A model for elective patient scheduling integrating regular and additional production

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Abstract:

In Portugal, in order to overcome the challenge of reducing waiting lists and times for elective surgery, a new streamline of surgical activity emerged – additional production. This concept is based on the idea of maximizing the efficiency of the installed capacity, through the utilization of extended operating room hours, with surgeries being performed outside working hours of the staff, whose members are paid according to a fee-for-service approach. Since additional production has to respect specific regulations, is dependent from base production, and follows a different paying schema, the task of elective patient scheduling becomes even more complex. Moreover, criteria for selecting patients to be scheduled under each regime are still unclear.

Therefore, an optimization model for the elective patient scheduling problem, that combines the mentioned method of additional production and regular base production, is proposed in this dissertation, through a two-phase integer linear programming approach. The model's input data was provided by Hospital do Espírito Santo de Évora. Despite the model tries to mimic the essential features of the scheduling process, several scenarios for the management of the two production regimes were tested and their outcomes were analysed and compared according to different performance measures. One of the tested scenarios managed to find a decent compromise between the stakeholders' interests – surgical team, administration and patients – the waiting list situation is improved, equity in the scheduling process is ensured and surgical team's remuneration under additional production is maximized. This optimization tool can certainly contribute to get the maximum potential from the additional production regime.

Keywords: *Operating Room; Operating Room Scheduling; Elective Patient Scheduling; Additional Production; Integer Linear Programming; Optimization Model*

1. Introduction

In Portugal, due to the growing number of patients registered in waiting lists for surgery and consequent long waiting periods to undergo a surgery, it was created in 2004 a universal system entitled SIGIC – Sistema Integrado de Gestão de Inscritos em Cirurgia – with the main objective of reducing these waiting lists for elective surgery (Presidência Do Conselho De Ministros, 2004).

SIGIC has managed to meet the proposed objectives, enabling significant reductions in waiting lists and waiting times for elective surgery. The positive impact of SIGIC is directly related with the emergence of a new streamline of surgical activity – Additional Production – which is an incentive mechanism that rewards the surgical teams by paying for each act performed outside the regular staff working hours, through a Fee-for-Service approach. This type of paying schema is named MRA - Modalidade Remuneratória Alternativa (Ministério da Saúde, 2015) or Internal Additional Production. Besides the financial incentives for the surgical team, additional production uses extended operating room (OR) hours, increasing the efficiency of the installed capacity. Therefore, it enables an increase in productivity and contributes to the ultimate objective of reducing waiting lists and waiting times for elective surgery. It should be highlighted that additional production is destined to answer unmet needs of Base Production – the hospital's contracted production according to historical data and evolution of demand - only being authorized when installed capacity is fulfilled. For base production, the payment schema is MRC – Modalidade Remuneratória Condicional – involving production carried out during the staff's working hours and remunerated through the monthly salary of the surgical teams (Ministério da Saúde, 2015).

The ultimate goal of this dissertation is to develop an optimization model to support elective patient scheduling, considering both base and additional production as possible streamlines of surgical activity. The model should be applicable to the context of a Portuguese public hospital, and, in order to test it, real data from Hospital do Espírito Santo de Évora (HESE) was inputted. Lastly, the work intends to analyse and compare different strategies for the management of the two production streams, as well as evaluate possible improvements to the current management strategies.

The paper is organized as follows. Chapter 2 presents a literature review on the problem of elective patient scheduling, covering a wide variety of different contexts, motivations and methodologies, and organized according to a defined framework. In Chapter 3 the mathematical model's formulation is presented. A two-phase mixed integer linear programming problem was the chosen optimization methodology. A description of the inputted data is provided in Chapter 4. Chapter 5 presents, discusses and compares the model's obtained results of different performance metrics, for each defined management scenario. To conclude the paper, Chapter 6 highlights the essential contributions and the pitfalls of the developed research.

2. Literature Review

The literature on the topics of OR Planning and Scheduling is vast and presents a wide range of different factors and considerations which can be taken into account in the problem formulation, representing different perspectives and points of view from the different stakeholders involved in the process, as well as different objectives from different hospital institutions. Moreover, several different methods and solution techniques are used to address the problems. In order to better organize and present the essential literature findings, this literature review follows a framework based on different comprehensive fields: Patient Characteristics, Decision Type, Performance Measures, Problem Constraints, Operations Research Methodology, Integration of Uncertainty and Integration of Upstream and Downstream Units. The scope of this dissertation is OR Scheduling, therefore, as far as decision delineation is concerned, this review is restricted to the Operational Decision Level which comprises the problem of scheduling a surgery, defining a date, start time and an operating room, as well as possibly other necessary resources for the intervention. The search was also restricted to manuscripts published since 2009, in the English language. For articles published before that year, Cardoen et al., (2010) review should be consulted. The used databases were PubMed and Web of Sciences, searching for the topics: "Operating Room/Theatre Planning", "Operating Room/Theatre Scheduling", "Elective Scheduling Methods", and "Elective Surgery/Patient/Case Scheduling".

As far as *Patient Characteristics* are concerned, a distinction can be established between Elective Patients and Non-Elective Patients. Elective patients are the ones whose surgeries can be well planned in advance, while non-elective patients refer to unexpected and usually urgent cases that must be integrated into the schedule immediately (Cardoen et al., 2010). The vast majority of the analysed manuscripts are restricted to elective cases which can be differentiated between inpatients, who need to stay hospitalized overnight, and outpatients (also named ambulatory cases), who enter and leave the hospital on the same day (Cardoen et al., 2010). Some papers do not discriminate between inpatients and outpatients, while others restrict the scope of the investigation to one of the two types. Pato et al., (2012) decompose the problem in two phases, the first one is restricted to inpatient scheduling (conventional surgeries), while the second refers to outpatient scheduling only (ambulatory surgeries), to reduce the problem's global dimension. Some papers integrate both elective and non-elective patients and there are mainly two approaches described in the literature, with contradictory results, to deal with non-elective cases: dedicated and shared policies (Duma & Aringhieri, 2019): the first policy reserves one or more ORs each day exclusively for non-elective surgeries, while the latter integrates elective and non-elective cases within the same OR sessions. Combining the two mentioned policies, a hybrid policy is also commonly applied. A dedicated policy avoids possible delays and waiting times, which are common when a shared policy is adopted. However, more efficient resource utilization is achieved by applying a shared policy (Kamran et al., 2019).

Regarding *Decision Type*, the operational decision level comprises two different decision types - Advance Scheduling and Allocation Scheduling. Advance scheduling consists in assigning a date and OR to each surgical case, while Allocation Scheduling involves determining the exact start time of each surgery and, therefore, establishing the sequence of operations in each OR, on each day (S. Zhu et al., 2019). The literature frequently addresses either one of the two stages or both. Fei et al., (2010) integrate both stages sequentially to design the weekly surgery schedule for an OR: firstly, the surgery date is given for each patient (advance scheduling), accounting for the availability of surgeons and ORs, then the sequence of surgeries in each OR, in each day is determined, accounting the recovery beds' availability. Transversal to all decision levels, there is the scheduling type decision, which can be either an Open Scheduling Strategy or a Block Scheduling Strategy. Some literature also refer a Modified Block Scheduling Strategy, combining the two mentioned methods. In a block scheduling strategy, surgeons, groups of surgeons, or specialities are assigned to time blocks that divide the total OR capacity. Marques & Captivo, (2016) adopt a block scheduling strategy in which a single surgical speciality must be assigned to each OR and day, while Meskens et al., (2013) adopt a variation of this strategy in which some blocks are assigned to specific surgeons and others to specialities. On the other hand, an open scheduling strategy allows surgeons to choose, through a first come-first served based approach, any workday and any available OR for a surgical case, without pre-assigned slots, being much more flexible than the block scheduling approach (S. Zhu et al., 2019). Modified block scheduling combines open and block scheduling approaches, enabling blocks to be scheduled by other surgeons if their underutilization is likely to happen (S. Zhu et al., 2019).

OR scheduling models usually include some *constraints* considered to be relevant for the problem formulation, in a certain context. However, due to the amount of complexity induced by the inclusion of an increasing number of constraints, only a few are considered in the models and some important ones end up being excluded. Regarding human resources, their availability is frequently translated to constraints, especially surgeons' availability. Meskens et al., (2013) considers both surgeons' and nurses' availabilities and also add anaesthetists' availability. In Oliveira et al., (2020) there is also a constraint which defines that surgeons must have the necessary skill, evaluated by a defined parameter, to perform a certain surgery. Sometimes legal/regulatory constraints are imposed, as in Lin & Li, (2021) which define a maximum allowed number of working hours per day for a single surgeon. Preferences of human resources can also be incorporated in constarints, as in Meskens et al., (2013), that accounts the preferences of surgeons, nurses and anaesthetists for certain time slots, including an "affinities module" translated in contraints. As far as installations are concerned, most papers comprise constraints that cover their availability. Additionally, some paper assume that ORs are multifunctional, as they can be assigned to any scheduled surgery. On the contrary, some papers such as Fairley et al., (2019) and Roland et al., (2010), state that ORs are specialized due to the specialized equipment each one has. Prioritization systems may be incorporated in a model throughout constraints which define due dates for each priority level and force surgeries to be scheduled before that date. Pato et al., (2012) formulates a model for Portuguese hospitals, composed of 4 priority levels – deferred urgency, high priority, priority, normal.

Several *Performance Measures* are referenced throughout the reviewed literature, covering interests of the stakeholders involved in the scheduling process: waiting time, utilization, overtime, throughput, makespan, resource levelling or patient referrals/refusals. Utilization is one of the most referenced performance measures in the literature and it can be defined as the workload of a certain resource, in this case, the OR. The trade-off between having a fully planned OR without any time buffers – overutilization - and having underutilized costly operating rooms, but capable of accommodating uncertain events, avoiding overtime – underutilization – is frequently investigated (Cardoen et al., 2010). Alongside maximizing utilization, Lin & Li, (2021) minimize the total operating cost, which comprises both overtime cost and waste cost of unused idle time., two performance indicators frequently referred in the literature. Molina-Pariente et al., (2015) define an objective function that minimizes the period between the surgery scheduled date and its due date – tardiness–which is associated with patient waiting time, alonside maximizing throughput, i.e. the number of surgeries scheduled, one of the most common objectives found in literaute. Latorre-Núñez et al., (2016) develop a model whose objective is the makespan minimization, the period of time between the entrance of the first patient and the finishing of the last. In a context where non-elective cases are taken into consideration, it may be relevant to consider the objective of minimizing the cancellation of elective cases, addressing the trade-off between the maximization of utilization and an increase of cancellations, as done in Duma & Aringhieri, (2019).

A wide variety of operations research methodologies and solution techniques can be found in the reviewed literature to solve the OR planning and scheduling problem. According to S. Zhu et al., (2019), these methods can be categorized into Exact Algorithms, Heuristics and Simulations. Exact algorithms or mathematical programming always provide the optimal solution for an optimization problem and are suited for smaller and less complex problems. There are several different solution techniques that fit within this category, being integer programming the most common. Frequently, the problem's complexity determines that the problem cannot be solved in a reasonable time span when using an exact algorithm. Therefore, in those situations heuristics are often proposed, providing quality solutions within a reasonable time (Samudra et al., 2016). Simulation approaches are commonly used to evaluate and compare performances of different models under different scenarios, and can be either Discrete-Event simulations (DES) or Monte Carlo simulations (S. Zhu et al., 2019).

Uncertainty is inherent to surgical activity, and it is perhaps the most challenging aspect of the development of OR scheduling models. Some authors develop models that ignore such variability, adopting a deterministic approach. Nevertheless, operations research techniques are capable of handling uncertainty, lowering its negative impact on scheduling strategies, through the development of stochastic models (Cardoen et al., 2010). There are essentially two types of uncertainty that can be incorporated in the models, widely addressed in the literature: surgery duration uncertainty, reflecting differences between the predicted and real procedure durations, and arrival uncertainty, especially of non-elective arrivals (Samudra et al., 2016).

OR is not an isolated unit within the hospital, consequently, its performance and planning decisions are dependent on *upstream facilities*, such as services wards or pre-operative holding units. Moreover, those OR planning decisions have an impact on *downstream units* such as the ward, ICU (Intensive Care Unit) or PACU (Post-Anaesthesia Care Unit) (Samudra et al., 2016). Some literature adopts an integrated approach, in which these facilities are integrated into the scheduling model, nevertheless the majority of the reviewed articles still adopt an isolated approach, despite the proven utility of implementing an integrated one.

It was possible to verify that there are no models in the literature which consider the existence of two different streams of production, with different payment schemas. The present work intends to fill that gap, formulating a model suited for Portuguese public institutions, where surgeries can be scheduled under base production or additional production regimes. Marques & Captivo, (2017) presented a model for Portuguese hospitals where two different shifts with different payment schemas are considered, mixing both administration's and patients' interests. However, despite the similarities, those shifts do not exactly correspond to the two production regimes.

3. Mathematical Model

The problem under study is an OR scheduling problem, specifically an advance scheduling problem, which consists in assigning a day, time-block, operating room and surgeon to each elective surgery from a waiting list, without considering the order of surgeries at each slot. A weekly planning time horizon is considered, meaning that, for each week, a number of surgeries is selected to be scheduled. Instead of solvng the problem through an integrated approach, a two-phase integer linear programming approach was defined and for each phase a model was developed, corresponding to each one of the production regimes: the first phase's model schedules surgical cases under base production regime, and its output, in terms of unscheduled surgeries, is the input for the second phase's model, that corresponds to additional production.

Firstly, the models' indices and sets, are summarized in Table 1. Followingly, Table 2, Table 3 and Table 4 describe the surgical cases', surgeons' and time blocks' parameters, respectively. Decision variables are presented in Table 5. The problem's constraints and objective functions are described, for both phases, using the previously defined notation. The Constarints 1 to 11 refer to the problem's constraints for the first phase, scheduling under base production regime. The Constraints 12 to 21 refer to the second phase of the problem, scheduling under additional production regime.

Expression 1 ensures that the decision variable y_c takes the value of one in case the surgical case *c* is not scheduled within the planning horizon, and otherwise equals zero. Furthermore, it ensures that each surgical case *c* is only scheduled once within the planning horizon. In order to prevent surgeons from being assigned to several ORs, at each day *d* and time block *b*, i.e., simultaneously, Expression 2 was defined. The parameter $avl_{h\,d}$ presented before, translates the surgeon's availability to perform surgeries at each day *d* of the planning horizon.

Indices and sets	Description
$c \in C$	Set of all surgical cases that entered in the waiting list
$c \in C\_0$	Subset of the surgical cases which were already on the waiting list before the beginning of the first planning horizon
$s_c \in S$	Set of the surgeries' medical specialities
$h \in H$	Set of the hospital's active surgeons
$d \in D$	Set of days in the planning horizon
$b \in B_d$	Set of time blocks available in a day d
$o \in O$	Set of the hospital's ORs

***Table 1:** Models' indices and sets and respective description.*

Parameter	Description
$p_c \in \{1,2,3\}$	Priority level of surgical case *c*
dd_c	Due date of surgical case *c*
$d1_c$	Date of entry of surgical case *c* in the waiting list
$week_c$	Week of entry of surgical case *c* in the waiting list
$sgn_c \in \mathbb{N}$	Average surgeon time duration of surgery *c* (in minutes)
$tot_c \in \mathbb{N}$	Average total room occupation of surgery *c* (in minutes)
$cln_c \in \mathbb{N}$	Average cleaning time of surgery *c* (in minutes)

***Table 2:** Surgical case's parameters and respective description.*

Parameter	Description
$skills_{h\,s_c} \in \{0,1\}$	Equals 1 if surgeon h has the necessary skills to perform surgeries of speciality s_p ; 0 otherwise
$avl_{h\,d} \in \{0,1\}$	Equals 1 if surgeon h is available to perform surgeries at day d of the planning horizon; 0 otherwise
$lim_h \in \mathbb{N}$	Maximum limit of operating time a surgeon h may legally perform each planning horizon (in minutes)

***Table 3:** Surgeon's parameters and respective description.*

Parameter	Description
$mss_{s_c\,d\,b\,o} \in \{0,1\}$	Equals 1 if medical speciality s_c is assigned to OR o, at block b, at day d of the planning horizon; 0 otherwise
$block\_capacity$	Length (in minutes) of time blocks destined to base production
$block\_capacity\_add$	Length (in minutes) of time blocks destined to additional production

***Table 4:** Time blocks' related parameter and respective description.*

Decision Variable (First Phase)	Decision Variable (Second Phase)	Description
$x_{c\,d\,b\,o} \in \{0,1\}$	$z_{c\,d\,b\,o} \in \{0,1\}$	Equals 1 if case c is scheduled for day d of the planning horizon, at block b, at OR o; 0 otherwise
$w_{h\,d\,b\,o} \in \{0,1\}$	$v_{h\,d\,b\,o} \in \{0,1\}$	Equals 1 if surgeon h is assigned for day d of the planning horizon, at block b, at OR o; 0 otherwise
$t_{c\,h} \in \{0,1\}$	$l_{c\,h} \in \{0,1\}$	Equals 1 if case c is assigned to doctor h; 0 otherwise
$y_c \in \{0,1\}$	$k_c \in \{0,1\}$	Equals 1 if case c is not scheduled at the planning horizon; 0 otherwise

***Table 5:** List of the decision variables defined for each phase's model.*

$$\sum_{d \in D} \sum_{b \in B} \sum_{o \in O} x_{c\,d\,b\,o} + y_c = 1, \forall c \in C \quad (\mathbf{1})$$

$$\sum_{o \in O} w_{h\,d\,b\,o} \le 1, \forall d \in D, b \in B, h \in H \quad (\mathbf{2})$$

$$w_{h\,d\,b\,o} \le avl_{h\,d}, \forall d \in D, b \in B, o \in O, h \in H \quad (\mathbf{3})$$

$$t_{c\,h} \le skills_{h\,s_c}, \forall c \in C, h \in H, s_c \in S \quad (\mathbf{4})$$

$$x_{c\,d\,b\,o} \le mss_{s_c\,d\,b\,o}, \forall c \in C, d \in D, b \in B, o \in O, s_c \in S \quad (\mathbf{5})$$

$$\sum_{c \in C} (x_{c\,d\,b\,o} \times (tot_c + cln_c)) \le block\_capacity, \forall d \in D, b \in B, o \in O \quad (\mathbf{6})$$

$$\sum_{h \in H} t_{c\,h} \le 1, \forall c \in C \quad (\mathbf{7})$$

$$\sum_{d \in D} \sum_{b \in B} \sum_{o \in O} x_{c\,d\,b\,o} - \sum_{h \in H} t_{c\,h} = 0, \forall c \in C \quad (\mathbf{8})$$

$$\sum_{h \in H} w_{h\,d\,b\,o} = 1, \forall d \in D, b \in B, o \in O \quad (\mathbf{9})$$

$$x_{c\,d\,b\,o} + w_{h\,d\,b\,o} \le t_{c\,h} + 1, \forall c \in C, d \in D, b \in B, o \in O, h \in H \quad (\mathbf{10})$$

$$\sum_{c \in C} (t_{c\,h} \times sgn_c) \le lim_h, \forall h \in H \quad (\mathbf{11})$$

$$\sum_{d \in D} \sum_{b \in B} \sum_{o \in O} z_{c\,d\,b\,o} + k_c = 1, \forall c \in C \quad (\mathbf{12})$$

$$\sum_{o \in O} v_{h\,d\,b\,o} \le 1, \forall d \in D, b \in B, h \in H \quad (\mathbf{13})$$

$$v_{h\,d\,b\,o} \le avl_{h\,d}, \forall d \in D, b \in B, o \in O, h \in H \quad (\mathbf{14})$$

$$l_{c\,h} \le skills_{h\,s_c}, \forall c \in C, h \in H, s_c \in S \quad (\mathbf{15})$$

$$z_{c\,d\,b\,o} \le mss_{a\,d\,b\,o}, \forall c \in C, d \in D, b \in B, o \in O \quad (\mathbf{16})$$

$$\sum_{c \in C} \left(z_{c\,d\,b\,o} \times (tot_c + cln_c)\right) \le block\_capacity\_add, \forall d \in D, b \in B, o \in O \quad (\mathbf{17})$$

$$\sum_{h \in H} l_{c\,h} \le 1, \forall c \in C \quad (\mathbf{18})$$

$$\sum_{d \in D} \sum_{b \in B} \sum_{o \in O} z_{c\,d\,b\,o} - \sum_{h \in H} l_{c\,h} = 0, \forall c \in C \quad (\mathbf{19})$$

$$\sum_{h \in H} v_{h\,d\,b\,o} = 1, \forall d \in D, b \in B, o \in O \quad (\mathbf{20})$$

$$z_{c\,d\,b\,o} + v_{h\,d\,b\,o} \le t_{c\,h} + 1, \forall c \in C, d \in D, b \in B, o \in O, h \in H \quad (\mathbf{21})$$

Expression 3 ensures, according to that parameter, that only available surgeons are assigned to a certain day *d* and time block *b*. It is not mandatory that the case's proponent doctor is the surgeon who actually performs the surgery. However, it must be a qualified surgeon for that medical speciality. Therefore, Expression 4 guarantees that, according to parameter $skills_{h\,s_c}$, the surgeon *h* who performs the surgery is skilled in the case's speciality, s_cThe hospital's Master Surgery Schedule (MSS), defined at a tactical decision level, is a necessary input for the surgery scheduling, as it defines the assignment of the medical specialities for each OR, day and time block. As presented before, the MSS is provided by parameter $mss_{s_c\,d\,b\,o}$ and Expression 5 constrains the scheduling of a surgical case *c* to time blocks *b* which are assigned to the case's medical speciality, s_c. As referred before, each time block has a defined duration which must not be exceeded. Expression 6 ensures that the assigned cases can be fitted in the time block, without overtime, accounting for the average total room occupation of each case, sgn_c, and the cleaning times cln_c.The decision variable $t_{c\,h}$ translates the assignment of surgery *c* to surgeon *h*, taking the value of one in that case. It is necessary to guarantee that for each case *c* either there is a single surgeon *h* assigned or no surgeon is assigned, as ensured by Expression 7. In case a surgery *c* is scheduled, one and only one surgeon *h* must be assigned, and, contrarily, if a case *c* is not scheduled, there is no surgeon assigned to the case. These requirements are translated by Expression 8. At each time block, it must be assured that there is one and only one surgeon *h* assigned, as guaranteed by Expression 9. In order to establish the correct association between decision variables $x_{c\,d\,b\,o}$, $w_{h\,d\,b\,o}$ and $t_{c\,h}$, Expression 10 was defined. If surgeon *h* is assigned to the time block where surgery *c* is scheduled, surgeon h must be assigned to surgery *c*. Expression 11 guarantees that the operating hours each surgeon *h* performs each planning horizon do not exceed the established limit, lim_h.

Additional production's constraints are generally equivalent to the previous ones. The decision variables are substituted by the corresponding ones for additional production. Constraint 11 from the previous phase is not replicated in the second phase, as in additional production no limitation is defined regarding surgeon's operating hours. Furthermore, there are time blocks specifically allocated for additional production, defined in the MSS, which can accommodate any surgical speciality, and Constraint 16 restricts the surgery scheduling under additional regime to those blocks.

Regarding objective functions, Expression 22 corresponds to base production's objective function which prioritizes the scheduling of cases which are closer to the due date, or whose due date has already passed, while avoiding the scheduling of cases with lower priority and shorter longevity in the list.

$$min \sum_{c \in C} \sum_{d \in D} \sum_{b \in B} \sum_{o \in O} [x_{c\,d\,b\,o} \times (dd_c - current\_date) + y_c \times p_c \times (current\_date - d1_c)] \quad \textbf{(22)}$$

Several objective functions are considered for additional production regime, establishing different scenarios, whose outcomes will be analysed later. This regime has the main objective of answering the unmet needs from base production, contributing to achieve the contracted targets. It is appealing for surgeons, as they are paid for each surgery performed and, therefore, are interested in scheduling as many surgeries as possible, maximizing throughput, as translated by Expression 23.

$$max \sum_{c \in C} \sum_{d \in D} \sum_{b \in B} \sum_{o \in O} z_{c\,d\,b\,o} \quad \textbf{(23)}$$

From the point of view of the hospital administration, it is also important to maximize throughput to meet production objectives, nevertheless prioritization should not be overlooked. Expression 24 maximizes throughput, although cases are weighted by the corresponding priority.

$$max \sum_{c \in C} \sum_{d \in D} \sum_{b \in B} \sum_{o \in O} (z_{c\,d\,b\,o} \times p_c) \quad \textbf{(24)}$$

One of the core principles of additional production is also to enable the reduction of the time a patient waits for a surgery. Expression 25 also maximizes throughput, although in this case surgeries are weighted by the corresponding waiting times and priorities, allowing to integrate the patients' interests in the scheduling process.

$$max \sum_{c \in C} \sum_{d \in D} \sum_{b \in B} \sum_{o \in O} (z_{c\,d\,b\,o} \times (current\_date - d1_c)) \times p_c) \quad \textbf{(25)}$$

4. Data and Computational Experiments

This chapter describes the input data used to test the models, whose formulation was described previously. Furthermore, it describes the general functional structure of the proposed approach and presents how computational experiments were performed.

Firstly, regarding the set of surgical cases on the waiting list, it was possible to obtain real data from Hospital do Espírito Santo de Évora: a waiting list of 1884 unscheduled cases at the date of January 1st 2018, which correspond to the subset C_0, and, additionally, all the 202 cases which were added to the list throughout January 2018. The set C contains all the 2086 cases to be scheduled. Regarding the cases from subset C_0, about 87% had already surpassed their due dates, and those out-of-date cases are mostly levelled 1, in terms of priority. The surgical cases cover 8 different surgical specialities, s_c, composing the set $S =$ { "Cirurgia Geral" , "Oftalmologia" , "Urologia", "Cirurgia Plástica", "Ortopedia", "Estomatologia", "Otorrinolaringologia", "Cirurgia Pediátrica" }. It was also possible to obtain a set *H* of the active surgeons in the hospital.

A weekly planning horizon was chosen, hence a set *D* of 6 days was considered, as Sunday is not considered. At each day, a set B_d of 2 time blocks, corresponding to morning and afternoon, was considered. For regular production it was defined a block capacity of 360 minutes, while for additional production, despite there is no defined limitation, a duration of 480 minutes was established. There is a set *O* of 5 ORs in the hospital where surgeries can be carried out.

Regarding the case's parameters, it was possible to obtain information of each case's date of entry on the list ($d1_c$), due date (dd_c), clinical priority level (p_c) and the average duration of the procedure, in terms of surgeon time (sgn_c). The cleaning time after each case was assumed to be 30 minutes. Since there was no information regarding the total room occupation (tot_c), 30 minutes were added to the surgeon time (sgn_c).

It was also possible to get the information of the medical specialities usually performed by each doctor, enabling to construct parameter $skills_{h\,s_c}$. Additionally, most of the doctors' weekly availabilities were obtained to construct parameter $avl_{h\,d}$. Availabilities which were not obtained were generated randomly. The maximum limit of operating time per week for each surgeon, lim_h , was assumed to be 1800 minutes. Lastly, the hospital's weekly MSS was the basis to construct parameter $mss_{s_c\,d\,b\,o}$.

The models were tested for 5 consecutive weeks, corresponding to the month of January 2018. During the first planning week, only surgeries from the set C_0 scheduled. Then, for each week, surgeries which have entered the waiting list during the previous week are added to set C and are set to be scheduled. The two phases' models, corresponding to the two production regimes, run sequentially: firstly base production scheduling is done and the unscheduled surgeries are the input for additional production, followingly. The unscheduled surgeries after additional production scheduling remain in the list for the subsequent week, while scheduled surgeries are removed.

5. Results and Discussion

This chapter presents and discusses the obtained results from the computational experiments performed. Three different scenarios were tested, having in common objective function 22 for base production. Scenarios differ on the additional production's objective function: Scenario 1 used function 23, Scenario 2 used function 24 and Scenario 3 used function 25.

The first performed analysis was a comparison of the waiting list characteristics, in terms of length, average waiting time and average tardiness, for the three tested scenarios, after the end of the planning month. Table 6 summarizes the comparison, highlighting the cells corresponding to the best result in each indicator. The values reported by the hospital before the beginning of the first planning week, for the same indicators, are discriminated in the table as well, serving as a reference for the comparison.

	Waiting List Length	**Average Waiting Time**	**Average Tardiness**
Scenario 1	1551	221,3	-165,7
Scenario 2	1379	195,7	-139,7
Scenario 3	1350	251,5	-180,7
Reference (01-01-2018)	1884	268,2	-214,6

Table 6: *Summary of the obtained results in terms of waiting list characteristics (unscheduled cases) – length, average waiting time and average throughput - after the planning month for the three scenarios.*

Regarding the waiting list length, it was Scenario 3 that resulted in the shortest list, just above Scenario 2 list, although without a significant difference. Scenario 1 resulted in a waiting list significantly longer than the others. Due to the fact that under Scenario 3 the additional production's objective function maximizes throughput, weighting the cases by the corresponding waiting times, alongside the large number of cases with long waiting times, this scenario achieved a greater throughput.

Scenario 2 obtained the best results for the average waiting time and average tardiness. The good performance of this scenario is associated with the objective functions of the two regimes enabling an equilibrium between scheduling higher priority cases, under additional production, and scheduling cases whose due date had been expired for longer, under base production. As a result, most of the higher priority cases are scheduled timely, and lower priority cases that have been waiting for longer are finally scheduled.

Moreover, it should be highlighted that all scenarios enabled an improvement of the waiting list situation. In fact, according to the analysed indicators, when comparing with the values reported by the hospital before the beginning of the first planning week, the obtained results are significantly better.

Besides analysing characteristics of unscheduled patients, it is also relevant to conduct a comparative analysis for scheduled patients after the planning month. Firstly, it was analysed the proportion of scheduled surgeries per priority level, relative to the total number of cases of each priority level that had registered in the waiting list. The obtained results of each scenario are summarized in Table 7, and the greatest proportion obtained for each priority level is highlighted.

	Scenario 1	**Scenario 2**	**Scenario 3**
Level 1	27,0%	29,1%	38,5%
Level 2	16,0%	69,5%	13,4%
Level 3	11,7%	68,3%	8,3%

Table 7: *Summary of the obtained results in terms of the proportion of scheduled patients from each priority level, after the planning month, for the three scenarios.*

The results show that Scenario 2 enabled the scheduling of most cases of priority levels 2 and 3, achieving much greater proportions of scheduled patients than the other scenarios for these priority levels. Regarding priority level 1, it was difficult to achieve a large proportion of scheduled cases due to the vast number of level 1 cases that had registered in the waiting list. Despite Scenario 3 achieved the best proportion of scheduled level 1 surgeries, for the remaining priority levels the obtained proportions were the lowest. Overall, it was Scenario 2 that achieved the best balance between the proportions of scheduled surgeries of each priority level. In fact, base and additional production regimes complement each other in Scenario 2 to enable an equilibrium between prioritizing cases with greater severity (higher priority levels) and scheduling cases which have been waiting for long periods. On the other hand, in Scenario 3 both regimes prioritize the same profile of surgeries, with expired due dates and longer waiting times, and almost ignore the scheduling of higher priority surgeries.

Due to the fact that most of the surgeries in the waiting list were already out of date at the beginning of the planning week, very few surgeries were timely scheduled throughout the planning month. Table 8 summarizes the proportion of scheduled surgeries under each scenario which were scheduled before their due date. Under Scenario 2 more surgeries were timely scheduled than under the other scenarios, which is related with the larger number of higher priority surgeries scheduled under this scenario. Scenario 3 obtained the lowest percentage of timely scheduled surgeries as it precisely prioritized the surgical cases already out of date.

	Scenario 1	Scenario 2	Scenario 3
Timely Scheduled	6,6%	16,0%	1,2%

Table 8: *Summary of the obtained results regarding the percentage of scheduled cases which were timely scheduled, after the planning month, for the three scenarios.*

Analysing the evolution of the average waiting time of scheduled cases across the two production regimes, for the three scenarios, a general decreasing trend is verified, as shown by Table 9. As cases waiting for longer periods are gradually scheduled throughout the weeks, the average waiting time of scheduled cases decreases. Under Scenario 3 the obtained values are larger due to the fact that both additional and base production regimes prioritize the scheduling of cases waiting for longer. Scenario 2 balances the scheduling of cases with longer waiting times with the scheduling of higher priority cases with shorter waiting times, consequently, averages shorter waiting time values of scheduled cases.

	Scenario 1	Scenario 2	Scenario 3
Week 1	641,1	353,15	731,38
Week 2	500,3	320,35	588,09
Week 3	484,1	376,31	459,96
Week 4	399,6	383,16	376,68
Week 5	246,5	234,99	357,13

Table 9: *Summary of the obtained average waiting times of scheduled cases across the two regimes for each week and under each scenario.*

Regarding the average tardiness of scheduled cases, the same decreasing trend, in absolute values, is registered throughout the weeks for all scenarios, as shown by Table 10. In absolute values, Scenario 2 registered the lowest values, while Scenario 3 registered the highest, the same observed for the average waiting times. The reasons behind the obtained results are the same mentioned previously for the waiting times, although applied to tardiness.

	Scenario 1	Scenario 2	Scenario 3
Week 1	-583,8	-249,3	-673,5
Week 2	-441,9	-265,9	-528,8
Week 3	-427,1	-320,9	-401,2
Week 4	-340,5	-327,1	-318,6
Week 5	-188,9	-180,5	-277,2

Table 10: *Summary of the obtained average tardiness of scheduled cases across the two regimes for each week and under each scenario.*

6. Conclusions

The concept of additional production has revolutionized the surgical activity in Portugal, with proven results in reducing the waiting lists and times for elective surgeries, alongside ensuring compliance with due dates. However, without an optimization tool to support the scheduling process, this stream of production might not be explored in its full potential. In the current context, the proposed approach can be an important contribution to support hospital administrations get the maximum benefit from the regime, improving its outcomes.

The ideal surgery scheduling method should find the optimum balance between the compliance with due dates associated with priority levels and avoiding long patient waiting times. Due to the characteristics of the initial waiting list, with many cases with priority level 1 waiting for long periods, it was complicated to find a decent compromise. However, Scenario 2 managed to find a good balance by scheduling cases with greater longevity in the waiting list under base production and higher priority cases under additional production, ensuring that most of the cases with priority level 3 were timely scheduled. Despite the initial prediction was Scenario 3 satisfying the interests of all the stakeholders involved, it ended up being Scenario 2 to achieve the best compromise between surgical team's, patients' and administration's interests. Furthermore, Scenario 2 enabled an improvement of the waiting list situation, in terms of average waiting times and average tardiness, having as a reference the statistics provided by the hospital, from the beginning of the planning month.

Regarding the limitations of the study, it should be mentioned that the developed models do not reflect all the real-life aspects which constrain the process of elective patient scheduling. In fact, only surgeon's availability was considered in terms of human resources constraints, leaving out the availabilities of the remaining surgical team personnel, Regarding the material resources needed for each surgery, they were assumed to be always available as well. In terms of installations, the availability of beds in downstream facilities, which may constitute a bottleneck in the process, was not considered. Despite the great influence of these and other factors in the scheduling process, increasing the models' number of constraints would increase their complexity and compromise their feasibility. For sake of simplicity of the model, it was assumed to be deterministic, not accounting for any uncertainty in surgery durations. However, in a real-life scenario it is known that unpredictable events can happen, and surgical times end up being different from what was predicted. Another aspect which causes enormous impact in the OR scheduling process is the arrival of emergency cases, another source of stochasticity which the models do not consider, as only elective cases were accounted. The computational experiments were only performed for a single month, which is not enough to verify the long-term outcomes of the proposed approach. In case the experiments were done for a longer period, it would also be interesting to consider a dynamic MSS that would change according to the current waiting list situation. The possibility of adjusting the allocation of time slots to additional production on a weekly basis, according to the waiting list situation, would also be a significant improvement.

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