevance and is integrated into a problem depending on the objective of the researchers.

Patient satisfaction is extremely important in the sector of healthcare, as it indicates the quality of the services being delivered. One way to increase patient satisfaction is to incorporate patient preferences in the decisions involved when scheduling surgeries (Ahmed & Ali, 2020). On the basis of the problems addressed in the literature review of Chapter 3, this characteristic is rarely studied. Scheduling categories, such as Appointment Scheduling, regularly account for the patient preferences, regarding physician and time slot, when booking appointments. This opens opportunities to transfer knowledge from one group to another.

Within the contexts of surgery waiting lists and surgery scheduling problems, patient prioritization has a significant influence on the patient waiting times and the urgency with which the required surgical procedure is performed, as well as patient satisfaction (SIGA SNS, 2018). In Portugal, different levels of priority are established as a baseline for maximum response and patient waiting times with the objective of reducing these times and guaranteeing equal access to every patient. In OR Planning and Scheduling problems, researchers frequently include this characteristic into the developed models.

Workload balance influences the quality of the service delivered by the medical staff to the patients. Consequently, if the workload is not evenly distributed and well-organized, patient satisfaction may be negatively impacted. This characteristic has been regularly contemplated in the MSS and ECS problems throughout the years. However, in the framework of home healthcare problems, its presence is more significant since the number of activities to be conducted by nurses is substantial and dispersed throughout different locations. This provides a link between the OR scheduling and home healthcare frameworks allowing for knowledge transfer among both problems.

Another feature not very represented in the MSS and ECS problems is clustering. The activity of clustering medical specialties and their respective surgical procedures is capable of maximizing the benefits of a master surgery schedule and, as a result, reducing surgery waiting lists (Santoso, Sudiarso, Masruroh, & Herliansyah, 2018). Once again, in home healthcare problems, clustering methods are frequently applied when constructing schedules. Clusters are formed according to the type of task to be performed and its corresponding duration. Methods applied in these circumstances could be explored in the context of OR scheduling problems.

Fairness is a relevant aspect to consider when constructing schedules. It ensures that the quality of service is consistent and homogeneous, contributing to patient satisfaction, and influences the workload distribution of the medical staff while simultaneously helping to avoid conflicts (Liang, Guo, & Fung, 2015). Both in instructional and appointment scheduling, fairness from the perspective of the patients, is often associated with and formulated as the average patient waiting time. Therefore, patient satisfaction can be improved when considering fairness.

Apart from patient preferences, staff preferences are also a notable characteristic to be considered. This characteristic is very often incorporated into the MSS and ECS problems since it positively impacts the staff satisfaction and retention and, therefore, the continuity of the care delivered (Park, Kim, Eom, & Choi, 2021).

Within the context of healthcare, specifically OR planning, uncertainty is majorly present. Therefore, disregarding this element distances the problem being studied from the reality in hospitals experienced by medical staff and patients. Uncertainty is widely studied in the MSS and ECS problems throughout multiple scenarios, as well as combined with other characteristics.

In Figure 11, the lack of studies incorporating characteristics, such as Patients Preferences, with 2%, Fairness, and Clustering, in the Master Surgery and Elective Case Scheduling problems is demonstrated. Including patient preferences and fair values into the problems increases patient satisfaction significantly, hence, a research opportunity to consider these features is established. On the other hand, Patient Prioritization, Uncertainty, and Staff Preferences have been extensively studied throughout the years.

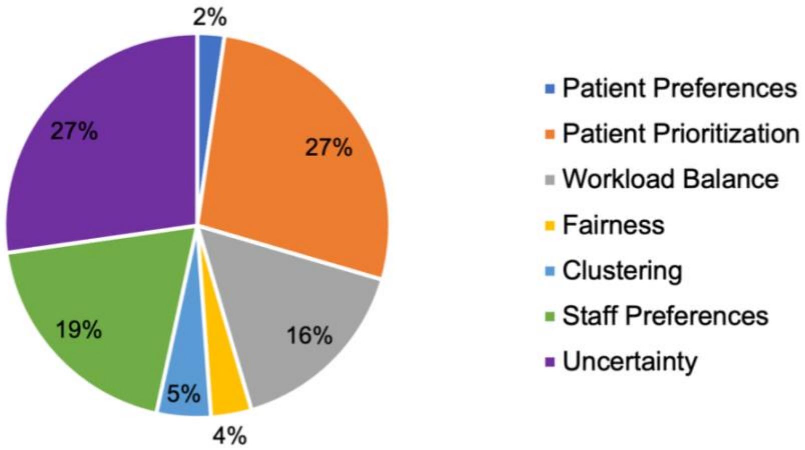

Figure 11. Characteristics treated in OR Planning and Scheduling Problems

Furthermore, the majority of the papers addressing MSS and ECS problems includes more than one of the described characteristics. Through Figure 12, it is possible to observe the most common and the least explored combinations of characteristics being contemplated simultaneously in the considered OR scheduling problems. Uncertainty appears to be the feature more often studied together with others, especially with patient prioritization and staff preferences. Studies that include elective and non-elective patients have to conform to certain priority rules and levels to differentiate the patients. Additionally, apart from uncertainty regarding the length of stay and surgery duration, non-elective patients have an inherent uncertainty associated with them, due to not being possible to predict their arrival to medical centers. Naturally, these two characteristics are frequently incorporated together into problems, for example, in Addis, Carello, & Tànfani (2014) and Zhang, Dridi, & Moudni (2019). Researchers that consider staff preferences, more often than not study scenarios where non-elective patients are also present (Kamran, Karimi, Dellaert, & Demeulemeester, 2019; Bandi & Gupta, 2020). This being the reason why these two characteristics are often simultaneously addressed. Another significant combination is between staff preferences and patient prioritization. Surgeons may present preferences concerning their case mix and diagnosis group. According to these preferences, different priorities and waiting times are assigned for each patient (VanBerkel & Blake, 2007; Pham & Klinkert, 2008). Patient prioritization is also, to some extent, studied together with workload balance.

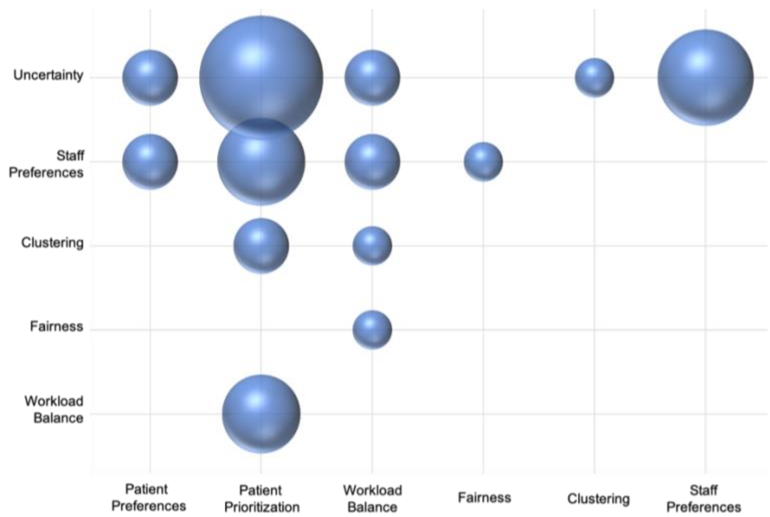

Figure 12. Characteristics addressed simultaneously in an OR Planning and Scheduling Problem

As shown in Figure 13, in the literature, there is an absence of studies regarding instructional scheduling where the prioritization of the students and uncertainty are considered by researchers. However, within the framework of scheduling exams and creating class timetables, it is logical to consider that there are no priority levels between students. Additionally, this contributes to the development of fair and balanced schedules. Moreover, staff preferences and fairness are the two characteristics that appear as the most included in this scheduling category.

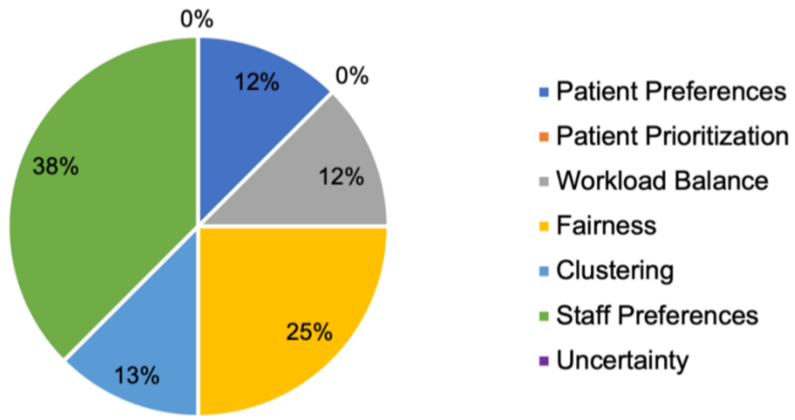

Figure 13. Characteristics treated in Instructional Scheduling Problems

Within the context of bed assignment problems, patient prioritization, as well as, patient preferences are highly addressed and integrated into multiple studies, as it can be observed in Figure 14. Workload balance and uncertainty are also fairly treated in the problem of assigning patients to beds. On the other hand, it is observed a lack of studies accounting for fairness and staff preferences. Be that as it may, considering fairness into a model is significantly important, since it ensures equity in health outcomes for all patients, in addition, to improving patient satisfaction.

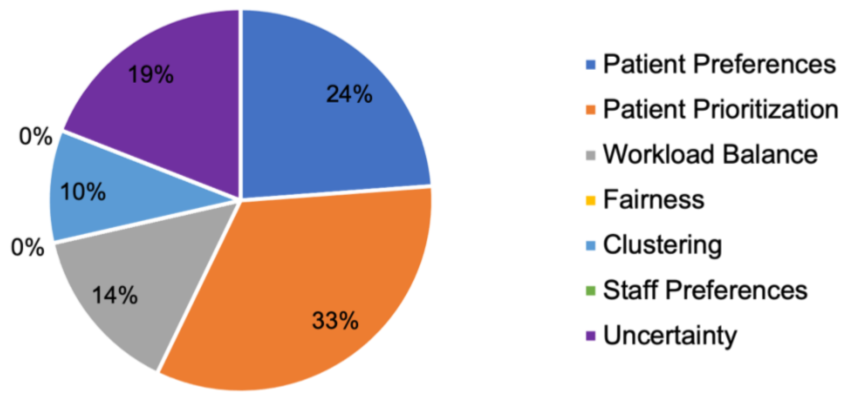

Figure 14. Characteristics treated in Bed Assignment Problems

In the case of problems regarding blood collection systems, the characteristics analysed previously are studied in similar amounts, with the exception of staff preferences and fairness (Figure 15). As explained in further detail in Subsection 6.6, addressing staff preferences has a positive impact when it comes to staff satisfaction and staff retention is also improved. Consequently, the service delivered to the customers/patients is of higher quality and their satisfaction also improves.

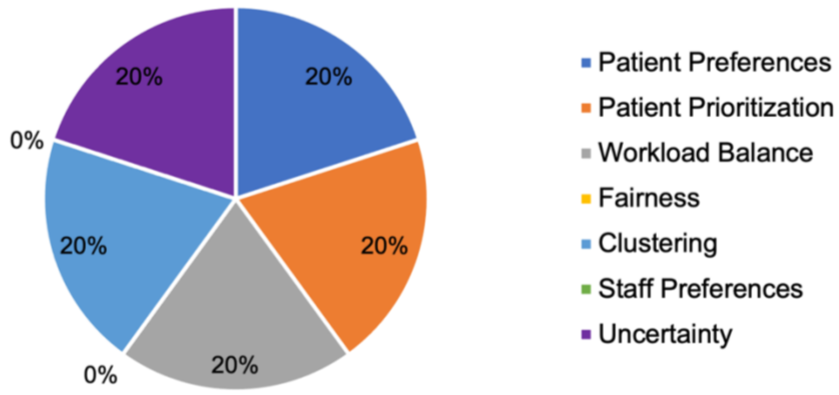

Figure 15. Characteristics treated in Blood Collection Problems

Similarly to Blood Collection problems, in the category of Appointment Scheduling, characteristics such as patient preferences, patient prioritization, and uncertainty, are thoroughly contemplated in various studies. This is demonstrated in Figure 16. Other aspects that appear frequently in the appointment booking problems are fairness and workload balance. Contrastingly, there is a lack of studies including clustering methods and staff preferences. Several authors state that applying clustering methods improves the planning and scheduling and control of patients, therefore increasing the efficiency of resources in the appointment system (Oostrum, Parlevliet, Wagelmans, & Kazemier, 2011).

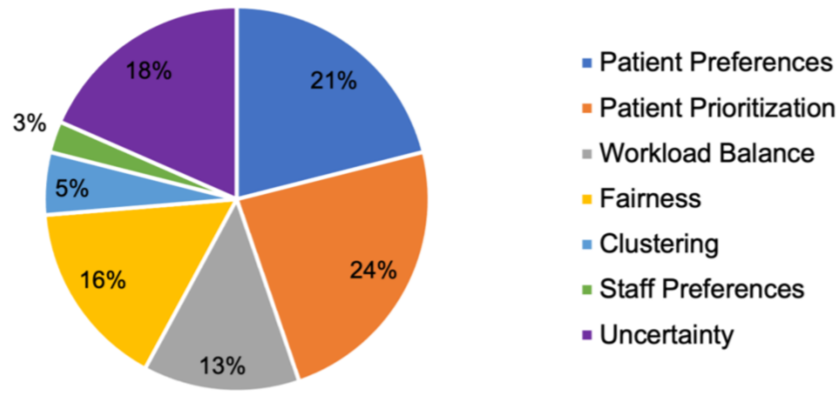

Figure 16. Characteristics treated in Appointment Scheduling Problems

In contrast to the other categories of scheduling problems, in the Home Healthcare context, workload balance and fairness are the aspects that appear as the most analysed in the literature, as it can be observed in Figure 17. Moreover, uncertainty, patient preferences, clustering, and staff preferences are also considerably present in home healthcare problems. Lastly, patient prioritization is not a characteristic regularly incorporated into the problems in question. In the case of home healthcare problems, assigning higher priority levels to some patients may help avoid rehospitalization and improve the quality of the service, and, subsequently, increase patient satisfaction.

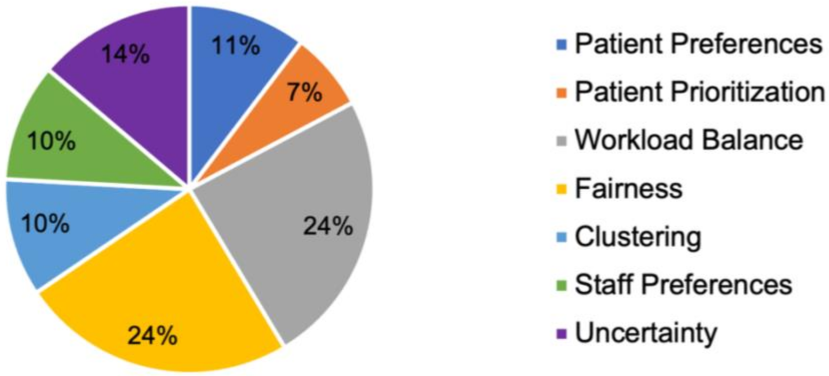

Figure 17. Characteristics treated in Home Healthcare Problems

7.2 Differences and Similarities

In consideration of the foregoing, it is possible to identify the problems most closely related to the Master Surgery and Elective Case Scheduling problems, both generally and specifically, depending on the characteristic in question. This contributes to the discussion of possible knowledge transfer between the different problems addressed in this research.

In the matter of similarities between the various scheduling categories, one can simply observe the figures presented above. Patient prioritization is a common aspect between every group of problems, with the exception of instructional scheduling. However, in this context, students should not have priority over others. This would negatively impact the fairness aspect when constructing timetables or scheduling exams and master theses. Considering workload balance is also recurrent within the problems being studied. OR scheduling and home healthcare problems are the situations where this characteristic is most incorporated into the respective models. Moreover, uncertainty is the most recurrent aspect amidst all the problems present in both reviews in this document, aside from instructional scheduling once more.

Furthermore, with regard to the differences between the OR problems and the ones included in the review of Chapter 5, there are a few which can be clearly identified. Among the problems analysed, the MSS and ECS problems are the only ones that disregard the patient preferences, in comparison to the dimension this characteristic is incorporated in the other scheduling problems. The lack of studies including patient preferences indicates the need for future research in order to reach the same level of engagement of other characteristics. Researchers should then invest more in methods where patient preferences can be contemplated, contributing to the improvement of patient satisfaction. This reasoning is supported by multiple authors stating that patient preferences are linked with augmented patient satisfaction and improved adherence and continuity of treatments (Ahmed & Ali, 2020; Marynissen & Demeulemeester, 2016). Furthermore, patient satisfaction is a performance measure used to evaluate the quality of service delivered, which affects the efficiency and timeliness of the respective service (Prakash, 2010). In this manner, this satisfaction can be achieved by giving patients more flexibility concerning, for example, the physician, the date and the time slot when scheduling surgeries, similarly to how it is done in appointment scheduling (Wang & Fung, 2015) and bed assignment (Guido, Groccia, & Conforti, 2018).

In contrast to patient preferences, staff preferences are majorly contemplated within the OR scheduling context, whereas in the remaining categories, such as appointment scheduling, bed assignment, and blood collection, there is an evident lack of work incorporating this aspect into the derived models. Researchers could take advantage of the significant number of OR scheduling studies that include staff preferences and have as objective to maximize affinities among members of a surgical team, as well as minimize overtime hours (Meskens, Duvivier, & Hanset, 2013), to implement such models in studies concerning the categories in which this aspect is absent.

Although clustering is not an extensively present feature in the scheduling problems exhibited previously, it still has a stronger appearance than in operating room planning problems. In OR scheduling problems, clustering is beneficial when it comes to the scheduling of surgeons. In the event that surgical cases in a certain surgery type and specialization are clustered, a single surgeon could perform them (Oostrum, Parlevliet, Wagelmans, & Kazemier, 2011). This not only facilitates the scheduling of surgeons but respects their preference for having surgical cases sequenced and not spread out. Among the other categories of scheduling, for example home healthcare and instructional scheduling, different clustering techniques are applied with the intention of meeting various objectives, such as maximizing the efficiency of resource allocation, reducing computational costs and time, and minimizing time conflicts between different exams (Quintana, Cervantes, Saez, & Isasi, 2017; To & Win, 2010).

Lastly, fairness is an aspect that is not often contemplated in the setting of OR scheduling and planning problems, as well as in bed assignment and blood collection. However, in instructional scheduling, appointment scheduling, and home healthcare, there is a strong component of this characteristic. According to (Yan, Tang, Jiang, & Fung (2015), fairness is a factor associated with a homogenous quality of service, for example, average patient waiting times, depending on the patient position number and required procedure, and, consequently with patient satisfaction. In this manner, there is an opportunity to invest in new research and to adapt the constraints used to model fairness in the latter scheduling groups, such as in Zander & Mohring (2016) and Turkcan, Zeng, Muthuraman, & Lawley (2011) in appointment scheduling, to the methods applied in OR problems.

Taking into consideration the differences and similarities stated above between the Master Surgery Scheduling and Elective Case Scheduling problems and the categories of other scheduling problems studied, it is clear that it is possible to transfer knowledge from one group to another.

In Table 4, presented below, the significance of specific characteristics in OR Planning and Scheduling problems is listed. Additionally, the problems with which knowledge transfer is possible are stated along with the advantages of including more frequently the respective characteristic.

Table 4. Summary Table

Characteristic	Presence in OR Planning Problems	Possible Knowledge Transfer	Advantages
Patient Preferences	Insignificant	Bed Assignment Appointment Scheduling	Increased patient satisfaction Improved adherence and continuity of treatments
Patient Prioritization	Very Significant	—	—
Workload Balance	Significant	Home Healthcare	Improved quality of service Increased patient satisfaction
Clustering	Insignificant	Instructional Scheduling Home Healthcare	Facilitate the scheduling of surgeons Respect for staff preferences
Fairness	Insignificant	Instructional Scheduling Appointment Scheduling Home Healthcare	Homogenous quality of service Increased patient satisfaction
Staff Preferences	Very Significant	Bed Assignment Blood Collection Appointment Scheduling	Maximize staff retention and care continuity Minimize overtime hours
Uncertainty	Very Significant	—	—

8. Conclusions and Future Work

The demand for health care is continuously growing and long waiting times for elective surgeries are a persistent concern present in various countries. Operating room planning is an essential activity for addressing these problems and providing high-quality services to the overall population. This is due to the Operating Room being the facility that has the greatest influence within hospitals and medical centres. More specifically, it is responsible for producing the majority of the funding for the hospitals while simultaneously being a significantly expensive unit, accounting for most of their expenditures. Effective scheduling techniques and planning strategies are critical to the success of the OR and the efficient use of various resources, such as surgeons, nurses, rooms, and medical equipment.

Consequently, in Portugal, special programs have been implemented to help fight the long waiting lists for surgery and reduce the waiting times for patients. One of these programs is named SIGIC, which regulates all surgical activities and covers every step involved in the management of its users since their enrolment in the program up until after the surgery is performed. The success this initiative has had since its implementation in 2006 strongly emphasizes the importance of investing in OR planning and its respective problems, particularly, the MSS and ECS. Decisions made regarding both these problems have a direct impact on the development of strategies and schedules for the overall layout of a medical centre.

The literature on the Master Surgery Scheduling and Elective Case Scheduling is relatively extensive. Different papers study multiple objectives, for example, the minimization of the patient waiting times, the levelling of resources, the maximization of the OR utilization, among several others. However, only quite a small number of researchers and studies have attempted to position these problems in the general scheduling literature. Fügener, Hans, Kolisch, Kortbeek, & Vanberkel (2014) study the MSS problem and present a general assignment model with the objective of minimizing downstream costs. The Job Shop problem is one of the most studied theories in the scheduling literature and some authors have started to resort to it to formulate the OR problems. For example, Pham & Klinkert (2008) regard the ECS problem as an MMBJS, where the objective function minimizes the makespan as well as the sum of the starting times for surgical operations. Given the wide range of the literature on scheduling problems and the variety of contexts and applications, it is reasonable to predict that future research will introduce and compare them to the health care setting, particularly the Operating Room environment.

The main goal of this dissertation is to position the MSS and ECS problems in the scheduling literature. Due to these problems being addressed in the context of health care, there is a need to position them in a larger framework and take advantage of the dimension of the existing literature on scheduling problems. To achieve this objective an overview of general scheduling problems is provided. The problems being analysed are divided into five different categories, namely, Instructional Scheduling, Bed Assignment, Blood Collection, Appointment Scheduling, and Home Healthcare. The review of these problems reveals that the key features shared by each problem discussed are capacity limits, restricted resources, and the selection of time slots. Other characteristics present in the problems included in both literature reviews were Patient Preferences, Patient Prioritization, Workload Balance, Fairness, Clustering, Staff Preferences, and lastly, Uncertainty. Additionally, none of the problems presented in this research review have adapted or compared the specific methodologies and solutions with the Master Surgery Scheduling and Elective Case Scheduling problems.

For each category of problems selected, the characteristics mentioned above were included in a descriptive and percentage analysis, allowing to visualize in which problems are those features present or not, and in the case that they are, where are they most common. It was possible to conclude that characteristics such as patient preference and prioritization are increasingly present in bed assignment and appointment scheduling problems. Workload balance is the prevailing criterion studied in home healthcare, with its presence being more significant than in the other scheduling categories. Additionally, clustering methods and fairness aspects are also vastly incorporated into this group of problems, as well as in instructional scheduling. In the latter category, staff preferences are taken into account, more often than not by researchers when constructing class and exams schedules. Uncertainty is represented in multiple, with emphasis on bed assignment, appointment scheduling and home healthcare. Lastly, in the MSS and ECS problems, the characteristics emphasized are patient prioritization, staff preferences and uncertainty.

This analysis facilitated the statement of the differences and similarities between the multiple matters and the identification of those that are most directly related to the two Operating Room Planning and Scheduling problems previously mentioned. Patient preferences stands out as the only characteristic that is frequently incorporated in the bed assignment and appointment scheduling respective studies and is barely mentioned in the setting of OR scheduling. This leaves scope for future research where this characteristic can be included in the MSS and ECS problems and utilized to increase patient satisfaction. There is also space for higher incorporation of clustering methods to maximize the benefits of a master surgery schedule and minimize the surgery waiting lists. Finally, there is a lack of studies contemplating fairness in the OR scheduling problems. There is an opportunity to adapt the constraints used to model fairness in the scheduling groups where this feature is present and apply them to MSS and ECS problems allowing for an increase in the quality of the service delivered and a decrease in average waiting times. Concluding, in the OR setting and for these characteristics, there are multiple opportunities to invest in further research and take advantage of the knowledge already existing in other scheduling categories to improve performance measures, for example, waiting time, quality of service, and patient satisfaction.

This dissertation clearly showed that there are research gaps concerning the OR scheduling problems. More specifically, regarding characteristics, namely patient preferences, clustering, and fairness. It is shown that other scheduling categories present more knowledge of these features. This way, for future research, other general scheduling problems can be studied, as well as different characteristics than the ones included in this research work to expand this analysis. Furthermore, a comparison of operational research methods and solutions applied both in general scheduling and the MSS and ECS problems could be performed.

References

ACSS. (26 de February de 2021). *Inscritos em LIC dentro do TMRG*. Obtido de Transparência SNS: https://transparencia.sns.gov.pt/explore/dataset/inscritos-lic-dentro-tmrg/analyze/?disjunctive.regiao&disjunctive.instituicao&sort=tempo&dataChart=eyJxdWVyaWVzIjpbeyJjaGFydHMiOlt7InR5cGUiOiJsaW5lIiwiZnVuYyI6IlNVTSIsInlBeGlzIjoibm9fZGVfZG9lbnRlc19pbnNjcml

Adan, I., & Vissers, J. (2002). Patient mix optimisation in hospital admission planning: A case study. *International Journal of Operations and Production Management 22(4)*, 445–461. doi:10.1108/01443570210420430 .

Addis, B., Carello, G., & Tànfani, E. (2014). A robust optimization approach for the Advanced Scheduling Problem with uncertain surgery duration in Operating Room Planning – an extended analysis. *Hot Working Tech 27(12)*, 3631–3644.

Aggarwal, A., Harris, I. A., & Naylor, J. M. (2016). Patient preferences for emergency or planned hip fracture surgery: a cross-sectional study. *Journal of Orthopaedic Surgery and Research 11*, doi:10.1186/s13018-016-0454-2.

Agnetis, A., Coppi, A., Corsini, M., Dellino, G., Meloni, C., & Pranzo, M. (2014). A decomposition approach for the combined master surgical schedule and surgical case assignment problems. *Health Care Management Science 17*, 49–59. doi:10.1007/s10729-013-9244-0.

Ahmed, A., & Ali, H. (2020). Modeling patient preference in an operating room scheduling problem. *Operations Research for Health Care 25*, doi:10.1016/j.orhc.2020.100257.

Ahmed, A., Chou, C.-A., & Shehadeh, K. S. (2014). Joint Effect of Appointment Scheduling Rules and Resource Selection on Outpatient Clinics Performance. *Industrial and Systems Engineering Research Conference.*

Ala, A., & Chen, F. (2020). An Appointment Scheduling Optimization Method in Healthcare with Simulation Approach . *IEEE 7th International Conference on Industrial Engineering and Applications*, doi:10.1109/iciea49774.2020.9101995.

Alfonso, E., Xie, X., & Augusto, V. (2012). A queueing network approach for appointment scheduling of blood donors. *14th IFAC Symposium onInformation Control Problems in Manufacturing*, (pp. 303–308. doi:10.3182/20120523-3-ro-2023.00212). Bucharest.

Alfonso, E., Xie, X., & Augusto, V. (2015). A simulation-optimization approach for capacity planning and appointment scheduling of blood donors based on mathematical programming representation of event dynamics. *IEEE International Conference onAutomation Science and Engineering (CASE)*, doi:10.1109/coase.2015.7294167.

An, Y.-J., Kim, Y.-D., Jeong, B. J., & Kim, S.-D. (2012). Scheduling healthcare services in a homehealthcare system. *Journal of the Operational Research Society 63*, 1589–1599. doi:10.1057/jors.2011.153.

Ansarifar, J., Tavakkoli-Moghaddam, R., Akhavizadegan, F., & Amin, S. H. (2018). Multi-objective integrated planning and scheduling model for operating rooms under uncertainty. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 232*, 930–948. doi:10.1177/0954411918794721.

Aringhieri, R., Landa, P., & Tànfani, E. (2015a). Assigning surgery cases to operating rooms: A VNS approach for leveling ward beds occupancies. *The 3rd International Conference on Variable Neighborhood Search (VNS'14)* (pp. 173–180. doi:10.1016/j.endm.2014.11.023). Electronic Notes in Discrete Mathematics 47.

Aringhieri, R., Landa, P., Soriano, P., Tànfani, E., & Testi, A. (2015b). A two level Metaheuristic for the Operating Room Scheduling and Assignment Problem. *Computers & Operations Research 54*, 21–34. doi:10.1016/j.cor.2014.08.014 .

Astaraky, D., & Patrick, J. (2015). A simulation based approximate dynamic programming approach to multi-class, multi-resource surgical scheduling. *European Journal of Operational Research 245(1)*, 309–319. doi:10.1016/j.ejor.2015.02.032 .

Atighehchian, A., Sepehri, M. M., & Shadpour, P. (2015). Operating Room Scheduling in Teaching Hospitals: A Novel Stochastic Optimization Model. *International Journal of Hospital Research 4(4)*, 171-176.

Augusto, V., Xie, X., & Perdomo, V. (2010). Operating theatre scheduling with patient recovery inboth operating rooms and recovery beds. *Computers & Industrial Engineering 58(5)*, 231–238. doi:10.1016/j.cie.2009.04.019.

Bandi, C., & Gupta, D. (2020). Operating Room Staffing and Scheduling. *Manufacturing & Service Operations Management*, 1–17. doi:10.1287/msom.2019.0781.

Barbosa-Póvoa, A. P., Silva, C., & Carvalho, A. (2017). Opportunities and Challenges in Sustainable Supply Chain: An Operations Research Perspective. *European Journal of Operational Research*, doi:10.1016/j.ejor.2017.10.036.

Barros, N. M. (2016). *Optimizing the Master Surgery Schedule in a Private Hospital. Master Thesis.* Lisboa.

Baş, S., Carello, G., Lanzarone, E., & Yalçındağ, S. (2018). An appointment scheduling framework to balance the production of blood units from donation. *European Journal of Operational Research 265*, 1124–1143. doi:10.1016/j.ejor.2017.08.054.

Bedem, S. v. (2016). *A Constructive Tool To Predict Timetable Feasibility Under User Defined Constraints [Master Thesis Industrial Engineering & Management].*

Beliën, J., & Demeulemeester, E. (2007). Building cyclic master surgery schedules with leveled resulting bed occupancy. *European Journal of Operational Research 176*, 1185-1204. doi:10.1016/j.ejor.2005.06.063.

Beliën, J., Demeulemeester, E., & Cardoen, B. (2008). A decision support system for cyclic master surgery scheduling with multiple objectives. *Journal of Scheduling 12(2)*, 147–161. doi:10.1007/s10951-008-0086-4 .

Blake, J. T., & Donald, J. (2002). Mount Sinai Hospital Uses Integer Programming to Allocate Operating Room Time. *Interfaces 32(2)*, 63-73. doi:10.1287/inte.32.2.63.57.

Borchani, R., Masmoudi, M., & Jarboui, B. (2019). Hybrid Genetic Algorithm for Home Healthcare routing and scheduling problem. *6th International Conference on Control, Decision and Information Technologies (CoDIT'19)*, doi:10.1109/codit.2019.8820532. Paris, France.

Borgman, N. J., Vliegen, I. M., Boucherie, R. J., & Hans, E. W. (2018). Appointment scheduling with unscheduled arrivals and reprioritization. *Flexible Services and Manufacturing Journal 30*, 30–53. doi:10.1007/s10696-016-9268-0.

Bovim, T. R., Christiansen, M., Gullhav, A. N., Range, T. M., & Hellemo, L. (2020). Stochastic master surgery scheduling. *European Journal of Operational Research 285*, 695–711. doi:10.1016/j.ejor.2020.02.001.

Bram L. Gorissen, I. Y. (2015). A Practical Guide to Robust Optimization. *Omega 53*, 124-137. doi:10.1016/j.omega.2014.12.006.

Brennan, P. F., & Strombom, I. (1998). Improving Health Careby Understanding Patient Preferences: The Role of Computer Technology. *Journal of the American Medical Informatics Association 5*, 257–262. doi:10.1136/jamia.1998.0050257.

Cardoen, B., Demeulemeester, E., & Beliën, J. (2010a). Operating room planning and scheduling problems: a classification scheme. *International Journal of Health Management and Information 1*, 71-83.

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

Cavdur, F., & Kose, M. (2016). A Fuzzy Logic and Binary-Goal Programming-Based Approach for Solving the Exam Timetabling Problem to Create a Balanced Exam Schedule. *International Journal of Fuzzy Systems 18(1)*, 119–129 doi:10.1007/s40815-015-0046-z.

Chaabane, S., Meskens, N., Guinet, l., & Laurent, M. (2008). Comparison of two methods of operating theater planning: Application in Belgian Hospital. *Journal of Systems Science and Systems Engineering 17*, 171-186. doi:10.1007/s11518-008-5074-x.

Chen, P.-S., Robielos, R. A., Palaña, P. K., Valencia, P. L., & Chen, G. Y.-H. (2015). Scheduling Patients' Appointments: Allocation of Healthcare Service Using Simulation Optimization. *Journal of Healthcare Engineering 6(2)*, 259–280. doi:10.1260/2040-2295.6.2.259.

Conforti, D., Guido, R., Mirabelli, G., & Solina, V. (2018). A decision support service for hospital bed assignment. *XXIII Summer School "Francesco Turco" - Industrial Systems Engineering*, (pp. 466-473).

Creemers, S., Beliën, J., & Lambrecht, M. (2012). The optimal allocation of server time slots over different classes of patients. *European Journal of Operational Research 219*, 508–521. doi:10.1016/j.ejor.2011.10.045.

Decerle, J., Grunder, O., Hassan, A. H., & Barakat, O. (2018). Impact of the workload definition on the multi-objective home health care problem. *IFAC-PapersOnLine 51*, 346–351. doi:10.1016/j.ifacol.2018.08.308.

Demirbilek, M., Branke, J., & Strauss, A. K. (2021). Home healthcare routing and scheduling of multiple nurses in a dynamic environment. *Flexible Services and Manufacturing Journal 33*, 253–280. doi:10.1007/s10696-019-09350-x.

Denton, B. T., Miller, A. J., Balasubramanian, H. J., & Huschka, T. R. (2010). Optimal Allocation of Surgery Blocks to Operating Rooms Under Uncertainty. *Operations Research 58(4)*, 802–816. doi:10.1287/opre.1090.0791 .

Denton, B., Viapiano, J., & Vogl, A. (2007). Optimization of surgery sequencing and scheduling decisions under uncertainty. *Health Care Manage Science 10(1)*, 13–24. doi:10.1007/s10729-006-9005-4 .

Devesse, V., Santos, M. O., & Toledo, C. (2017). Fairness in Physician Scheduling Problem in Emergency Rooms. *Revista de Sistemas de Informação da FSMA 18*, 9-20.

Dexter, F., & Traub, R. D. (2002). How to Schedule Elective Surgical Cases into SpecificOperating Rooms to Maximize the Efficiency of Use ofOperating Room Time. *Anesthesia & Analgesia 94*, 933–942. doi:10.1097/00000539-200204000-00030.

Dorgham, K., Ben-Romdhane, H., Nouaouri, I., & Krichen, S. (2020). A Decision Support System for Smart Health Care. Em N. Gupta, & S. Paiva, *IoT and ICT for Healthcare Applications* (pp. 85-98. doi:10.1007/978-3-030-42934-8). EAI/Springer Innovations in Communication and Computing.

Doulabi, S. H., Rousseau, L.-M., & Pesant, G. (2016). A Constraint-Programming-Based Branch-and-Price-and-Cut Approach for Operating Room Planning and Scheduling. *INFORMS Journal on Computing 28(3)*, 432–448. doi:10.1287/ijoc.2015.0686 .

Durán, G., Rey, P. A., & Wolff, P. (2017). Solving the operating room scheduling problem withprioritized lists of patients. *Annals of Operations Research 258*, 395–414. doi:10.1007/s10479-016-2172-x.

Erdogan, S. A., Gose, A., & Denton, B. T. (2015). Online appointment sequencing and scheduling. *IIE Transactions 47*, 1267–1286. doi:10.1080/0740817x.2015.1011355.

Ernst, A., Jiang, H., Krishnamoorthy, M., & Sier, D. (2004). Staff scheduling and rostering: A review of applications, methods and models. *European Journal of Operational Research 153*, 3–27. doi:10.1016/S0377-2217(03)00095-X.

Errarhout, A., Kharraja, S., & Corbier, C. (2016). Two-stage Stochastic Assignment Problem in the Home Health Care. *IFAC-PapersOnLine 49*, 1152–1157. doi:10.1016/j.ifacol.2016.07.659.

Essen, J. T., Houdenhoven, M. v., & Hurink, J. L. (2015). Clustering clinical departments for wards to achieve a prespecified blocking probability. *OR Spectrum 37*, 243–271. doi:10.1007/s00291-014-0368-5.

Feldman, J., Liu, N., Topaloglu, H., & Ziya, S. (2012). Appointment Scheduling under Patient Preference and No-Show Behavior. *Operations Research 62 (4)*, doi: 10.1287/opre.2014.1286.

Fiarni, C., Gunawan, A. S., Ricky, Maharani, H., & Kurniawan, H. (2015). Automated Scheduling System for Thesis and Project Presentation Using Forward Chaining Method With Dynamic Allocation Resources. *Procedia Computer Science 72*, 209-216.

Fügener, A., Hans, E. W., Kolisch, R., Kortbeek, N., & Vanberkel, P. T. (2014). Master surgery scheduling with consideration of multiple downstream units. *European Journal of Operational Research 239(1)*, 227–236. doi:10.1016/j.ejor.2014.05.009 .

Fügener, A., Schiffels, S., & Kolisch, R. (2017). Overutilization and underutilization of operating rooms - insights from behavioral health care operations management. *Health Care Management Science*(20), 115–128. doi:10.1007/s10729-015-9343-1123.

Gärtner, F. R., Portielje, J. E., Langendam, M., Hairwassers, D., Agoritsas, T., Gijsen, B., . . . Stiggelbout, A. M. (2019). Role of patient preferences in clinical practice guidelines: a multiple methods study using guidelines from oncology as a case. *BMJ Open 9*, doi:10.1136/bmjopen-2019-032483.

Goli, A., Tirkolaee, E. B., Mahdavi, I., & Zamani, M. (2019). Solving a University Exam Scheduling Problem Using Genetic and Firefly Algorithms. *International Conference on Industrial Engineering and Operations Management.* Pilsen.

Gomes, J. F. (2015). *Abordagem holística ao Master Surgery Scheduling [Master Thesis].* Porto.

Guido, R., Groccia, M. C., & Conforti, D. (2018). An efficient matheuristic for offline patient-to-bed assignment problems. *European Journal of Operational Research 268*, 486–503. doi:10.1016/j.ejor.2018.02.007.

Güler, M. G., Geçici, E., Köroğlu, T., & Becit, E. (2021). A web-based decision support system for examination timetabling. *Expert Systems with Applications 183*, doi:10.1016/j.eswa.2021.115363.

Gunawan, A., & Ng, K. M. (2011). Solving the Teacher Assignment Problem by Two Metaheuristics. *International Journal of Information and Management Sciences 22*, 73-86.

Gunawan, A., Ng, K. M., & Ong, H. L. (2008). A Genetic Algorithm for the Teacher Assignment Problem for a University in Indonesia. *Information and Management Sciences 19(1)*, 1-16.

Guo, Y., & Yao, Y. (2019). On Performance of Prioritized Appointment Scheduling for Healthcare. *ournal of Service Science and Management 12*, 589–604. doi:10.4236/jssm.2019.125040.

Gupta, D., & Denton, B. (2008). Appointment scheduling in health care: Challenges and opportunities. *IIE Transactions 40*, 800–819. doi:10.1080/07408170802165880.

Güre, S. B., Carello, G., Lanzarone, E., & Yalçındağ, S. (2018). Unaddressed problems and research perspectives in scheduling blood collection from donors. *Production Planning & Control 29*, 84–90. doi:10.1080/09537287.2017.1367860.

Hamid, M., Hamid, M., Musavi, M., & Azadeh, A. (2019). Scheduling elective patients based on sequence-dependent setup times in an open-heart surgical department using an optimization and simulation approach. *SIMULATION 95*, 1141–1164. doi:10.1177/0037549718811591.

Hanum, F., Romliyah, M. A., & Bakhtiar, T. (2015). Exam Invigilators Assignment Problem: A Goal Programming Approach. *Applied Mathematical Sciences 9 (58)*, 2871 - 2880. doi: 10.12988/ams.2015.52134.

Heshmat, M., Nakata, K., & Eltawil, A. (2018). Solving the patient appointment scheduling problem in outpatient chemotherapy clinics using clustering and mathematical programming. *Computers & Industrial Engineering*, doi: 10.1016/j.cie.2018.07.033.

Heydar, M., O'Reilly, M. M., Trainer, E., Fackrell, M., Taylor, P. G., & Tirdad, A. (2021). A stochastic model for the patient-bed assignment problemwith random arrivals and departures. *Annals of Operations Research*, doi:10.1007/s10479-021-03982-9.

Hooshmand, F., MirHassani, S., & Akhavein, A. (2017). A scenario-based approach for master surgery scheduling under uncertainty. *International Journal of Healthcare Technology and Management 16(3/4)*, 177-203. doi:10.1504/ijhtm.2017.088849 .

Hsu, V. N., Matta, R. d., & Lee, C.-Y. (2003). Scheduling Patients in an Ambulatory Surgical Center. *Naval Research Logistics 50(3)*, 218–238. doi:10.1002/nav.10060 .

Hübner, A., Walther, M., & Kuhn, H. (2016). Approach to Clustering Clinical Departments. *Health Care Systems Engineering for Scientists and Practitioners*, 111-120. doi: 10.1007/978-3-319-35132-2_11.

Huynh, T. T., Pham, Q. D., & Pham, D. D. (2012). Genetic algorithm for solving the master thesis timetabling problem with multiple objectives. *2012 Conference on Technologies and Applications of Artificial Intelligence*, doi:10.1109/taai.2012.50.

Jafari, H., & Salmasi, N. (2015). Maximizing the nurses' preferences in nurse scheduling problem: mathematical modeling and a meta-heuristic algorithm. *Journal of Industrial Engineering International 11*, 439–458. doi:10.1007/s40092-015-0111-0.

Kamran, M. A., Karimi, B., & Dellaert, N. (2018). Uncertainty in advance scheduling problem in operating room planning. *Computers & Industrial Engineering 126*, 252–268. doi:10.1016/j.cie.2018.09.030.

Kamran, M. A., Karimi, B., Dellaert, N., & Demeulemeester, E. (2019). Adaptive operating rooms planning and scheduling: A rolling horizon approach. *Operations Research for Health Care 22*, 100200. doi:10.1016/j.orhc.2019.100200.

Khan, K., & Sahai, A. (2020). Tabu Ant Colony Optimisation for School Timetable Scheduling Problem. *International Journal of Engineering Research and Applications 10(5)*, 1-9.

Khaniyev, T., Kayış, E., & Güllü, R. (2020). Next-day operating room scheduling with uncertain surgery durations: Exact analysis and heuristics. *European Journal of Operational Research 286*, 49–62. doi:10.1016/j.ejor.2020.03.002.

Koppka, L., Wiesche, L., Schacht, M., & Werners, B. (2018). Optimal distribution of operating hours over operating rooms using probabilities. *European Journal of Operational Research 267*, 1156–1171. doi:10.1016/j.ejor.2017.12.025.

Kroer, L. R., Foverskov, K., Vilhelmsen, C., Hansen, A. S., & Larsen, J. (2018). Planning and Scheduling Operating Rooms for Elective and Emergency Surgeries with Uncertain Duration. *Operations Research for Health Care 19*, 107-119. doi:10.1016/j.orhc.2018.03.006.

Lamiri, M., Grimaud, F., & Xie, X. (2009). Optimization methods for a stochastic surgery planning problem. *International Journal of Production Economics 120(2)*, 400–410. doi:10.1016/j.ijpe.2008.11.021 .

Latorre-Núñez, G., Lüer-Villagra, A., Marianov, V., Obreque, C., Ramis, F., & Neriz, L. (2016). Scheduling operating rooms with consideration of all resources, post anesthesia beds and emergency surgeries. *Computers & Industrial Engineering 97*, 248–257. doi:10.1016/j.cie.2016.05.016.

Lei, X., Na, L., Xin, Y., & Fan, M. (2014). A Mixed Integer Programming Model for Bed planning considering stochastic length of stay. *IEEE International Conference onAutomation Science and Engineering (CASE)*, doi:10.1109/coase.2014.6899456.

Li, F., Gupta, D., & Potthoff, S. (2016). Improving operating room schedules. *Health Care Management Science 19*, 261–278. doi:10.1007/s10729-015-9318-2.

Li, N., Li, X., Zhang, C., & Kong, N. (2021). Integrated optimization of appointment allocation and access prioritization in patient-centred outpatient scheduling . *Computers & Industrial Engineering 154*, doi:10.1016/j.cie.2021.107125.

Liang, F., Guo, Y., & Fung, R. Y. (2015). Simulation-Based Optimization for Surgery Scheduling in Operation Theatre Management Using Response Surface Method. *Journal of Medical Systems 39*, 159. doi:10.1007/s10916-015-0349-5.

Lin, T.-S., Liu, P.-Y., & Lin, C.-C. (2019). Home Healthcare Matching Service System Using the Internet of Things. *Mobile Networks and Applications 24*, 736–747. doi:10.1007/s11036-018-1087-y.

Litvak, E., & Long, M. C. (2000). Cost and Quality Under Managed Care: Irreconcilable Differences? *The American Journal of Managed Care 6(3)*, 305-312. PMID: 10977431.

Lopes, A. J. (2012). *Gestão do Bloco Operatório [Dissertação de Mestrado].* Universidade do Minho.

Lv, S.-m. (2018). An Annealing Memetic Algorithm for Instructional Scheduling. *International Journal of Emerging Technologies in Learning 13(11)*, 17-28. doi:10.3991/ijet.v13i11.9601 .

Magerlein, J. M., & Martin, J. B. (1978). Surgical Demand Scheduling: A Review. *Health Services Research 13(4)*, 418-433.

Marques, I., Captivo, M. E., & Pato, M. V. (2012). An integer programming approach to elective surgery scheduling. *OR Spectrum 34(2)*, 407–427. doi: 10.1007/s00291-011-0279-7.

Marques, I., Captivo, M. E., & Pato, M. V. (2015). A bicriteria heuristic for an elective surgery scheduling problem. *HealthCare Manag Sci 18(3)*, 251-266. doi: 10.1007/s10729-014-9305-z.

Marynissen, J., & Demeulemeester, E. (2016). Literature Review on Integrated Hospital Scheduling Problems. *KU Leuven, Faculty of Economics and Business*, doi:10.2139/ssrn.2873413.

Meskens, N., Duvivier, D., & Hanset, A. (2013). Multi-objective operating room scheduling considering desiderata of the surgical team. *Decision Support Systems 55*, 650-659. doi: 10.1016/j.dss.2012.10.019.

Min, D., & Yih, Y. (2010). An elective surgery scheduling problem considering patient priority. *Computers & Operations Research 37(6)*, 1091–1099. doi:10.1016/j.cor.2009.09.016 .

Ministério da Saúde. (2015). *SIGLIC*. Obtido em 5 de March de 2021, de https://www.spms.min-saude.pt/2015/10/siglic/

Mittal, S., Schulz, A. S., & Stiller, S. (2012). Robust Appointment Scheduling. 356-370. doi:10.4230/LIPIcs.APPROX-RANDOM.2014.356.

Mobasher, A., Ekici, A., & Özener, O. Ö. (2015). Coordinating collection and appointment scheduling operations at the blood donation sites. *Computers & Industrial Engineering 87*, 260–266.. doi:10.1016/j.cie.2015.05.020.

Molina-Pariente, J. M., Hans, E. W., Framinan, J. M., & Gomez-Cia, T. (2015). New heuristics for planning operating rooms. *Computers & Industrial Engineering 90*, 429–443. doi:10.1016/j.cie.2015.10.002.

Monroy, A. C., Ramírez, V. C., Neira, E. M., Caicedo, R. F., & Sánchez, V. P. (2021). A greedy-tabu approach to the patient bed assignment problem in the Hospital Universitario San Ignacio. *Decision Science Letters 10*, 21–38.

Moosavi, A., & Ebrahimnejad, S. (2020). Robust operating room planning considering upstream and downstream units: A new two-stage heuristic algorithm. *Computers & Industrial Engineering 143*, 106387. doi:10.1016/j.cie.2020.106387.

Muklason, A., Parkes, A. J., McCollum, B., & Ozcan, E. (2010). Initial Results on Fairness in Examination Timetabling. *6th Multidisciplinary International Conference on Scheduling : Theory and Applications (MISTA 2013).* Ghent, Belgium.

Mutingi, M., & Mbohwa, C. (2013). A HOME HEALTHCARE MULTI-AGENT SYSTEM IN A MULTI-OBJECTIVE ENVIRONMENT. *SAIIE25 Proceedings.* Stellenbosch, South Africa.

Mutingi, M., & Mbohwa, C. (2014). Home Healthcare Staff Scheduling: A Taxonomic State-of-the-Art Review. *IEEE International Conference on Industrial Engineering and Engineering Management.*, 1107-1111. doi:10.1109/IEEM.2013.6962582.

OECD. (1 de June de 2021). *Health Care Utilisation: Waiting times*. Obtido de OECD.Stat: https://stats.oecd.org/index.aspx?queryid=30167#

Oostrum, J. M., Houdenhoven, M. V., Hurink, J. L., Hans, E. W., Wullink, G., & Kazemier, G. (2008). A master surgical scheduling approach for cyclic scheduling in operating room departments. *OR Spectrum 30*, 355-374. doi:10.1007/s00291-006-0068-x.

Oostrum, J. M., Parlevliet, T., Wagelmans, A. P., & Kazemier, G. (2011). A Method for Clustering Surgical Cases to AllowMaster Surgical Scheduling. *INFOR: Information Systems and Operational Research 49*, 254–260. doi:10.3138/infor.49.4.254.

Optimus ISE AG. (2021). *History of the Operating Room*. Obtido em 1 de March de 2021, de Optimus Integrated Surgical Environment: https://www.optimus-ise.com/historical/history-of-the-operating-room/

Ozkarahan, I. (1995). Allocation of surgical procedures to operating rooms. *Journal of Medical Systems 19*, 333–352. doi:10.1007/bf02257264.

Park, J., Kim, B.-I., Eom, M., & Choi, B. K. (2021). Operating room scheduling considering surgeons' preferences and cooperative operations. *Computers & Industrial Engineering 157*, doi: 10.1016/j.cie.2021.107306.

Penn, M. L., Potts, C. N., & Harper, P. R. (2017). Multiple criteria mixed-integer programming for incorporating multiple factors into the development of master operating theatre timetables. *European Journal of Operational Research 262*, 194–206. doi:10.1016/j.ejor.2017.03.065.

Persson, M. J., & Persson, J. A. (2010). Analysing management policies for operating room planning using simulation. *Health Care Management Science 13(2)*, 182–191. doi:10.1007/s10729-009-9122-y .

Pham, D.-N., & Klinkert, A. (2008). Surgical case scheduling as a generalized job shop scheduling problem. *European Journal of Operational Research 185(3)*, 1011–1025. doi:10.1016/j.ejor.2006.03.059 .

Phillips, A., Waterer, H., Ehrgott, M., & Ryan, D. (2015). Integer Programming Methods for Large Scale Practical Classroom Assignment Problems. *Computers & Operations Research 53*, 42–53. doi:10.1016/j.cor.2014.07.012.

Prakash, B. (2010). Patient satisfaction. *Journal of Cutaneous and Aesthetic Surgery 3*, 151-155. doi: 10.4103/0974-2077.74491.

Proença, I. M. (2010). *Planeamento de Cirurgias Electivas: Abordagens em Programação Inteira.* Lisboa.

Qi, J. (2016). Mitigating Delays and Unfairness in Appointment Systems. *Management Science*, 1-18. doi:10.1287/mnsc.2015.2353.

Quintana, D., Cervantes, A., Saez, Y., & Isasi, P. (2017). Clustering technique for large-scale home care crew scheduling problems. *Applied Intelligence 47*, 443–455. doi:10.1007/s10489-017-0908-1.

Ramos, N. Q. (2018). *Operating Room Planning and Scheduling of Elective Patients [Master Thesis].* Lisboa.

Restrepo, M. I., Rousseau, L.-M., & Vallée, J. (2020). Home healthcare integrated staffing and scheduling. *Omega 95*, doi:10.1016/j.omega.2019.03.015.

Sampol, C. (2018). *MedicalExpo e-Magazine*. Obtido em 1 de March de 2021, de http://emag.medicalexpo.com/a-brief-history-of-the-operating-room/

Samudra, M., Riet, C. V., Demeulemeester, E., Cardoen, B., Vansteenkiste, N., & Rademakers, F. E. (2016). Scheduling operating rooms: achievments, challenges and pitfalls. *Journal of Scheduling 19*, 493–525. doi:10.1007/s10951-016-0489-6.

Santoso, L. W., Sudiarso, A., Masruroh, N. A., & Herliansyah, M. K. (2018). Cluster analysis to determine the priority of operating room scheduling. *AIP Conference Proceedings 1977*,. doi:10.1063/1.5042914.

Schäfer, F., Walther, M., Hübner, A., & Kuhn, H. (2019). Operational patient-bed assignment problem in large hospital settings including overflow and uncertainty management. *Flexible Services and Manufacturing Journal 31*, 1012–1041. doi:10.1007/s10696-018-9331-0.

Schmidt, R., Geisler, S., & Spreckelsen, C. (2013). Decision support for hospital bedmanagement using adaptable individual length of stay estimations and shared resources. *BMC Medical Informatics and Decision Making 13*, doi:10.1186/1472-6947-13-3.

Shield Jr., W. C. (9 de July de 2018). *Medical Definition of Operating Room*. Obtido de MedicineNet: https://www.medicinenet.com/operating_room/definition.htm

SIGA SNS. (2018). *Perguntas Frequentes sobre a Gestão da Lista Cirúrgica.* Obtido em 7 de March de 2021

SNS, Portuguese National Health System. (2016). *SIGIC*. Obtido em 5 de March de 2021, de https://www2.acss.min-saude.pt/DepartamentoseUnidades/UnidadeAcessoeContratualiza%C3%A7%C3%A3o/SIGIC/tabid/262/language/pt-PT/Default.aspx

SNS. (2019). *Relatório Anual: Acesso a Cuidados de Saúde nos Estabelecimentos do SNS e Entidades Convencionadas em 2019.* SNS.

Soudi, A., Heydari, M., & Mazdeh, M. M. (2019). A new approach for integrated surgical procedure scheduling with arrival uncertainty. *International Journal of Operational Research 34(3)*, 430-449. doi:10.1504/ijor.2019.098315 .

Sperandio, F., Gomes, C., Borges, J., Brito, A. C., & Almada-Lobo, B. (2014). An Intelligent Decision Support System for the Operating Theater: A Case Study. *IEEE Transactions on Automation Science and Engineering 11(1)*, 265–273. doi:10.1109/tase.2012.22.

Taramasco, C., Olivares, R., Munoz, R., R. S., Villar, M., & Albuquerque, V. H. (2019). Thepatientbedassignmentproblemsolvedbyautonomousbatalgorithm. *Applied Soft Computing 81*, doi:10.1016/j.asoc.2019.105484.

Thomas, B. G., Bollapragada, S., Akbay, K., Toledano, D., Katlic, P., Dulgeroglu, O., & Yang, D. (2013). Automated Bed Assignments in a Complex and Dynamic Hospital Environment. *Interfaces 43(5)*, 435–448. doi:10.1287/inte.2013.0701 .

To, T. V., & Win, S. S. (2010). Clustering Approach to Examination Scheduling. *3rd International Conference on Advanced Computer Theory and Engineering(ICACTE).*

Topaz, M., Trifilio, M., Maloney, D., Bar-Bachar, O., & Bowles, K. H. (2018). Improving patient prioritization during hospital-homecare transition: A pilot study of a clinical decision support tool. *Research in Nursing & Health 41*, 440–447. doi:10.1002/nur.21907.

Tsai, P.-F. J., & Teng, G.-Y. (2014). A stochastic appointment scheduling system on multiple resources withdynamic call-in sequence and patient no-shows for an outpatient clinic. *European Journal of Operational Research 239*, 427–436. doi:10.1016/j.ejor.2014.04.032.

Tsai, P.-F., & Lin, F.-M. (2014). An Application of Multi-Attribute Value Theory to Patient-Bed Assignment in Hospital Admission Management: an Empirical Study. *Journal of Healthcare Engineering 5*, 439–456. doi:10.1260/2040-2295.5.4.439.

Tunçalp, F., & Örmeci, L. (2019). A preference-based appointment scheduling problem with multiple patient types. *Journal of Industrial Engineering 30(2)*, 93-110.

Turkcan, A., Zeng, B., Muthuraman, K., & Lawley, M. (2011). Sequential clinical scheduling with service criteria. *European Journal of Operational Research 214*, 780-795.

Unidade Central de Gestão de Inscritos para Cirurgia. (2015). *Relatório síntese da atividade cirúrgica programada – Ano 2014.*

VanBerkel, P. T., & Blake, J. T. (2007). A comprehensive simulation for wait time reductionand capacity planning applied in general surgery. *Health Care Management Science 10*, 373–385. doi:10.1007/s10729-007-9035-6.

Vanberkel, P. T., Boucherie, R. J., Hans, E. W., Hurink, J. L., van Lent, W. A., & van Harten, W. H. (2011). An exact approach for relating recovering surgical patient workload to the master surgical schedule. *Journal of the Operational Research Society 62(10)*, 1851–1860. doi:10.1057/jors.2010.141.

Wang, J., & Fung, R. Y. (2015). Dynamic appointment scheduling with patient preferences and choices. *Industrial Management & Data Systems 115 (4)*, 700-717. doi:10.1108/IMDS-12-2014-0372.

Wang, W.-Y., & Gupta, D. (2011). Adaptive Appointment Systems with Patient Preferences. *Manufacturing & Service Operations Management 13*, 373–389. doi:10.1287/msom.1110.0332.

Weaver, P. (2006). A Brief History of Scheduling - Back to the Future. *myPrimavera Conference.* Canberra.

Wullink, G., Houdenhoven, M. V., Hans, E. W., Oostrum, J. M., Lans, M. v., & Kazemier, G. (2007). Closing Emergency Operating Rooms Improves Efficiency. *Journal of Medical Systems 31(6)*, 543–546. doi:10.1007/s10916-007-9096-6 .

Xiao, G., Jaarsveld, W. v., Dong, M., & Klundert, J. v. (2016). Stochastic programming analysis and solutions to scheduleovercrowded operating rooms in Chin. *Computers & Operations Research 74*, 78-91. doi:10.1016/j.cor.2016.04.017.

Xue, J., Li, M., & Xuan, Z. (2018). Research on appointment scheduling model based on medical management. *10th International Conference on Measuring Technology and Mechatronics Automation*, doi:10.1109/icmtma.2018.00097.

Yan, C., Huang, G. G., Kuo, Y.-H., & Tang, J. (2021). Dynamic appointment scheduling for outpatient clinics with multiple physicians and patient choice. *Journal of Management Science and Engineering*, doi:10.1016/j.jmse.2021.02.002.

Yan, C., Tang, J., Jiang, B., & Fung, R. Y. (2015). Sequential appointment scheduling consideringpatient choice and service fairness. *International Journal of Production Research 53*, 7376–7395. doi:10.1080/00207543.2015.1081426.

Yang, M., Ni, Y., & Yang, L. (2021). A multi-objective consistent home healthcare routing and scheduling problem in an uncertain environment. *Computers & Industrial Engineering 160*, doi:10.1016/j.cie.2021.107560.

Yousefi, N., Hasankhani, F., & Kiani, M. (2019). Appointment scheduling model in healthcare using clustering algorithms. *arXiv: Signal Processing*.

Zander, A., & Mohring, U. (2016). Dynamic appointment scheduling with patient time preferences and different service time lengths. *Lecture Notes in Management Science 8*, 72–77.

Zhang, J., Dridi, M., & Moudni, A. E. (2019). A two-level optimization model for elective surgery scheduling with downstream capacity constraints. *European Journal of Operational Research 276*, 602–613. doi:10.1016/j.ejor.2019.01.036.

Zhou, S., & Yue, Q. (2019). Appointment scheduling for multi-stage sequential service systems with stochastic service durations. *Computers & Operations Research 112*, doi:10.1016/j.cor.2019.07.015.

Zhou, S., & Yue, Q. (2021). Sequencing and scheduling appointments for multi-stage service systems withstochastic service durations and no-shows. *International Journal of Production Research*, 1-20. doi:10.1080/00207543.2020.1862431.

Zhou, Y., & Lou, Y. (2017). An Optimization Model of Outpatient Appointment Scheduling Window with Patient No-show. *13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discover*, doi:10.1109/fskd.2017.8393257.

Zhu, S., Fan, W., Yang, S., Pei, J., & Pardalos, P. M. (2018). Operating room planning and surgical case scheduling: a review of literature. *Journal of Combinatorial Optimization*(37), 757–805. doi:10.1007/s10878-018-0322-6.