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(Article begins on next page)

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Patient–centred objectives as an alternative to maximum utilisation: comparing surgical case solutions

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Abstract Operating Room (OR) planning and scheduling is a research topic widely discussed in the literature, in which several performance criteria have been proposed to evaluate the OR planning decisions. Although the OR utilisation is the leading objective, from research experiences, long waiting lists lead to a satisfactory filling of ORs even fixing other objectives. In this paper we analyse the impact on OR utilisation of two patient–centred objectives: the waiting time minimisation and the workload balance. In the former the most commonly used patient–centred criterion is taken into account, while the latter leads to a smooth stay bed occupancies determining a smooth workload in the ward and, by consequence, an improved quality of care provided to patients. To the best of our knowledge, a comparison of the planning determined by these criteria is not yet available in literature.

Keywords: surgery process scheduling, patient–centred, objective functions, comparison.

1 Introduction

Operating Room (OR) planning and scheduling is a research topic widely discussed in the literature [9, 12, 21]. At the operational decision level [23], the problem arising is also called "surgery process scheduling" of elective patients, which usually consists in (i) selecting patients from an usually long waiting list and assigning them to a specific OR session (i.e., an operating room on a specific day) over a planning horizon [17, 20, 3], and (ii) determining the precise sequence of surgical procedures

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and the allocation of resources for each OR session [13, 18]. A further problem was recently introduced: the Real Time Management (RTM) of operating rooms [2, 10] is the decision problem arising during the fulfilment of the surgery process scheduling, that is the problem of supervising the execution of such a schedule and, in case of delays, to take the more rational decision regarding the surgery cancellation or the overtime assignment. The RTM with also non-elective patients is studied in [11] in which a competitive analysis of the online algorithms is also discussed. Such problems are further challenged by the inherent stochasticity of their main parameters, such as the surgery duration, the length of stay and the arrival of non-elective patients [6, 1, 14].

Several performance criteria have been reported to evaluate the OR planning decisions [9]. Usually, the maximisation of the OR utilisation is the most important criterion, since ORs are the largest cost and revenue centre of hospitals. [12]. However, long waiting lists could lead to a satisfactory OR utilisation due to the broader variety of surgery durations that can be selected adopting other objectives. Note that long waiting lists is a common situation in many hospitals belonging to publicly funded health care systems. Taking into account a patient–centred perspective, one of the most commonly used criterion is the waiting time, which is addressed weighting the patients according to the time elapsed from the referral day [24, 22, 3]. Conversely, the workload balance criteria is designed for workers in the wards, leading to a smooth – without peaks – stay bed occupancies that determines a smooth workload and, by consequence, an improved quality of care provided to patients [5, 19, 4].

The main contribution of this paper is the comparison of the surgical planning determined by the these criteria. To the best of our knowledge, some attempts are available in the literature but they are applied to different operative contexts [7, 16] or taking into account different goals [8]. To perform the comparison, we will consider the surgical case assignment problem under the two criteria. Note that the surgical case assignment problem has been proved to be $\mathbb{NP}$–hard in [3]. We compute the solutions of such problems considering a set of instances generated by using the instance generator proposed in [15].

2 Mathematical Formulations

In this section, we propose simple integer linear programs to model the surgical case assignment problem under the two criteria considered, that is the minimisation of the waiting times and the workload balance. In the following we will consider a single specialty with a large number of stay beds and a long waiting list of patients. These assumptions would avoid or limit the impact on the solutions of exogenous factors. The time horizon is one week composed of five operating days (from Monday to Friday).

Let I, K and T be respectively the sets of patients, operating rooms and working days of the planning horizon, each indexed by the corresponding letter, i, k and t.

Note that each OR session in the planning horizon is uniquely defined by a pair of indices (k,t). We denote by s_{kt} the time capacity of the OR session (k,t). For each patient $i \in I$, the following information are given: the waiting time w_i, expressed in days and computed from the referral day; the expected duration of the surgery p_i, expressed in minutes; the expected Length of Stay (LOS) μ_i, expressed in days. Note that we assume that the value of μ_i includes also the operating day, and that $\mu_i \leq 3$ to avoid the case in which a bed is used by a patient operated on the previous week.

Let x_{ikt} be the binary decision variable that models the assignment of the patient i to the OR session (k,t) ($x_{ikt} = 1$), or not ($x_{ikt} = 0$).

$$M_1 : \quad \max \quad z_{waiting} = \sum_{i \in I} w_i \sum_{k \in K} \sum_{t \in T} x_{ikt} \tag{1a}$$

$$\text{s.t.} \quad \sum_{k \in K} \sum_{t \in T} x_{ikt} \leq 1 \,, \qquad i \in I \tag{1b}$$

$$\sum_{i \in I} p_i x_{ikt} \leq s_{kt} \,, \qquad k \in K, t \in T \tag{1c}$$

The model M_1 minimises the waiting time. The selection of the patients from the waiting list and their assignment to OR sessions is modelled by the constraints (1b) and (1c): constraints (1b) state that a patient can be scheduled at most once, while constraints (1c) impose that the sum of the surgery times of the patients scheduled in each OR session (k,t) may not exceed the time capacity s_{kt}. The objective function (1a) leads to a solution made of those patients having longest waiting time at the moment of planning. In other words, the model would favour those patients with longest waiting time instead of those with shorter ones.

$$M_2 : \quad \max \quad z_{balance} = y \tag{2a}$$

$$\text{s.t.} \quad \sum_{k \in K} \sum_{t \in T} x_{ikt} \leq 1 \,, \qquad i \in I \tag{2b}$$

$$\sum_{i \in I} p_i x_{ikt} \leq s_{kt} \,, \qquad k \in K, t \in T \tag{2c}$$

$$\sum_{k \in K} x_{ikt} = y_{it} \,, \qquad i \in I, t \in T \tag{2d}$$

$$\sum_{h=t}^{\max\{t+\mu_i, \ell''\}} z_{ih} \geq \mu_i y_{it} \,, \qquad i \in I, t \in T \tag{2e}$$

$$\sum_{h=\min\{t-\mu_i, \ell'\}}^{t} y_{ih} \geq z_{it} \,, \qquad i \in I, t \in T \tag{2f}$$

$$\sum_{i \in I} z_{it} \geq y \,, \qquad t \in T \tag{2g}$$

The model M_2 balances the workload. As in the previous model, constraints (2b) and (2c) represent the selection of the patients from the waiting list and their assignment to OR sessions. Constraints (2d) define the value of the auxiliary variables y_{it}, which is equal to 1 when the patient i is operated on the day t, 0 otherwise. Such a variable is then used to count the number of stay beds used each day t of the planning horizon T by fixing the value of the auxiliary variables z_{it}, which is equal to 1 when the patient i take up a stay bed during the day t, 0 otherwise through the constraints (2e) and (2f), in which the parameters ℓ' and ℓ'' represent the first and the last working days in T, respectively. In order to model the work balance, we adopt a bottleneck approach: the objective function (2a) seeks to maximise the number of busy stay beds during the day with the minimal bed usage (constraints (2g)).

3 Comparison

In our comparison we consider a set of benchmark of 11 instances whose case mix has been generated using [15], rounding the value to the nearest integer to obtain p_i. With a different case mix, each instance is composed of 300 patients whose w_i and mu_i are uniformly distributed in $[1, 365]$ and $\{1, 2, 3\}$, respectively. The operating theatre is composed of 4 ORs for a total operating time of 9600 minutes. The two models are implemented and solved using Cplex Optimization Studio 12.5 with a running time limit set to 300 seconds.

Table 1 Comparing M_1 and M_2 solutions: main parameters.

	time		gap		N		D		avg. p_i	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
CHI	300.05	299.91	1.27%	1.27%	177	190	9598	9308	54.2	49.0
ENT	300.06	0.67	0.16%	0.00%	157	156	9573	9003	61.0	57.7
EYE	300.14	0.48	0.16%	0.00%	194	182	9583	9007	49.4	49.5
GYN	300.14	0.69	0.12%	0.00%	162	162	9576	8999	59.1	55.5
MIX	300.13	0.69	0.07%	0.00%	203	211	9579	9279	47.2	44.0
NEU	300.08	1.22	0.03%	0.00%	254	266	9588	9413	37.7	35.4
ONC	300.08	0.73	0.14%	0.00%	168	162	9582	9207	57.0	56.8
ORT	300.06	1.09	0.17%	0.00%	164	167	9577	8997	58.4	53.9
PLA	300.09	0.8	0.30%	0.00%	146	150	9558	9114	65.5	60.8
THO	300.06	161.78	0.20%	0.00%	162	182	9571	9506	59.1	52.2
URO	300.06	0.42	0.26%	0.00%	170	172	9577	9097	56.3	52.9

Table 1 reports the results of the comparison. For each instances (denoted as in [15]), the running time, the gap, the number N of operated patients, the total utilisation D of the ORs (minutes), and the average p_i of the operated patients are reported for both model M_1 and M_2.

A first remark concerns the running time: the solution of the model M_1 requires a larger computational effort than the model M_2 even if the average solution gap of the model M_1 is still quite limited. We observe that the solutions of the model M_1 has always a larger OR utilisation than M_2, that is 99.8% and 95.6% over the total operating time, respectively. We observe that the OR utilisation of M_1 is always close to 9600 minutes because of the proxy effect of its objective function. Quite surprisingly, the number N of operated patients not complies with the OR utilisation: those of the model M_2 is larger than those in M_1 in 7 instances over 11. Note that there is not a correlation between the value of N and D: actually, for the instance ORT, the difference between the values of D is 580 in favour of M_1 (the largest one) while the difference between the values of N is 3 in favour of M_2; for instances THO, the difference between the values of D is 65 in favour of M_1 (the smallest one) while the difference between the values of N is 20 in favour of M_2 (the largest one).

Table 2 Comparing M_1 and M_2 solutions: occupied stay beds.

	model M_1						model M_2					
	1	2	3	4	5		1	2	3	4	5	
CHI	41	73	70	70	58	**32**	79	79	79	79	79	**0**
ENT	40	66	70	50	55	**30**	60	64	65	60	60	**5**
EYE	40	66	91	72	68	**51**	65	66	66	65	65	**1**
GYN	33	61	78	66	56	**45**	59	65	59	59	59	**6**
MIX	43	77	81	90	81	**47**	85	88	85	85	85	**3**
NEU	49	126	116	83	96	**77**	115	115	115	115	115	**0**
ONC	34	57	67	67	69	**35**	57	57	59	57	57	**2**
ORT	34	56	78	65	62	**44**	68	69	68	68	68	**1**
PLA	29	51	57	56	51	**28**	56	56	56	56	57	**1**
THO	30	66	79	58	57	**49**	79	79	79	79	79	**0**
URO	32	61	65	61	75	**43**	63	63	63	63	64	**1**

Table 2 reports the number of occupied stay beds for each day of the planning horizon. Further, the columns with bold values report the difference between the maximum and the minimum of those values. The reported results show the impact of not considering the balance of the workload in the solution of model M_1: while in M_2 the average difference between the maximum and the minimum of occupied stay beds is 1.8, the same value in M_1 is 43.7. We remark that the LOS of each patient can have an impact: actually, the sum of the beds over the time horizon is greater than the value of N. In the following tables we report the results for the instance CHI and THO varying the LOS distribution as follows: in the scenario 1, the 60% of the patients have $\mu_i = 1$, the 20% have $\mu_i = 2$, and the remaining 20% have $\mu_i = 3$; on the contrary, in the scenario 2, the 60% of the patients have $\mu_i = 3$, the 20% have $\mu_i = 2$, and the remaining 20% have $\mu_i = 1$.

Table 3 reports the same type of results of those reported in Table 1 but only for the instances CHI and THO. While the number of operated patients is almost the

Table 3 Comparing M_1 and M_2 solutions: impact on the solution varying the LOS of the patients.

	time		gap		N		D		avg. p_i	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
										Scenario 1
CHI	300.08	1.92	0.07%	0.00%	176	181	9588	9360	54.5	51.7
THO	300.06	100.08	0.20%	0.00%	162	169	9571	9567	59.1	56.6
										Scenario 2
CHI	300.05	299.89	0.06%	1.19%	177	193	9590	9361	54.2	48.5
THO	300.08	2.25	0.17%	0.00%	161	176	9571	9232	59.4	52.5

same for model M_1 in both scenarios, for model M_2 the value of N increases in the scenario 2, that is when the patients with maximum LOS are the majority.

Table 4 Comparing M_1 and M_2 solutions: occupied stay beds varying the LOS of the patients.

	model M_1						model M_2					
	1	2	3	4	5		1	2	3	4	5	
												Scenario 1
CHI	41	61	58	58	47	**20**	71	71	71	71	71	**0**
THO	28	45	55	51	58	**30**	62	62	62	62	62	**0**
												Scenario 2
CHI	41	78	89	82	68	**48**	84	84	103	84	84	**19**
THO	28	68	81	66	77	**53**	74	74	108	74	74	**34**

Table 4 reports the same type of results of those reported in Table 2 but only for the instances CHI and THO. For the scenario 1, the results confirm the previous remarks. On the contrary, the results for the scenario 2 show a significant increment of the difference between the maximum and the minimum of occupied stay beds for model M_2: actually, such a difference is due to a peak in the third day while the other days are balanced; such a peak is due to the larger number of patients with $\mu_i = 3$.

4 Conclusions

We proposed and analysed two integer linear programming models for the surgical case assignment problem using patient–centred objectives as an alternative to the maximum OR utilisation.

Quantitative analysis confirmed the ability of the two models to ensure a high level of OR utilisation dealing with long waiting lists. The two criteria provided different results. The minimisation of the waiting times is a fairness criterion among patients that allowed us to have an OR utilisation close to 100% in all cases. Conversely, the workload balance is a criterion to have a smooth workload along the week, which has been able to schedule a high number of patients in most cases.

The result of the model M_1 showed that waiting time minimisation should be a proxy of the OR utilisation maximisation, when the waiting list is quite long. From this perspective, the most considerable and counter-intuitive result is the non-compliance between the OR utilisation and the number of the planned patients, as reported in Table 1.

A further work can be the study of the impact of these criteria when they are adopted over time and if used concurrently with other optimization modules, such as the RTM of operating rooms.

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