EXACT AND HEURISTIC APPROACHES FOR ELECTIVE SURGERY SCHEDULING

Inês Marques
FCTS/FEG, Univ. Lusófona de Humanidades e Tecnologias and Centro de Investigação Operacional
Campo Grande, 376, 1749-024 Lisboa, Portugal
ines.marques@fc.ul.pt

M. Eugénia Captivo
Universidade de Lisboa, Faculdade de Ciências and Centro de Investigação Operacional
Edifício C6 - Piso 4, Campo Grande, 1749-016 Lisboa, Portugal
mecaptivo@fc.ul.pt

Margarida Vaz Pato
Instituto Superior de Economia e Gestão, Universidade Técnica de Lisboa and Centro de Investigação Operacional
Rua do Quelhas, 6, 1200-781 Lisboa, Portugal
mpato@iseg.utl.pt

ABSTRACT

Resources rationalization and reduction of waiting lists for surgery are the main objectives in the Portuguese National Health Plan. In this context, the elective surgery scheduling problem has been studied with two conflicting objectives: maximize surgical suite occupation and maximize the number of surgeries scheduled.

We present integer linear programming models along with constructive and improving heuristics specially designed to address the problem. Hybrid heuristics, using the constructive procedures together with optimization of a partial model, are also presented. The heuristics used low computational resources and provided good quality solutions for both objectives under study. We present and discuss the results of our computational experiments with real data from a Portuguese hospital.

KEYWORDS. Elective case scheduling. Integer linear programming. Heuristics.

Main area: SA - OR in Health

1. Introduction

The healthcare sector consumes resources typically very expensive, e.g. equipments, staff, buildings and renewable resources. In recent years, the rationalization of resources in this sector has become a priority for managers and other stakeholders. The operating theatre is one of the major consumers of resources in a hospital. This hospital service represents a large percentage of the hospital budget and also has direct implications in the service quality of many other hospital units, such as wards and recovery units. The operating theatre is therefore a central service where the efficient use of resources is particularly relevant for the hospital managers. One way of rationalizing within the operating theatre is through the development of improved surgical plans thus promoting the better usage of the available resources. Hence, this work is devoted to the elective surgery scheduling problem for one hospital in Lisbon.

This healthcare institution is incorporated within the Portuguese National Health Service and it is a general, central and university hospital. However, it does not include two services with great relevance in the hospital organization: maternity and outpatient emergency. This makes the surgical planning problem exclusively dedicated to elective surgeries. The hospital has five surgical specialties competing for the operating room time and historically performs about 5000 surgeries per year. The operating theatre has six operating rooms, one of which is reserved for ambulatory surgeries, i.e. those whose length of stay is less than 24 hours. All rooms are equipped with the same basic equipment, thus the surgical specialties can occupy anyone of the six operating rooms. The specialized equipment is mobile. However, given its fragile nature, the planner must assign rooms to surgical specialties throughout the day. At the end of each surgery, cleaning and disinfecting protocols must take place. These procedures take about 30 minutes and are performed by auxiliary staff. Each operating room has a permanent nurse team assigned throughout the surgical suite’s regular time. The auxiliary staff does not constitute a scarce resource to this planning problem. Each patient is assigned a surgeon at waiting list booking time, which thus constitutes an input for this problem. Practical experience in this hospital shows that recovery unit beds and specialty ward beds do not limit the activity of the surgical suite. The regular working schedule of the operating theatre is between 8.30 am and 8 pm, from Monday to Friday. Surgery plans have a weekly horizon and are finalized on Friday for the following week.

The elective surgery scheduling problem consists of scheduling elective surgeries from the waiting list. Each scheduled surgery is assigned to a day, an operating room and a starting time. Surgeries must be scheduled in order to meet its due date defined by the associated level of priority. Surgeries with deferred urgency level of priority should be scheduled on Monday, high priority surgeries throughout the planning week, and the remaining surgeries may be scheduled or not during the planning week. The problem cannot allow overlapping of surgeries in the same operating room as well as overlapping of surgeons among operating rooms in the same time period and day. Upper bounds on daily and weekly operating time limits for each surgeon are also considered. Two objectives are independently considered: maximize the occupation of the operating theatre and maximize the number of surgeries scheduled.

This problem arises at an operational level of decisions for operating room planning, combining advance scheduling and allocation scheduling. Scheduling is performed in open scheduling strategy. Only elective patients are considered and surgery durations are assumed deterministic. The authors present two integer linear programming (ILP) models (section 2) as well as constructive and improving heuristics (section 4) developed to address this elective surgery scheduling problem within a decomposition methodology (section 3). Results were obtained with real data from the hospital and are analyzed on section 5. Finally, section 6 is devoted to some final remarks.There are other integer programming approaches to the elective case scheduling problem (e.g. Cardoen et al., 2009a, 2009b; Velásquez and Melo, 2006). Heuristic methods have also been developed to this problem (e.g. Hans et al., 2008; Liu et al., 2011; Riise and Burke, 2011; Roland et al., 2010; van der Lans et al., 2006). Nevertheless, the specificities of the different realities under study contribute to the diversity of each work and make it difficult to compare among the various approaches and results.

2. Mathematical models

Every Friday, a set C of surgeries from the hospital's waiting list is selected, by increasing order of priority, for scheduling in the next planning week. The following subsets of C are defined: by specialty $j \in J$ (being J the set of surgical specialties) - C_j^{SP}; and by priority level - C_1^{PR} and C_2^{PR} are the set of surgeries in C classified as Deferred Urgency and High Priority, respectively. The set $C \backslash C_1^{PR}$ consists of surgeries considered for scheduling which are not classified as Deferred Urgency priority level. To perform these surgeries one has a set of surgeons H. Surgeries must be scheduled to a room in the set of rooms R, and on a day in the set of days available for scheduling, D. Time has a discrete representation as a set of time periods available for scheduling, T. Let γ be the number of time periods corresponding to the 30 minutes needed to cleaning and disinfecting the operating room after each surgery.

Surgery $c \in C$ has surgeon h_c assigned ($h_c \in H$). Each surgery has an estimated duration that leads to the number of time periods required to execute surgery c, represented by p_c. Consequently, subset $T_c \in T$ is defined, such that surgery c can start at the beginning of any time period in T_c, in order to be completed within the surgical suite regular time. Overtime is not permitted in planning and is made barred by restricting the variables domain to the respective set T_c.

Daily and weekly operating time limits for each surgeon $h \in H$ are represented, respectively, by $T_{hd}^{MAX_D}$ and $T_h^{MAX_W}$. For each surgeon h, $T_{hd}^{MAX_D}$ may differ over the different days. The parameter i_{ctd} reflects the impossibility for surgery $c \in C$ to start at the beginning of period $t \in T_c$ and day $d \in D$ due to surgeon or patient unavailability. This parameter has a value of 0 when the surgeon or the patient is not available to start the respective surgery at the beginning of period t on day d; otherwise, has value of 1. For all Deferred Urgency surgeries ($c \in C_1^{PR}$), $i_{ctd} = 0, \forall\, d > 1$.

Since surgeries are non-preemptive jobs, starting time variables were considered in formulating the problem (Sousa and Wolsey, 1992). Thus, the decision variables used in the models are:

$$x_{crtd} = \begin{cases} 1, & \text{if surgery } c \text{ starts at the beginning of period } t \text{ on day } d \text{ in room } r \\ 0 & \text{otherwise } (c \in C,\ r \in R,\ t \in T_c,\ d \in D) \end{cases}$$

Additional variables were also considered to register on a daily basis the surgical specialty assigned to each room:

$$y_{jrd} = \begin{cases} 1, & \text{if a surgery of specialty } j \text{ starts in room } r \text{ on day } d \\ 0 & \text{otherwise } (j \in J,\ r \in R,\ d \in D) \end{cases}$$

Variables y_{jrd} can be avoided in the formulation. However, introduction of these variables in the models, though slightly increasing the total number of variables, significantly reduces the number of constraints that prevent one from using any operating room for more than one surgical specialty on the same day. Moreover, preliminary experiments showed better results using these additional variables.

The ILP model used to formulate the elective case scheduling problem within the context of maximize surgical suite occupation is:

$$\max \quad \sum_{c \in C} \sum_{r \in R} \sum_{t \in T_c} \sum_{d \in D} p_c\, x_{crtd} \qquad (1)$$

$$\text{subject to:} \sum_{r \in R} \sum_{t \in T_c} x_{crtd} = 1, \quad \forall c \in C_1^{PR} \qquad (2)$$

$$\sum_{r \in R} \sum_{t \in T_c} \sum_{d \in D} x_{crtd} = 1, \quad \forall c \in C_2^{PR} \tag{3}$$

$$\sum_{r \in R} \sum_{t \in T_c} \sum_{d \in D} x_{crtd} \leq 1, \quad \forall c \in C \setminus (C_1^{PR} \cup C_2^{PR}) \tag{4}$$

$$\sum_{c \in C} \sum_{\substack{t'=t-p_c+1-\gamma \\ t' \in T_c}} x_{crt'd} \leq 1, \quad \forall r \in R, t \in T, d \in D \tag{5}$$

$$\sum_{r \in R} x_{crtd} \leq i_{ctd}, \quad \forall c \in C, t \in T_c, d \in D \tag{6}$$

$$\sum_{r \in R} y_{jrd} \leq 1, \quad \forall r \in R, d \in D \tag{7}$$

$$\sum_{c \in C_j^{SP}} \sum_{t \in T_c} x_{crtd} \leq y_{jrd} \, |T|, \quad \forall j \in J, r \in R, d \in D \tag{8}$$

$$\sum_{\substack{c \in C: \\ h_c = h}} \sum_{\substack{t'=t-p_c+1 \\ t' \in T_c}} \sum_{r \in R} x_{crt'd} \leq 1, \quad \forall h \in H, d \in D, t \in T \tag{9}$$

$$\sum_{\substack{c \in C: \\ h_c = h}} \sum_{r \in R} \sum_{t \in T_c} p_c \, x_{crtd} \leq T_{hd}^{MAX_D}, \quad \forall d \in D, h \in H \tag{10}$$

$$\sum_{\substack{c \in C: \\ h_c = h}} \sum_{d \in D} \sum_{r \in R} \sum_{t \in T_c} p_c \, x_{crtd} \leq T_h^{MAX_W}, \quad \forall h \in H \tag{11}$$

$$x_{crtd} \in \{0,1\}, \ \forall c \in C, \ r \in R, \ t \in T_c, \ d \in D \tag{12}$$

$$y_{jrd} \in \{0,1\}, \ \forall j \in J, \ r \in R, \ d \in D \tag{13}$$

In the above formulation, objective function (1) maximizes surgical suite occupation. Constraint set (2) forces Deferred Urgency level priority surgeries to be scheduled on Monday in order to meet the 72 hour deadline for their completion. Constraint set (3) imposes High Priority surgeries to be scheduled during the planning week. It should be noted that it is not certain that surgeries classified as Deferred Urgency and Highly Priority may all be scheduled within the respective periods. However, practical experience, as well as the number of surgeries of this type usually found in the waiting list and its distribution by the surgical specialties, shows that such impositions do not generally render the problem unfeasible. The model could easily be changed in order to include this explicitly, using slack variables in constraints (2) and (3) with the corresponding penalty terms in the objective function. The option of mandatory scheduling High Priority surgeries during the week arises as a means of easing the following week's planning. Constraints (4) state that the remaining surgeries, classified as Priority or Normal, may be scheduled or not during the planning week.

Constraints (5) guarantee that surgeries do not overlap in the same room. These constraints also impose γ empty periods for room cleaning at the end of each surgery (based on the definition of the lower sum limit). Constraints (6) provide the possibility to consider surgeons' or patients' unavailability periods. Constraint set (7) prevents assignment of more than one surgery specialty to each room and day. Therefore, it is not permitted to exchange surgery specialty in the room during the day. Constraints (8) are the linking constraints for variables x and y. Constraints (9) ensure that surgeons do not overlap between rooms in the same time period and day. In the real situation of the hospital involved, surgeons may exchange operating rooms. On the one hand, this exchange is feasible as the rooms are physically side by side. On the other hand, permission to exchange operating rooms by surgeons allows them to work in another operating room during hygiene periods in the previous room (about 30 minutes idle). This is also the reason why the cleaning time is not incorporated in the surgeries' duration. Constraint sets (10) and (11) impose a daily and weekly operating time limit on each surgeon. The time limit on Monday (day 1 on the planning's horizon) can be enlarged in order to guarantee the scheduling of all Deferred Urgency surgeries of the respective surgeon. Finally, constraints (12) and (13) express the variables' domain.

When we consider reduction of waiting lists for surgery then the objective should be maximize the number of surgeries scheduled. The ILP model used for the elective case scheduling problem within the context of maximize the number of surgeries scheduled just differs from the previous one on the objective function to be considered. In that case the objective function is:

$$\max \quad \sum_{c\in C}\sum_{r\in R}\sum_{t\in T_c}\sum_{d\in D} x_{crtd} \qquad (14)$$

Due to the need of having γ empty periods for room cleaning at the end of each surgery, when we intend to maximize surgical suite occupation, longer surgeries are preferable to short surgeries. But when the objective is the reduction of waiting lists for surgery then shorter surgeries are preferable to long surgeries.

3. Solution approach

The problem is highly complex and attains a large dimension in hospital real instances (Marques, 2010; Marques et al., 2012). Hence, the elective surgeries scheduling problem was decomposed into two hierarchical phases according to the nature of surgeries: conventional surgeries are planned in the first phase and ambulatory surgeries are planned in the second phase. The first phase generates a high dimension problem, while the second one is of rather reduced dimension. The output of the conventional planning phase is included as input for the ambulatory surgery planning to ensure feasibility of the whole week's schedule due to common resources (surgeons) between the two phases.

Three approaches are applied to solve this problem. In the first one, an ILP solver is used with limited time in each planning phase. If the solver times out without optimality, the best feasible integer solution obtained is improved using a simple improvement heuristic.

Despite the problem decomposition, the first phase problem still remains a high dimension issue. Hence, a constructive heuristic is developed to schedule the conventional surgeries on this planning phase. The second method is therefore similar to the previous one but uses this constructive heuristic instead of the model optimization in this first phase.

The third solution approach combines both previous approaches. On the conventional surgeries scheduling phase this hybrid method uses an ILP solver to optimize a reduced mathematical model that tackles only the deferred urgency surgeries. The remaining conventional surgeries are scheduled using the constructive heuristic.

Thus, the three approaches developed differ in the first planning phase, that is, when conventional surgeries are scheduled. The second planning phase is devoted to schedule ambulatory surgeries, consequently has a much lower dimension and is always solved through an ILP solver.

4. Constructive and improvement heuristics

The improvement heuristic developed to maximize surgical suite occupation can be summarized in the following four steps:

1. Re-schedule surgeries as early as possible in the day, while retaining the same order.
2. Try to schedule unscheduled surgeries in the time available at the end of each day, respecting each room's surgery specialty and ensuring that each surgery is completed within surgical suite regular time.
3. Try to exchange two or three consecutive scheduled surgeries, with Priority or Normal level of priority, for one unscheduled surgery whose duration is no greater than the duration of the consecutive ones.

4. If the last surgery scheduled at the end of the day is classified as Priority or Normal, try to exchange this last surgery for one unscheduled surgery occupying the remainder of the regular time in the day.

Every heuristic step must be performed taking into account feasibility, defined by constraints (2)-(13). In particular, the heuristic satisfies surgery priorities as described in the model.

Note that while step 1 only serves to support step 2, and does not contribute directly to any change in the solution value, each of the following three steps directly permits the objective function value to increase.

Almost the same set of four steps can be used to summarize the improvement heuristic developed for the case where the objective is the reduction of waiting lists for surgery:

1. Re-schedule surgeries as early as possible in the day, while retaining the same order.
2. Try to schedule unscheduled surgeries in the time available at the end of each day, respecting each room's surgery specialty and ensuring that each surgery is completed within surgical suite regular time.
3. Try to exchange one long scheduled surgery, with Priority or Normal level of priority, for two or more shorter unscheduled surgeries whose total duration is not greater than the duration of that long surgery.
4. If the last surgery scheduled at the end of the day is classified as Priority or Normal, try to exchange this last surgery for one or two shorter unscheduled surgery occupying the remainder of the regular time in the day.

When the objective is to maximize the number of surgeries scheduled, steps 3 and 4 perform exactly the opposite. Therefore, in this case step 3 tries to exchange one scheduled surgery by two non-scheduled surgeries with non superior duration and step 4 tries to exchange the last surgery scheduled at the end of the day by two non-scheduled surgeries that fill the remainder of the regular time in the day.

In descending order of duration, and descending order of antiquity and taking into account the problem feasibility defined by constraints (2)-(13), the constructive heuristic developed is organized in the following three steps:

1. Schedule all deferred urgency surgeries on Monday.
2. Schedule all high priority surgeries on the first day and rooms that can be scheduled.
3. Try to schedule the remaining surgeries on the first day and rooms that can be scheduled.

The only difference of the constructive heuristic for reduction of waiting lists from the version for maximizing suit occupancy is that the surgeries are initially ordered by increasing order of duration, and descending order of antiquity and taking into account the problem feasibility defined by constraints (2)-(13).

5. Computational results

The solution approaches were tested with real data from the hospital, for seven planning weeks of 2007. Details on the tested instances and the hospital historical data can be found in Marques (2010). The ILP models were solved using CPLEX 11.0 with CONCERT 2.5 (ILOG CPLEX 11.0, 2007; ILOG CONCERT 2.0, 2004). The heuristics were coded in C++ language and tests were performed in a Core2 Duo, 2.53 GHz computer with 4GB of RAM. Time limit to run CPLEX was set to 30000 seconds.

Surgeon and patient unavailability, represented by constraints (6), were not included in the computational tests for conventional surgery planning (first phase scheduling) since it was not possible to obtain the relevant data. However, these sets of constraints were included in computational tests for ambulatory surgery planning (second phase scheduling) to ensure feasibility of the whole week's planning, thus linking conventional and ambulatory surgeries planning. In addition, total time spent by each surgeon in the conventional surgeries' schedule was reduced in the total daily and weekly operating time limit to be used in constraints (10) and (11) for ambulatory surgeries planning.

Tested instances were created from the waiting list for surgery for the seven planning weeks. Instances are identified by a reference to the number of conventional surgeries considered for planning ($|C|$ in the first planning phase) and, in subscript, a reference to the type of expected duration used for each surgery (respectively, 1 and 2 for mean and median values), as shown in Table 1.

Instance	General solver + IH			Constructive heuristic + IH			Hybrid heuristic + IH		
	Time (sec.)	Gap (%)	OR occup. rate	Time (sec.)	Gap (%)	OR occup. rate	Time (sec.)	Gap (%)	OR occup. rate
C_250_1	16202.5	2.78	78.43	111.07	4.53	77.11	127.8	5.91	76.11
C_250_2	15198.4	2.53	77.72	168.13	5.16	75.83	118.9	6.01	75.24
C_300_1	21337.7	2.78	79.23	55.99	4.10	78.16	139.2	5.52	77.12
C_300_2	17340.5	3.02	78.12	139.25	3.74	77.55	100.5	4.09	77.31
C_500_1	21558.1	1.83	81.85	108.03	3.32	80.64	67.1	4.00	80.13
C_500_2	10220.9	3.64	79.77	106.23	2.89	80.28	149.7	3.30	79.92
C_1000_1	-	-	-	331.33	2.60	82.11	40.0	3.44	81.47
C_1000_2	-	-	-	187.14	2.64	81.86	157.4	2.90	81.64
Average	16896	2.80	78.97	150.90	3.62	79.19	112.6	4.40	78.62

Table 1 Average results obtained for the elective surgery scheduling problem considering maximization of surgical suite occupation

Table 1 shows the average results obtained with the three solution approaches for each instance type considering the objective of maximizing the surgical suite occupation. In this table, column 1 refers to the test instance type. The following columns report the average results obtained. For each approach, three columns appear: the first two columns show the computational time used and the gap corresponding to the final surgical plan; the third one displays the potential operating room occupation rate (*OR occup. rate*) corresponding to this surgical plan (without the cleaning time).

The instances that considered 1000 conventional surgeries were unsolved with the general solver. CPLEX was also unable to obtain feasible solutions for other seven lower dimension instances. The approaches that used the constructive and the hybrid heuristics obtained a valid surgical plan for all the instances tested. In average, these plans were developed in 0.9% of the time required by the approach that used the general solver but attained a higher mean gap. The constructive heuristic method originated solutions with lower gap on average than the ones obtained using the hybrid heuristic but needed on average more 38.3 seconds to provide the surgical plans. The improvement heuristic used residual computational time and improved the gap for 61.9% of the solutions in the conventional surgeries' planning phase.

Considering the objective of maximizing the surgical suite occupation, the methods presented in this paper built a valid surgical plan for all tested weeks, producing a potential surgical suite occupation rate in regular time superior to 75% (not including the cleaning time), well above the corresponding rate currently obtained in hospital planning (under 40%). Furthermore, the solutions also achieve to improve the waiting list reduction rate of the hospital surgical plans, which shows that the hospital surgical plans are clearly dominated by the corresponding proposed surgical plans with respect to these two conflicting criteria.

Table 2 shows similar results when the objective of maximizing the number of surgeries scheduled is considered. In this table, the third column for each approach (*WL reduct. rate*) shows the waiting list reduction rate associated to the surgical plan. The results obtained with this criterion are similar to the ones presented above for the objective of maximizing the surgical suite occupation rate.

Instance	General solver + IH			Constructive heuristic + IH			Hybrid heuristic + IH		
	Time (sec.)	Gap (%)	WL reduct. rate	Time (sec.)	Gap (%)	WL reduct. rate	Time (sec.)	Gap (%)	WL reduct. rate
C_250_1	16937.1	3.66	11.01	13.6	5.06	10.86	42.8	5.84	10.77
C_250_2	17272.0	3.46	11.25	13.9	5.47	11.03	15.2	4.96	11.07
C_300_1	20229.6	3.87	11.43	12.2	6.28	11.17	18.7	7.67	11.02
C_300_2	18315.4	3.66	11.69	34.0	5.91	11.44	11.6	5.69	11.46
C_500_1	6138.3	2.55	13.00	10.0	5.50	12.12	15.6	5.63	12.10
C_500_2	14799.1	3.18	13.08	30.8	5.44	12.52	40.2	5.62	12.49
C_1000_1	-	-	-	11.4	4.47	13.06	15.8	4.91	13.00
C_1000_2	-	-	-	31.7	2.71	13.99	33.4	3.40	13.89
Average	17 081	3.54	11.65	19.7	5.10	12.02	24.2	5.46	11.98

Table 2 Average results obtained for the elective surgery scheduling problem considering the reduction of waiting lists for surgery

To analyze week plans resulting from the approach proposed in this paper for our case study, the authors explored the final solution from instance C_300_1, comparing it with the respective hospital planning. It refers to the planning week from 12 to 16 February 2007. This planning week was arbitrarily chosen. The remainder displayed a similar behavior.

In order to evaluate the approaches suggested in this paper, it is also interesting to understand how the proposed plan can behave in “reality”. With all the data collected, the proposed plan viability can be analyzed by taking into account the difference between the duration of real surgery and the anticipated duration used for planning and its impact on the plan’s implementation. So, the real duration of the scheduled surgeries was used for a proposed plan simulation. Surgeries start at the scheduled time unless previous surgeries took more time than expected. Starting surgeries in an overtime period was not allowed in this simulation. Should this occur, surgeries were canceled and would therefore not be held, with the exception of surgeries classified as urgency deferred priority level: as they have to be performed on the first planning day in order to respect the term, an overtime start was allowed. Another possibility requiring that a surgery be delayed occurs when the respective surgeon was performing another delayed surgery in another operating room at the time it was expected to begin.

Founded on the same instance under analysis, Table 3 provides a balance of the week 12-16 February 2007 addressed on the basis of some indicators. As such, the analysis was performed on the week plan and the hospital information record (Hospital plan and Hospital record), besides the week plan and record simulation for both the solution obtained from the models developed using CPLEX (without using improvement heuristic — IP plan and IP simulation), and the proposed solution (the solution obtained from the models with onwards application of the improvement heuristic — Proposed plan and Prop. plan simulation).

Table 3 displays the number of time periods booked and used (meaning, respectively, the number of occupied time periods on the plan and on the record/simulation) in regular time and overtime, as well as the weight of each of the contributors to the difference verified in the number of time periods between the plan and the record/simulation. These contributors constitute the differences between the real duration and the expected duration, duration of canceled surgeries and of added surgeries in the case of hospital information.

	Regular time occupancy rate (%)	Waiting list reduction rate (%)
Hospital – Week 12-16 February 2007		
Plan	37.54	5.68
Record	42.75	5.47
Proposed – Instance C_300$_1$ - maximization of surgical suite occupation		
Plan	78.84	6.98
Simulated record	71.81	6.68
Proposed – Instance C_300$_1$ - reduction of waiting lists for surgery		
Plan	63.84	10.88
Simulated record	70.22	9.15

Table 3 Week balance: production indicators

6. Final remarks

The elective surgery scheduling problem was studied in a real Portuguese public hospital context. Two optimization criteria were considered for the problem: maximizing the surgical suite occupation and maximizing the number of surgeries scheduled. Three different approaches have been presented and the respective results commented on. These results clearly show that the two criteria considered are conflicting. In the first case, longer surgeries are planned (with less cleaning periods) contrary to what happens in the second case where shorter surgeries are chosen. The heuristic approaches developed originated valid surgical plans for all tested weeks and produced significant potential improvements over the plan obtained in hospital for the same weeks.

This methodology has proved to be applicable in the real context studied hence it is highly suitable to embed in a decision support system to plan the operation theatre activity in hospitals.

Acknowledgements

The authors would like to thank Dr. Manuel Delgado for his enthusiastic interest in this work, Dra. Margarida Baltazar for her patient provision of all necessary data and head nurse Fátima Menezes for the friendly and patient description of the entire process. This work is supported by National Funding from FCT - Fundação para a Ciência e a Tecnologia, under the project: PEst-OE/MAT/UI0152.

References

Cardoen, B., Demeulemeester, E. and Beliën, J. (2009a), Optimizing a multiple objective surgical case sequencing problem, *International Journal of Production Economics*, 119(2), 354-366.

Cardoen, B., Demeulemeester, E. and Beliën, J. (2009b), Sequencing surgical cases in a day-care environment: an exact branch-and-price approach, *Computers & Operations Research*, 36(9), 2660-2669.

Hans, E.W., Wullink, G., van Houdenhoven, M. and Kazemier, G. (2008), Robust surgery loading, *European Journal of Operational Research*, 185(3), 1038-1050.

ILOG CONCERT 2.0, *User's Manual*, ILOG, Incline Village, Nevada, 2004.

ILOG CPLEX 11.0, *User's Manual*, ILOG, Incline Village, Nevada, 2007.

Liu, Y., Chu, C. and Wang, K. (2011), A new heuristic algorithm for the operating room scheduling problem, *Computers & Industrial Engineering*, 61(3), 865-871.

Marques, I., , Planeamento de cirurgias electivas – abordagens em programação inteira, PhD dissertation, Faculdade de Ciências, Universidade de Lisboa, 2010 (http://repositorio.ul.pt/bitstream/10451/2413/1/ulsd059038_td_Ines_Proenca.pdf, 5, 2012).

Marques, I., Captivo, M.E. and Pato, M.V. (2012), An Integer Programming Approach to Elective Surgery Scheduling. Analysis and Comparison Based on a Real Case, *OR Spectrum*, 34(2), 407-427.

Riise, A. and Burke, E.K. (2011), Local search for the surgery admission planning problem, *Journal of Heuristics*, 17(4), 389-414.

Roland, B., Martinelly, C.D., Riane, F. and Pochet, Y. (2010), Scheduling an operating theatre under human resource constraints, *Computers & Industrial Engineering*, 58(2), 212-220.

Sousa, J.P. and Wolsey, L.A. (1992), A time indexed formulation of non-preemptive single machine scheduling problems, *Mathematical Programming*, 54, 353-367.

Velásquez, R. and Melo, M.T. (2006), A set packing approach for scheduling elective surgical procedures, *Operations Research Proceedings 2005*, Springer Berlin Heidelberg, 425-430.

van der Lans, M., Hans, E.W., van Houdenhoven, M., Hurink, J.L. and Wullink, G., Anticipating urgent surgery in operating room departments, *BETA working paper*, WP-158, University of Twente, 2006.