

# Maximizing the efficiency of residents operating room scheduling: a case study at a teaching hospital

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## Abstract

**Paper aims:** To find efficient operation room scheduling for residents considering several resources constraints and ensuring a minimum number of surgeries for approval in the training program.

**Originality:** We find no research in current literature addressing operation room resource allocation for residents training in order to meet legislation approval criteria.

**Research method:** The number of procedures to be performed by each resident was defined by Brazilian legislation and by the rules obtained from interviews with the chief professor of a vascular hospital. To solve the allocation of doctors to surgeries planning problem, also addressed in literature as Master Surgical Schedule (MSS), we propose a mathematical programming approach.

**Main findings:** The mathematical model showed that some of the current rules of resource availability bring about infeasible planning when trying to achieve the legislation quantitative rules for the residents training.

**Implications for theory and practice:** The model allowed the decision maker to plan and schedule vascular surgeries in a better and faster way, through an automated system, instead of allocating residents to surgeries manually, which takes many hours per month. Furthermore, changing the input data in the proposed model can allow other hospitals or specialists to get efficient results in less time.

## Keywords

Scheduling; master surgical scheduling. Mathematical programming. Vascular surgery. Hospital.

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## 1. Introduction

Vascular diseases are serious illnesses – their treatment is complex and requires specialized surgical procedures, which are performed in tertiary health centers. In order to perform these procedures, sophisticated equipment, qualified teams and intensive care units (ICU) prepared for the postoperative period are necessary. The increase in the life expectancy of a population causes a higher prevalence of this type of disease, which has imposed a significative burden to the Brazilian Unified Health System (SUS) (Mendes et al., 2014).

According to Barbagallo et al. (2015), offering a better quality of service with limited resources, and at a lower cost, is a global health challenge. This makes the goal of optimization a central theme in modern hospital management, as it allows for increases in resource efficiency through the development of advanced methods to plan and program the hospitals' processes. On the other hand, residents have to fulfill a number of specific procedures as part of their educational requirements facing many variabilities. This may result in a high amount of overtime hours to succeed in each stage of their educational process and bring negative effects that decrease the quality of provided care (Erhard et al., 2018).



In this context, a teaching hospital deals with a challenge: increasing resource efficiency planning while subject to several rules from various regulational requirements (from the Ministry of Health, the Ministry of Education and various professional councils) (Assad et al., 2018a). Therefore, to achieve an efficient planning of resident allocation, we propose a mathematical programming approach. This technique associates the annual minimum number of surgeries that must be realized by each resident to operating room planning, through optimal resource allocation.

## 2. Theoretical background: hospital management and operating room planning

In several regions of the world, health care industry is facing a dilemma due, on one hand, to the poor quality standards of services offered and, on the other hand, to strong pressure to increase efficiency and productivity, and to reduce costs (Vähätalo & Kallio, 2015; Spiegel & Assad, 2018).

Optimization issues in healthcare have received considerable attention for over three decades. More recently, however, with declining birth rates in almost all developed countries, and increasing average longevity overall, optimization issues in healthcare have become notoriously important, attracting research institutions and great social interest. Over the years, attention has gradually expanded from resource allocation and strategic planning to include operational issues, such as resource scheduling and treatment planning (Rais & Viana, 2011; Silva et al., 2018; Assad et al., 2018b).

According to Barbagallo et al. (2015), hospital budgets account for almost half of all expenditures in most health systems, and the most important reasons for hospital admission are procedures or surgical interventions.

Van Sambeek et al. (2010) categorize decision-making models related to design and control processes that involve patient flows in hospitals. The authors' objective is to map out how hospitals try to achieve the goals of higher quality and higher resource allocation efficiency in the field of operations management (OM) and operational research (OR). The synthesis of this categorization is presented in Table 1.

Table 1. Optimizing hospital processes models: classifications and categories.

Classifications	Categories
Type of model	Computer simulation Descriptive Analytical
Type of problem	Process Design Capacity problem Scheduling problem
Kind of department	Operating room Inpatient Outpatient Imaging diagnosis Other
Objective of study	Designing a model Comparing models Using a model Critiquing/ proposing a model
Outcome measures	Waiting times Needed capacity Cost Utilization others
Validated in practice	Yes/no
Generic	Yes/no

Source: adapted from Van Sambeek et al. (2010).

Abdelrasol et al. (2014) state that operating room planning can be divided into 3 decision levels: (i) case mix problem, (ii) master surgical scheduling and (iii) surgery scheduling. The last decision level can be broken down into (1) operational offline and (2) operational online (Hulshof et al., 2012). According to Assad (2017), the decision level and types of decisions taken in each are as summarized in Table 2. The relation between operating room planning and decision support techniques in the OM & OR contexts is syntetized in Figure 1.

Table 2. Decision levels and type of problems in operating room planning.

Decision level	Planning horizon	Type of problem	Decisions taken
Strategic	1 year	Case mix Problem (CMP)	Decide which surgeries will be offered by the hospital
Tactical	1, 2 or 3 months	Master Surgical Schedule Problem (MSSP)	Define which surgeon (or specialty) will be allocated in which rooms in a time horizon.
Operational Off-line	Week or day	Surgical Case Assignment Problem (SCAP)	Allocate each surgeon to each surgery on days defined by the MSSP and define order of execution.
Operational Online	Hours	Rescheduling	Rescheduling when unplanned events occur (dealing with real time variabilities).

Source: adapted from Assad (2017).

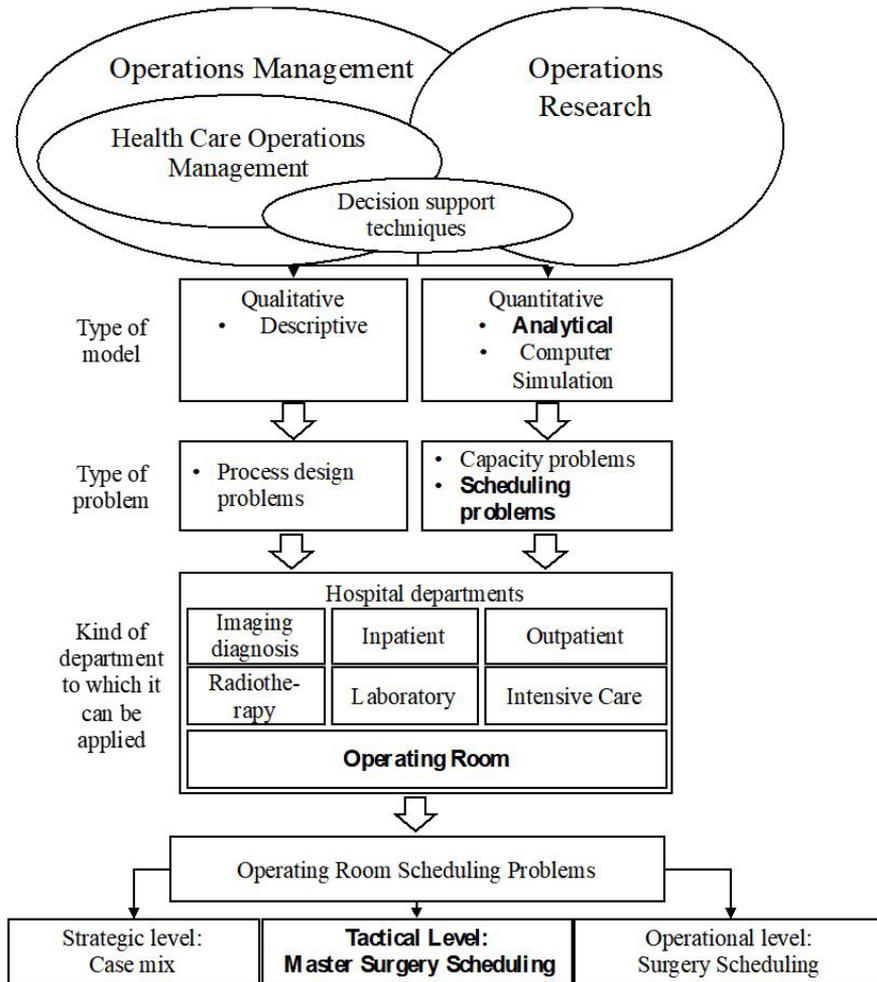


Figure 1. Synthesis of operating room planning literature review. Source: adapted from Assad (2017).

Although mathematical programming models have been widely used to solve Master Surgery Scheduling Problems (Persson & Persson, 2007; Van Oostrum et al., 2008; Beliën et al., 2009; Wang et al., 2010; Day et al., 2012; He et al., 2012; Paul & Jotshi, 2013; Sufahani & Ismail, 2014; Saadouli et al., 2015; Villarreal & Keskinocak, 2016) there is no research in which quantitative legislation criteria are considered, according to Erhard et al. (2018).

Therefore, in order to cover this literature review gap Assad et al. (2018a) proposed a mixed integer linear programming model and the current research merges it with a brief theoretical background better discussed in Assad (2017) in an enhanced version.

### 3. Research method

Following the classification proposed by Yin (2001), this research is an exploratory single case study. Its objective is to deepen the comprehension regarding a problem that is not yet sufficiently studied, to suggest hypotheses and questions, or to develop the theory (Miguel, 2007). The case study is divided in three parts: literature review (results presented in Table 3 – see Assad (2017) for more information), resource parametrization and mathematical modelling.

Table 3. Synthesis of literature review on MSSP.

Authors	Objective of the model	Constraints considered	Type of data utilized	Planning horizon	Formulation of the optimization model <sup>1</sup>	Type of solution <sup>2</sup>
Persson & Persson (2007)	Minimize costs related to not operating on a patient considering their priority	surgery room, human resources, and beds	Real data	Weekly	MILP	Exact
Van Oostrum et al. (2008)	Minimize room allocation and peaks of bed occupation	surgery room, human resources, and beds	Real data	Weekly	MILP	Heuristic
Beliën et al. (2009)	Minimize the peak of bed occupation	surgery room, human resources, and beds	Real data	Weekly	MILP and IQP	Exact and heuristic
Wang et al. (2010)	Maximize priority surgeries controlling staff workload	surgery room and human resources	Real data	Weekly and offline daily	MILP	Heuristic
He et al. (2012)	Minimize costs related to human resources (nursing)	surgery room and human resources (nursing)	Real data	Weekly	MILP	Exact
Day et al. (2012)	Maximize revenue and staff satisfaction	surgery room and human resources	Real data	Biweekly	MILP	Heuristic
Jeang & Chiang (2012)	Minimize idle time and overtime	surgery room and human resources	Real data	Biweekly	MINLP	Exact
Paul & Jotshi (2013)	Minimize room allocation	surgery room and human resources	Real data	Weekly and offline daily	MILP	Exact
Sufahani & Ismail (2014)	Level occupation between surgery rooms	surgery room and human resources	Real data	Weekly	MILP	Exact
Saadouli et al. (2014)	Maximize amount of surgeries	surgery room and human resources	Real data	Weekly	MILP	Exact
Saadouli et al. (2015)	Maximize amount of surgeries	surgery room, post-anesthesia recovery (PAR)	Real data	Weekly	MILP	Exact
Villarreal & Keskinocak (2016)	Minimize resource allocation (nursing)	budget	Real data	Yearly (48 weeks)	MILP	Heuristic
This article	Minimize resource allocation	Surgery room, human resources, equipment, blood bags	Real data	Annual	MILP	Exact

<sup>1</sup>Optimization models may be formulated in different ways, among which stand out the following: integer programming (IP), mixed integer linear programming (MILP), integer quadratic programming (IQP), and mixed integer non-linear programming (MINLP); <sup>2</sup>Depending on the complexity of the modeling and/or the size of the model, finding the optimal solution, considering all combinations of the feasible solutions space (exact solution) may result in very long resolution times. To avoid long solution times, many authors propose faster solution methods (heuristics), that disconsider part of the feasible solutions space to obtain a solution (not necessarily the optimal one). Source: adapted from Assad (2017).

According to Barbagallo et al. (2015), the management of the surgery center must follow the three steps described in Figure 2. The scope of this research will be limited to the parametrization of resources necessary for the execution of surgeries in the vascular clinic, and to the proposition of optimization models to estimate the relation between resources necessary for respecting the normative instruments that govern surgical services applied to the case of vascular surgery.

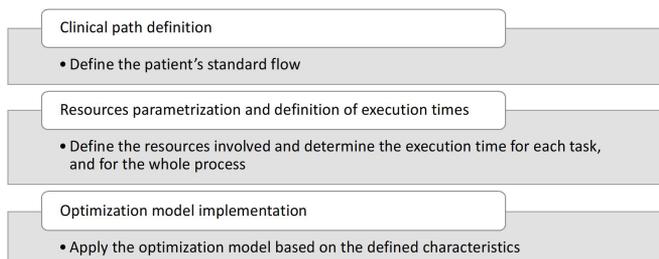


Figure 2. Optimized planning steps for operation room management. Source: adapted from Barbagallo et al. (2015).

#### 4. Problem description: vascular surgeries at a teaching hospital

Teaching hospitals are subject to several rules from many regulational requirements (from the Ministry of Health, the Ministry of Education and various professional councils). Regarding the residency program, the National Commission of Medical Residency (*Comissão Nacional de Residência Médica – CNRM*) (The specific legislation that governs the residency programs in Brazil is available at (in Portuguese) (Brasil, 2006) and the National Commission of Multiprofessional Healthcare Residency (*Comissão Nacional de Residência Multiprofissional em Saúde – CNRMS*) stand out. Both define the minimal requirements for obtaining the surgeon license in each specialty. Currently, these minimal requirements are defined by the CNRM Resolution number 02/2006, from May 17th, 2006 (Brasil, 2006). For the vascular surgery specialty, this resolution demands that each resident carries out at least 150 surgeries, with a minimum of 50 arterial surgeries per year of the program, and at least 30% of small size surgeries, 40% of medium size surgeries, and 40% of large size surgeries in a one-year timespan. Differently from other specialties, these numbers are the same for both the general surgeons on the first year of residency in vascular surgery (R1) and for those on the second year (R2). The hospital being studied also offers a subspecialty of vascular surgery named endovascular surgery that may be performed by the vascular surgeon, and that lasts for a year. Typically, after concluding the second year, the new vascular surgeons participate in this residency program (R3). Surgeries are divided in small size, medium size, and large size surgeries (Table 4).

Despite the validity of the division as a normative instrument, the chief surgeon of vascular surgery categorizes surgeries of this specialty in seven aggregated groups: varicose veins and veins surgeries, aorta surgeries, fistula surgeries, femoral surgeries, carotid surgeries, amputation surgeries, and endovascular procedures.

Table 4. Minimum amount of procedures defined by the current legislation.

CNRM Resolution number 02/2006	Minimum amount of procedures to be performed by the professional to obtain the license to offer vascular surgery service	
Classification of vascular surgery procedures	Procedures	Amount of surgeries throughout the year
Small size	Vascular accesses, arteriovenous fistulas, vascular radiology, small amputations and debridement	45
Medium size	Embolectomies; femoral-popliteal, femoral-femoral, axillo-femoral, iliac-femoral, distal grafts; venous surgeries; amputations, sympathectomies and vascular radiology.	60
Large size	Surgery of the carotid arteries, aneurysms, aortoiliac and femoral grafts, arterial reoperations	45
Total	-	150

Source: adapted from the Ministry of Education (Brasil, 2006).

This additional categorization brought the necessity to build Table 5 together with the surgeon chief of vascular surgery to draw the intersection between these surgery groups and the procedures described by the normative instrument regarding “size” and group. On the second to last column, arterial surgeries are assigned with an X. This emphasizes the importance of the development of decision support models in collaboration with their future users. On the last line, the number of surgeries by size are established, following the same proportion established by the CNRM Resolution Number 02/2006 (Brasil, 2006).

Through Table 5, it is possible to notice that a resident may reach the minimum number of surgeries by size established by the CNRM Resolution by executing many procedures in more than one category throughout the year. Despite this, the professors (preceptors) of vascular surgery (staff) understand that a less experienced resident should execute and improve their ability in more simple procedures, while more experienced ones should improve their ability in procedures of higher complexity. This relation is presented in Table 6, where X indicates which resources are necessary to execute each type of surgery. On the columns R1 Doctor, R2 Doctor, and R3 Doctor, the X indicates that this resident doctor is enabled to execute that type of procedure. However, only one resident doctor is allocated to perform each surgery. As in the case of Table 5, Table 6 was also built together with the chief surgeon of vascular surgery. The chief surgeon also indicated that the R3 resident doctor doesn't perform amputation surgeries, even though he/she is enabled to do amputations of any size.

This research considers that the sterile processing department (*Central de Material de Esterilização – CME*) cannot sterilize the surgical instruments for reuse on the same day; that is, throughout the day, the CME only stores the surgical instruments. The stock levels of each type of surgical instruments are described on Table 7. It is also assumed that the hospital's blood bank has the capacity to provide blood bags for up to 1 patient per day.

Table 5. Classification of procedures regarding category and size.

Surgery size	Great categories – classification per blocks of surgery	Procedures	Arterial surgeries	Number of surgeries per year (CNRM Resolution number 02/2006)
Small	Varicose veins and veins	Venous surgeries		-
	Aorta	-	X	
	Fistula	Vascular access	X	
	Femoral	-	X	
	Carotid	-	X	
	Amputation	Amputation		
	Endovascular	Vascular radiology		
Subtotal	Small size	-	-	15
Medium	Varicose veins and veins	Venous surgeries		-
	Aorta	-	X	
	Fistula	Vascular access	X	
	Femoral	Femoral-popliteal, femoral-femoral, axillo-femoral, iliac-femoral, distal grafts	X	
	Carotid	axillo-femoral	X	
	Amputation	Amputation		
	Endovascular	Vascular radiology		
Subtotal	Medium size			20
Large	Varicose veins and veins	Venous surgeries		-
	Aorta	Axillo-femoral, surgery of the carotid arteries, aneurysms, aortoiliac and femoral grafts, arterial reoperations		
	Fistula	Vascular access	X	
	Femoral	Axillo-femoral, surgery of the carotid arteries, aneurysms, aortoiliac and femoral grafts, arterial reoperations	X	
	Carotid	Axillo-femoral, surgery of the carotid arteries, aneurysms, aortoiliac and femoral grafts, arterial reoperations	X	
	Amputation	Amputation		
	Endovascular	Vascular radiology		
Subtotal	Large size	-	-	15
Total	-	-	-	50

Source: Chief of vascular surgery service and Ministry of Education (Brasil, 2006).

The relation between the amount of residents by type (R1 doctor, R2 doctor, and R3 doctor) and the minimum frequency in which they should be allocated is presented in Table 8

The operating hours of the operating room, to meet the demand for elective surgeries, are from 7 am to 7 pm, on weekdays only. However, working hours were considered to be from 8 am to 5 pm (540 minutes) in order to ensure 25% of slack time (the current literature assumes slack time between 20 and 30 percent of total time) (M'Hallah & Al-Roomi, 2014). It is also assumed that the time horizon (one year) in working days is 250 days.

## 5. Nomenclature and mathematical problem formulation: a surgery planning and scheduling

Proposing a surgery plan and a surgery schedule that respect all rules imposed by the legislation and by the hospital is a difficult and time-consuming task. This task is currently performed manually by the chief surgeon.

This article proposes a mathematical model to increase the efficiency of surgical planning. In other words, the model has the objective of finding the configuration that minimizes resource allocation (rooms, anesthetists and equipment), while respecting the minimum amount of surgeries. In addition, the proposed model considers as business rules: the minimum frequency of scheduling of the group of residents per week; the maximum amount of rooms available in the week; the maximum number of anesthetists available in the week; and the maximum amount of equipment available in the week.

Table 6. Relation between types of surgery and necessary inputs.

Resource parametrization		Necessary resources								Time (in minutes)			Human Resources			Minimum amount of surgeries				
Surgery size	Great categories – classification per blocks of vascular surgery	Phlebo-extractor	Advanced extracranial surgery	Advanced aorta surgery	Varicose Veins Box	Arteriovenous fistula Box	Femoral Box	Amputation Box	C-arm required for the procedure?	Blood bags required for the procedure?	Time of room preparation	Time of patient preparation	Surgery duration	Anesthetist required for the procedure?	R1 Doctor	R2 Doctor	R3 Doctor	R1 Doctor	R2 Doctor	R3 Doctor
	Aorta			X					X	X	20	0	-	-	X	X	X	0	0	0
	Fistula					X					20	0	60	-	X	X	X	20	0	0
	Femoral	X					X		X	X	20	0	150	X	X	X	X	5	15	0
	Carotid		X						X		20	0	-	-	X	X	X	0	0	0
	Amputation							X			20	0	40	-	X	X	X	10	0	0
	Endovascular (Laparoscopy)					X	X		X		20	0	60	-	X	X	X	0	10	15
Medium	Varicose veins and veins	X			X						20	20	75	X	X	X	X	10	5	0
	Aorta			X					X	X	20	20	-	-	X	X	X	0	0	0
	Fistula					X					20	20	110	X	X	X	X	20	0	0
	Femoral	X					X		X	X	20	20	210	X	X	X	X	10	15	15
	Carotid		X						X		20	20	135	X	X	X	X	0	15	10
	Amputation							X			20	20	50	X	X	X	X	10	0	0
	Endovascular (Laparoscopy)					X	X		X		20	20	135	-	X	X	X	0	10	20
Large	Varicose veins and veins	X			X						20	90	105	X	X	X	X	5	5	0
	Aorta			X					X	X	20	90	240	X	X	X	X	0	15	5
	Fistula					X					20	90	110	X	X	X	X	5	5	0
	Femoral	X					X		X	X	20	90	210	X	X	X	X	5	10	5
	Carotid		X						X		20	90	135	X	X	X	X	0	5	10
	Amputation							X			20	90	90	X	X	X	X	5	5	0
	Endovascular (Laparoscopy)					X	X		X		20	90	165	X			X	0	0	10

Source: chief of vascular surgery service.

Table 7. Amount of surgery instruments available at the CME.

CME – Surgery instruments	Amount available at CME
Phlebo-extractor	1
Advanced extracranial surgery	2
Advanced aorta surgery	2
Varicose Veins Box	5
FAV Box	2
Femoral Box	3
Amputation Box	2

Table 8. Number of residents by type.

Type of resident	Number of residents	Minimum frequency of weekly allocation
R1 Doctor	2	3
R2 Doctor	2	3
R3 Doctor	2	3

The nomenclature and mathematical model formulation are presented in Tables 9, 10 and 11. The model was implemented in the commercial software AIMMS® 3.14 with the standard solver CPLEX® 12.6 (Bisschop & Roelofs, 2011) on a computer with Intel Core i5 and 16 Gb of RAM.

**Table 9.** Statement of Master Surgical Schedule model indexes.

Indexes	Meaning	Domain	Sub indexes
ar	arterial surgery	AR = [2:5]	
s	Surgery	C = [1:7]	
d	Day	D = [1:250]	ar
e	Equipment	E = [1:1]	
i	Resource	R = [1:3]	
m	Material	M = [1:7]	
z	Surgery size	P = [1:3]	s, e
c	Class (group) of residents	R = [1:3]	
r	Room	S = [1:2]	

**Table 10.** Statement of Master Surgical Schedule model variables.

Variables	Meaning and type	Type
AcClSu <sub>c,s,z</sub>	Number of surgeries (s) of size (z) performed by residents of type (c) in the year	Integer
AnSu <sub>s,z</sub> <sup>r,d</sup>	Decision of allocating an anesthetist to perform surgery (s) of size (z) in room (r) on day (d)	Binary
AnDay <sup>r,d</sup>	Decision of allocating an anesthetist in room (r) on day (d)	Binary
AuxAn <sup>r,d</sup>	Auxiliary variable created to associate variables AnSu <sub>s,1</sub> <sup>r,d</sup> and AnDay <sup>s,d</sup>	Integer
AuxEq <sub>e</sub> <sup>r,d</sup>	Auxiliary variable created to associate variables EqSu <sub>e,s,1</sub> <sup>r,d</sup> and EqDay <sub>e</sub> <sup>r,d</sup>	Integer
AuxCl <sub>r</sub> <sup>d</sup>	Auxiliary variable created to associate variables ClSu <sub>c,s,1</sub> <sup>r,d</sup> and ClDay <sub>r</sub> <sup>d</sup>	Integer
EqSu <sub>e,s,z</sub> <sup>r,d</sup>	Decision of allocating equipment (e) in surgery (s) of size (z) in room (r) on day (d)	Binary
EqDay <sub>e</sub> <sup>r,d</sup>	Decision of allocating equipment (e) in room (r) on day (d)	Binary
MatSu <sub>m,s,z</sub> <sup>r,d</sup>	Decision of allocating surgical material (m) in surgery (s) of size (z) in room (r) on day (d)	Binary
ClSu <sub>c,s,z</sub> <sup>r,d</sup>	Decision of allocating a resident of type (c) to perform surgery (s) of size (z) in room (r) on day (d)	Binary
ClDay <sub>r</sub> <sup>d</sup>	Decision of allocating any resident of type (r) on day (d)	Binary
Room <sup>r,d</sup>	Decision of allocating or blocking room (r) on day (d) for the surgical service	Binary
BloodSu <sub>s,z</sub> <sup>r,d</sup>	Decision of allocating blood bag in surgery (s) of size (z) in room (r) on day (d)	Binary

**Table 11.** Statement of Master Surgical Schedule model parameters.

Parameters	Meaning	Values
durSu <sub>s,z</sub>	Duration of surgery (s) of size (z)	Table 6
fClwk	Minimum frequency of groups of residents per week	Table 12
haClSu <sub>s,r,z</sub>	Resident's (c) habilitation to perform surgery (s) of size (z)	Table 6
M	Large number	100.000
weight <sub>i</sub>	Weight assigned to each type of resource (i)	Table 12
nAnwk	Maximum number of anesthetists available in the week	Table 12
nSuYr	Minimum number of surgeries year for each resident	Table 4
nSuAr	Minimum number of arterial surgeries for each resident	Table 5
nSuArSz <sub>z</sub>	Minimum number of arterial surgeries per size for each resident	Table 5
nSuSz <sub>z</sub>	Minimum number of surgeries of size for each resident	Table 4
nSuCl <sub>c,s,p</sub>	Minimum number of surgeries (s) of size (z) for resident of type (c) established by the preceptor	Table 6

Table 11. Continued...

Parameters	Meaning	Values
$\overline{nEqwk}_e$	Maximum number of equipment (e) assigned in the week	Table 12
$nMat_m$	Number of surgical materials (m) available at SMC	Table 7
$nCl_c$	Number of residents per type (c)	Table 8
$\overline{nroomwk}$	Maximum amount of rooms assigned in the week	Table 12
$nblood$	Number of patients attended by hemotherapy service (blood) per day	1
$rSuAn_{s,z}$	Anesthetist-surgery relation (s,z)	Table 6
$rSuEq_{s,z,e}$	Surgery-equipment relation (s,z,e)	Table 6
$rSuMat_{s,z,m}$	Surgery-material relation (s,z,m)	Table 6
$rSublood_{s,z}$	Surgery-blood relation (s,z)	Table 6
$tPrep_z$	Preparation time for surgery of size (z)	Table 6
$tPreroom$	Room preparation time	Table 6
$troom$	Room time	540 minutes

Objective function:

$$\text{Min } \sum_{e,r,d} \text{Weight}_1 * \text{Room}^{r,d} + \text{Weight}_2 * \text{AnDay}^{r,d} + \text{Weight}_3 * \text{EqDay}_e^{r,d} \quad (1)$$

The objective function (1) minimizes the room allocation ( $Room^{r,d}$ ), anesthetists ( $AnDay^{r,d}$ ) and equipment ( $EqDay_e^{r,d}$ ) throughout the year. Prioritization is defined by the weights ( $Weight_i$ ). For example, if the weight assigned to the resource room is greater than the weights assigned to the other ones, the solver will seek the lowest possible room allocation value that meets all the constraints that will be presented below.

Constraints:

$$\sum_{s,z,c} ClSu_{c,s,z}^{r,d} * (\text{durSu}_{s,z} + tPrep_z + tPreroom) \leq troom \quad \forall r, d \quad (2)$$

$$\sum_{s,z,r} ClSu_{c,s,z}^{r,d} * (\text{durSu}_{s,z} + tPrep_z + tPres) \leq troom \quad \forall c, d \quad (3)$$

$$ClSu_{c,s,z}^{r,d} \leq Room^{r,d} \quad \forall c, s, z, r, d \quad (4)$$

$$AClSu_{c,s,z} = \sum_{r,d} ClSu_{c,s,z}^{r,d} \quad \forall c, s, z \quad (5)$$

$$AClSu_{c,s,z} \geq nSuCl_{c,s,z} * nCl_c \quad \forall c, s, z \quad (6)$$

$$\sum_s AClSu_{c,s,z} \geq nSuSz_z * nCl_c \quad \forall c, z \quad (7)$$

$$\sum_{ar,l} AClSu_{c,ar,z} \geq nSuAr * nCl_c \quad \forall c \quad (8)$$

$$\sum_{ar} AClSu_{c,ar,z} \geq nSuArSz_z * nCl_c \quad \forall c, z \quad (9)$$

$$\sum_{s,z} AClSu_{c,s,z} \geq nSuyr * nCl_c \quad \forall c \quad (10)$$

$$AnSu_{s,z}^{r,d} = \sum_c ClSu_{c,s,z}^{r,d} \quad \forall s, z, r, d \quad (11)$$

$$\text{AnDay}^{r,d} + \text{AuxAn}^{r,d} = \sum_{s,z} \text{AnSu}_{s,z}^{r,d} \quad \forall r, d \quad (12)$$

$$\text{AnDay}^{r,d} * M \geq \sum_{s,z} \text{AnSu}_{s,z}^{r,d} \quad \forall r, d \quad (13)$$

$$\text{EqDay}_e^{r,d} + \text{AuxEq}_e^{r,d} = \sum_{s,z} \text{EqSu}_{e,c,p}^{r,d} \quad \forall e, r, d \quad (14)$$

$$\text{EqDay}_e^{s,d} * M \geq \sum_{s,z} \text{EqSu}_{e,s,z}^{r,d} \quad \forall e, r, d \quad (15)$$

$$\text{ClDay}_c^d + \text{AuxCl}_c^d = \sum_{s,z,r} \text{ClSu}_{c,s,z}^{r,d} \quad \forall c, d \quad (16)$$

$$\text{ClDay}_c^d * M \geq \sum_{s,z,r} \text{ClSu}_{c,s,z}^{r,d} \quad \forall c, d \quad (17)$$

$$\text{MatSu}_{m,s,z}^{r,d} = \sum_c \text{ClSu}_{s,c,p}^{r,d} \quad \forall m, s, z, r, d \quad (18)$$

$$\sum_{s,z,r} \text{MatSu}_{m,s,z}^{r,d} \leq n\text{Mat}_m \quad \forall m, d \quad (19)$$

$$\text{BloodSu}_{s,z}^{r,d} = \sum_c \text{ClSu}_{s,c,p}^{r,d} \quad \forall s, z, r, d \quad (20)$$

$$\sum_{s,z,r} \text{BloodSu}_{s,z}^{r,d} \leq n\text{Blood} \quad \forall d \quad (21)$$

$$\sum_{d-4}^d \text{ClDay}_c^d \geq \underline{fClwk} \quad \forall c, d \quad (22)$$

$$\sum_{r,d-4}^d \text{Room}^{r,d} \leq \overline{n\text{Roomwk}} \quad \forall d \quad (23)$$

$$\sum_{r,d-4}^d \text{AnSu}^{r,d} \leq \overline{n\text{Anwk}} \quad \forall d \quad (24)$$

$$\sum_{r,d-4}^d \text{EqDay}_e^{r,d} \leq \overline{n\text{Eqwk}_e} \quad \forall e, d \quad (25)$$

Equation 2 ensures that each room is used in the operating hours of the surgery room (not allowing overtime) and Equation 3 ensures that each resident works until the limit of the working hours of the surgery room (not allowing overtime). The combination of Equations 2 and 3 prevents each resident from having workloads that are incompatible with the available room time by adding all the available rooms, what would mean, in practice, to allocate the professional in two rooms at the same time.

Equation 4 just allows any resident of type (c) to be allocated to perform the surgery (s) of size (z) in the room (r) and day (d) in case this room (r) is available for the surgery service on day (d). In order to increase the model's efficiency (reduce resolution and interactions time), this constraint is only created when  $\text{durSu}_{s,z} > 0$  and  $\text{hClSu}_{c,s,z} = 1$ , in other words, when the surgery (s) of size (z) exists and when the resident of type (c) is able to perform it.

Equation 5 accumulates the quantity of each surgery (s) of size (z) performed by the resident of type (c) and is created when  $\text{durSu}_{s,z} > 0$  and  $\text{hClSu}_{c,s,z} = 1$  following the same logic of the previous equation. The variable  $\text{AClSu}_{c,s,z}$  is used in Equations 6, 7, 8 and 9 to ensure the minimum quantity of the surgeries.

This model doesn't allocate the surgeon to the surgery, but rather designates the group of surgeons (in this case, R1, R2, or R3) who will perform it. Thus, it's necessary, in Equations 6 to 10, to multiply the number of surgeries by the number of surgeons of that group.

Equation 11 associates, for each surgery (s) of size (z), the necessity of an anesthetist. It is created when  $\text{durSu}_{s,z} > 0$  and  $\text{rSuAn}_{s,z} = 1$ , in other words, when the surgery (s) of size (z) exists and when it needs an anesthetist.

Equations 12 and 13 associate the daily and per-room allocation of the anesthetist (variable  $\text{AnDay}^{r,d}$ ) to the quantity of surgeries performed with an anesthetist for each surgery ( $\sum_{s,z} \text{AnSu}_{s,z}^{r,d}$ ) and that are necessary to meet the term  $\sum \text{Weight}_2 * \text{AnDay}^{r,d}$  of the objective function. Since the decision to allocate some anesthetists to the room (r) and day (d) is binary ( $\text{AnDay}^{r,d}$ ), it was necessary to create an auxiliary variable  $\text{AuxAn}^{r,d}$  in Equation 11 to receive the difference between the quantity of surgeries and the binary variable. However, it's necessary for this allocative decision to be equal to 1 every time an anesthetist is assigned to a room while, at the same time, one is trying to minimize  $\sum \text{Weight}_2 * \text{AnDay}^{r,d}$ . In order to solve this problem, one multiplies the binary decision variable by a large number (M), which, by its turn, must be greater than the right side of the equation. This method ensures that whenever the quantity of surgeries in a day and in a room is greater than 1, the decision variable will receive the value 1.

Equations 14 and 15 associate the daily and room allocation of the resource equipment (variable  $\text{EqDay}_e^{r,d}$ ) to the number of surgeries performed with equipment for each surgery ( $\text{EqSu}_{e,s,z}^{r,d}$ ) and that are necessary to meet the term  $\sum \text{Weight}_3 * \text{EqDay}_e^{r,d}$  of the objective function. The terms  $\text{EqDay}_e^{r,d}$ ,  $\text{AuxEq}_e^{r,d}$ ,  $\text{EqSu}_{e,s,z}^{r,d}$ , and M follow the same logic presented in the explanation of Equations 11 and 12.

Equations 16 and 17 associate the allocation of resident of type (r) on day (d) (variable  $\text{CIDay}_c^d$ ) and are necessary to meet Equation 21, which refers to the minimum frequency of resident scheduling per week. The terms  $\text{CIDay}_c^d$ ,  $\text{AuxCl}_c^d$ ,  $\text{CISu}_{c,s,l}^{r,d}$ , and M follow the same logic presented in the explanation of Equations 11 and 12.

Equation 18 associates the surgical material ( $\text{MatSu}_{m,s,z}^{r,d}$ ) necessary for each surgery (s) of size (z). It is created when  $\text{durSu}_{s,l} > 0$  and  $\text{rSuMat}_{s,z,m} = 1$ , in other words, when the surgery (s) of size (z) exists and when surgical material (m) is required. Equation 19 limits the quantitative of surgeries performed in the day (d) due to the availability of surgical materials (m).

Equation 20 associates the blood bag ( $\text{SanCi}_{s,z,d}$ ) necessary for each surgery (s) of size (z). It is created when  $\text{durSur}_{s,z} > 0$  and  $\text{rSuBlood}_{s,z} = 1$ , in other words, when the surgery (s) of of size (z) exists, and when blood bags are necessary.

Equation 21 limits the number of surgeries performed in the day (d) depending on the availability of blood bags made available by the hemotherapy service.

Equation 22 ensures, for any 5 consecutive days (week), that the group of residents (r) will be scheduled in at least  $\underline{\text{fClwk}}$  days. In this equation, it was necessary to define a time horizon different from the rest of the model to prevent the sum, for example, of 3 daily slots beginning on day 248 (in this case, the solver would try to add until day 251, which would be greater than the planning horizon). In other words, it is created for all periods excluding the last  $\underline{\text{fClwk}}$  days (in this case,  $250 - \underline{\text{fClwk}}$ ).

Equations 23, 24 and 25 ensure, for any 5 consecutive days (week), that the model allows an allocation of up to  $\overline{\text{nRoomwk}}$  rooms, up to  $\overline{\text{nAnwk}}$  anesthetists and up to  $\overline{\text{nEqwk}_e}$  of equipment.

## 6. Tested scenarios

The model presented in the previous section has parameters that haven't been presented so far and that have the role of assigning weights to the different scenarios and of considering business rules related to the minimum frequency of scheduling of the group of residents per week ( $\underline{\text{fClwk}}$ ), the maximum amount of rooms available in the week ( $\overline{\text{nRoomwk}}$ ), the maximum number of anesthetists available in the week ( $\overline{\text{nAnwk}}$ ), and the maximum amount of equipment (e) available in the week ( $\overline{\text{nEqwk}_e}$ ). These factors are relevant to our problem because they add internal rules of the hospital about weekly resource availability as well as the ideal frequency established by the chief of vascular surgery. As we do not know if there are feasible solutions given these constrains, we do not consider these factors on the first 10 scenarios. If we obtain feasible solutions on these scenarios, we will add these factors to bring the solution closer to reality.

In our operating room planning a time horizon of 250 days was considered and the current business rules are:  $\underline{\text{fClwk}} = 3$ ,  $\overline{\text{nRoomwk}} = 8$ ,  $\overline{\text{nAnwk}} = 4$  and  $\overline{\text{nEqwk}_e} = 6$ . Depending on its parameters, the triad combination of number of surgeons by type, minimum number of surgeries, and current business rules may not create feasible solutions, as it occurs in practice, because current rules are:  $\underline{\text{fClwk}} = 3$ ,  $\overline{\text{nRoomwk}} = 12$ ,  $\overline{\text{nAnwk}} = 4$  and  $\overline{\text{nEqwk}_e} = 4$ .

In order to assess not only the current business rules, but also the annual availability range of each resource and their criticality, we propose eleven scenarios in Table 12. The first column specifies the scenarios. Columns 2, 3, and 4 present the weights assigned to the operating room allocation ( $\text{Room}^{r,d}$ ), to the allocation of

Table 12. Weights and business rules by scenario.

Scenario	Weight, per allocative decision, related to:			Weekly allocation business rules			
	Surgery room	Anesthe-tist	Equip-ment	Minimum Frequency	Maximum number of rooms	Maximum number of anesthetists	Maximum amount of equipment
1	10 <sup>6</sup>	10 <sup>3</sup>	1	0	10	10	10
2	1	10 <sup>3</sup>	10 <sup>6</sup>	0	10	10	10
3	10 <sup>3</sup>	10 <sup>6</sup>	1	0	10	10	10
4	1	10 <sup>6</sup>	10 <sup>3</sup>	0	10	10	10
5	10 <sup>3</sup>	10 <sup>3</sup>	1	0	10	10	10
6	1	10 <sup>3</sup>	10 <sup>3</sup>	0	10	10	10
7	1000	1	10 <sup>3</sup>	0	10	10	10
8	1	1	1	0	10	10	10
9	10 <sup>6</sup>	10 <sup>3</sup>	1	3	8	8	8
10	10 <sup>6</sup>	10 <sup>3</sup>	1	3	8	7	6
11	10 <sup>6</sup>	10 <sup>3</sup>	1	3	8	4	6

anesthetists (AnSu<sup>r,d</sup>) and to the allocation of equipment (EqDay<sup>e,d</sup>). Columns 5, 6, 7, and 8 present the parameter values that have been adopted for each business rule.

Although only the last scenario has a “practical value”, all responses allow us to evaluate which rules have more impact, and which ones interfere little in programming. From this, we may inform the decision-maker as to which rules could be disregarded, reinforced, adopted or negotiated with other clinics or with the head of the operating room.

In this case, taking as example scenario 1 of Table 12, the solver will allocate the team of surgeons from the same residency year in as few rooms as possible (highest weight assigned in scenario 1). Then, once the number of rooms is defined, the solver will seek the least amount of anesthetist allocation (intermediate weight in scenario 1), by reallocating the surgeries in each room and in each day. At the end, after the number of rooms and anesthetists are specified, the solver will seek the least amount of equipment allocation (lower in scenario 1). Moreover, in this scenario, there is no obligation to schedule the group of residents in every week and up to two rooms available on each of the five days of the week are considered. In other words, there are 10 rooms which may all have anesthetists and equipment in the week if necessary, even if this is not desirable.

## 7. Results and discussion

In Table 13, the first column designates the scenario and the second presents, nominally, the order of the adopted resource prioritization (translating “the weights” shown in Table 12). The third and fourth column present the size of the model, that is, the number of decision variables (being whole or binaries) and how many constraints were used respectively. Given that a minimum frequency value of scheduling of the group of residents week has not been established ( $f_{C1wk} = 0$ ) in scenarios 1 to 8, constraint 21 is not active in these cases, and they have the same number of decision variables and constraints.

The fifth column presents the resolution times of the scenarios and the sixth column presents their respective gaps. These gaps are the percentage difference between the result found by linear relaxation (fractional solution without “practical value”) and the best whole solution (allocation of groups of residents, for example), found during the resolution time. In case the gap reaches the value of 0.00%, it means that the best whole solution found is the optimal solution.

The results of the best whole solutions found for each scenario are presented in columns 7, 8, 9, and 10. These solutions specify the time horizon of 250 days, the average use and the smaller number of rooms (# Rooms), the number of rooms with anesthetist (# Rooms with anesthetist) and the number of rooms with equipment (# Rooms with equipment), which refer, in the model, to the terms  $\sum_{r,d} Room^{r,d}$ ,  $\sum_{r,d} AnSu^{r,d}$  and  $\sum_{e,r,d} EqSu^{r,d}$ , respectively.

One may observe that, in order to carry out the surgeries defined by the regulation and the preceptor in the first five scenarios, the amount of allocated resources vary in the intervals from 273 to 347 for rooms, from 224 to 279 for rooms with anesthetists, and from 200 to 310 for rooms with equipment. In this case, as the surgical service in question currently has 8 operating rooms during the week (a rule defined by the direction of the surgical center), and therefore 400 rooms in the year (up to 2 surgery rooms per day up to 8 rooms per week during the 250 days), it can be stated that this constraint of rooms (Equation 22) does not limit the space of viable solutions.

Table 13. Model results by scenario.

Scenario results	Input data			Model answers					
	Objective function	Model Size		Computational resource	General solutions	Sizing model answers			
	Resource Criticality Order (Hierarchy)	# decision variables	# Constraints	Solution time (in seconds)	Gap (%)	Average usage (%)	# Rooms	# Anesthetists	# Equipment
1	Room; anesthetist; equipment	52,250	70,621	11,456.4	1.48	86.9	285	285	262
2	Equipment; anesthetist; room	52,250	70,621	10,026.2	0.03	73.3	339	274	200
3	Anesthetist; room; equipment	52,250	70,621	12,340.2	4.39	73.3	344	230	333
4	Anesthetist; equipment; room	52,250	70,621	10,178.3	4.39	69.1	364	230	310
5	Room and anesthetist; equipment	52,250	70,621	19,633.1	11.55	83.5	297	269	270
6	Anesthetist and equipment; room	52,250	70,621	68,774.9	12.19	70.1	354	278	200
7	Room and equipment; anesthetist	52,250	70,621	69,962.0	2.48	84.6	293	293	200
8	No hierarchy	52,250	70,621	106,748.5	10.44	84.9	290	280	200
9	Room; anesthetist; equipment	52,250	70,612	60,038.6	1.48	86.9	285	285	262
10	Room; anesthetist; equipment	52,250	70,612	60,051.3	1.83	86.6	286	286	254
11	Room; anesthetist; equipment	52,250	70,612			Infeasible solution			

However, due to the scarcity of other resources (anesthetists and equipment), the direction of the surgical center assigns, in the weekly horizon, only 3 days of rooms with anesthetists and 3 days of rooms with equipment. From the results of the model, it is concluded that these two rules make any solution impossible. Considering the annual horizon (250 days), these resources would be available only in 150 days (3 days a week over 50 weeks) whereas at least 224 rooms with anesthetist and 262 rooms with equipment (scenario 4) or 247 rooms with anesthetist (scenario 2) would be required.

So, the only resource that would not make sense to prioritize (assign greater weight) in detriment of others would be the surgery rooms. However, scenario 1 was chosen as ideal by the chief surgeon of the vascular surgery service with the argument that other surgical services receive fewer rooms in the week and this kind of solution could possibly free room spaces to be allocated according to other rules or even just to be available.

Thus, considering the priority order proposed in scenario 1, scenario 9 was built by changing the minimum frequency of scheduling of the group of residents per week to 3 ( $f_{Clwk} = 3$ ), and by changing the maximum amount of rooms, anesthetics and equipment (e) assigned in the week to 8 ( $n_{Roomwk} = n_{Anwk} = n_{Eqwk} = 8$ ).

Finally, scenario 10 was obtained by changing the previous parameters, respectively, to 3, 8, 7, and 6. Therefore, in the last scenario, the goal is to bring the last two parameters closer to the current business rules and check the impact of this change in the found solution. By the preceptor's choice, scenario 10 was admitted as the ideal one, due to the fact it is the closest to the current set of rules (scenario 11), which has no feasible solution.

## 8. Conclusion

The present research proposed a model of resource allocation to meet the minimum training criteria required by current legislation and by the chief surgeon of a vascular surgery service. Thus, besides efficiently designing the planning and scheduling of the elective surgeries of this service (the research question per se), it was possible to evaluate the pertinence of current business rules of the surgical center and of business rules internal to the service, responding, at a tactical level (Master Surgical Schedule), when each group of residents should be allocated in which room, with which resources, and how many times it should be scheduled to perform any surgery in a weekly horizon.

The results, for different orders of resource prioritization, indicate that intervals of 273 to 347 surgery rooms, 224 to 279 rooms with anesthetics, and 200 to 310 rooms with equipment are necessary annually for the accomplishment of the minimum number of surgeries necessary for the approval in the residence program

To ensure a feasible and efficient surgical planning, which, for each scenario, involved different logics of resource prioritization, the usage ratio of surgery rooms ranged from 67.6% to 85.6%.

Future works could incorporate constraints that take into account not only the availability of staff and ergonomic regulations (Erhard et al., 2018), but also criteria related to social preferences (Roland & Riane, 2011) among which one may mention: no major surgeries on Fridays, more specific rules for scheduling in the weekly horizon (for example: that the surgeon should be scheduled just on Mondays, Wednesdays and Fridays or just on Tuesdays, Thursdays only in the morning or only in the afternoon).

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