Improving Operating Room Efficiency by Applying Bin-Packing and Portfolio Techniques to Surgical Case Scheduling

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BACKGROUND: An operating room (OR) department has adopted an efficient business model and subsequently investigated how efficiency could be further improved. The aim of this study is to show the efficiency improvement of lowering organizational barriers and applying advanced mathematical techniques.

METHODS: We applied advanced mathematical algorithms in combination with scenarios that model relaxation of various organizational barriers using prospectively collected data. The setting is the main inpatient OR department of a university hospital, which sets its surgical case schedules 2 wk in advance using a block planning method. The main outcome measures are the number of freed OR blocks and OR utilization.

RESULTS: Lowering organizational barriers and applying mathematical algorithms can yield a 4.5% point increase in OR utilization (95% confidence interval 4.0%–5.0%). This is obtained by reducing the total required OR time.

CONCLUSIONS: Efficient OR departments can further improve their efficiency. The paper shows that a radical cultural change that comprises the use of mathematical algorithms and lowering organizational barriers improves OR utilization.

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Optimal use of scarce and expensive facilities such as operating rooms (ORs) requires efficient planning. The Erasmus University Medical Center (Erasmus MC), Rotterdam, The Netherlands, developed an OR business model based on controlled surgical case scheduling and management contracts. Nevertheless, OR department managers still explore new ways to improve OR efficiency.

The main inpatient OR department in Erasmus MC is run as a facilitating department that provides staffed and fully equipped ORs for the various surgical departments. A block planning approach has been adopted in which blocks of OR time are made available to surgical departments in advance (1,2). Departments may only assign patients to OR blocks that were made available to them. Regrettably, these organizational barriers result in suboptimal use of OR time. The OR business model furthermore incorporates the annual management contracts specifying the yearly amounts of OR time available for each surgical department. Capacity for emergency cases and uncertainty of case durations is accounted for by determining target OR utilizations for each surgical department independently. Any surgical case schedule, therefore, must include free OR time, or "planned slack." Since target utilizations differ, planned slack also differs among surgical departments.

In summary, for the planning of surgical cases the surgical departments must adhere to the following rules:

1. Submit elective case schedules 2 wk in advance;
2. Maximize use of OR time and not exceed block times;
3. Plan elective cases using historical mean case durations;
4. Include planned slack to deal with emergency cases and variability of case durations.

Provided these rules are adhered to, the OR department "guarantees" that all scheduled surgical cases and emergency cases will be performed, whatever happens during the day. Moreover, applying these rules consequently helps surgical departments in their yearly contract negotiations about OR time with the hospital board.

The hypothesis to be tested was: combining advanced mathematical algorithms with lowering of organizational barriers among surgical departments improves OR efficiency. Several methods to improve efficiency have been proposed in the literature. Strum

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Table 1. Clustering of 10 Erasmus Medical Center Surgical Departments into Four Units

Unit 1	Unit 2	Unit 3	Unit 4
Ear–nose–throat surgery	General surgery	Oral surgery	Gynecological surgery
Neurosurgery		Trauma	Urology
Ophthalmology		Orthopaedic surgery	
		Plastic surgery	

et al. (3) reported a benefit of approaching the OR planning problem as a news-vendor problem. Dexter et al. (4) recently showed the benefits of various approaches to surgical case scheduling. A broad overview of relevant literature is presented by McIntosh et al. (5). Mathematical algorithms to optimize surgical case schedules is a widely researched topic (3,6–8). Several studies addressed the application of bin-packing techniques, such as the Best Fit Descending heuristic (9,10) or Regret-Based Random Sampling (RBRS) (11), yet within single departments. Finally, there is evidence that approaching the OR scheduling problem as a portfolio problem (12) may deal with the unpredictability of case durations and improve efficiency (11). Similar portfolio techniques are already in use for case mix management problems (13,14).

Given the business model used by the main OR department of Erasmus MC, efforts are still focused on improving the current OR utilization. The aforementioned mathematical methods were examined. In addition, we report a computer simulation study assessing promising methods for creating efficient surgical schedules within scenarios that represent various degrees of lowering organizational barriers.

METHODS

Data

Erasmus MC is a university hospital and tertiary referral center in Rotterdam, The Netherlands. Erasmus MC has 1237 beds and admits 34,500 patients per year, 60%–70% of whom undergo operation. The main inpatient OR suite consists of 16 ORs, providing the complete spectrum of surgical cases, including transplantation and trauma surgery. Organizationally, the Erasmus MC inpatient OR department is subdivided into four units, each serving a set of specialties (Table 1). Prospective data, approved immediately after the surgical procedure, are available for more than 180,000 surgical cases since 1994. Data on expected and real case durations and variations in durations for the 10 largest surgical departments were retrieved. Based on frequency, mean duration, and standard deviation of case duration, data were classified into four to eight homogeneous categories per surgical department (Table 2). Table 3 shows the OR suite fixed weekly block plan. All OR blocks in this study consisted of 450 min.

Mathematical Representation of Erasmus MC's Surgical Case Scheduling

Surgical case scheduling involves finding the combination of surgical cases that makes optimal use of available OR time. In the field of applied mathematics, this problem is known as the bin-packing problem. Currently, surgical departments schedule their surgical cases using a First-Fit approach (15). Searching from the beginning, patients are selected from a waiting list and scheduled in the first available OR in a particular week.

Table 2. Characteristics of the 10 Main Surgical Departments in Erasmus Medical Center. Each Category Represents the Patient Mix for a Department

	General surgery		Gynecological surgery		Plastic surgery		Ear–nose–throat surgery		Orthopedic surgery	
Cat.	Mean[a] (SD)	Freq. (%)	Mean (SD)	Freq. (%)	Mean (SD)	Freq. (%)	Mean (SD)	Freq. (%)	Mean (SD)	Freq. (%)
1	150 (89)	8	80 (65)	2	119 (107)	5	102 (125)	4	107 (58)	9
2	67 (31)	3	52 (19)	14	63 (22)	14	40 (17)	33	61 (23)	10
3	100 (44)	12	73 (33)	19	82 (28)	17	65 (24)	19	83 (30)	18
4	135 (52)	19	98 (32)	25	112 (36)	21	102 (35)	12	109 (38)	21
5	171 (63)	20	125 (43)	32	139 (39)	22	127 (32)	14	160 (43)	21
6	213 (89)	3	156 (41)	2	187 (57)	11	182 (65)	8	199 (45)	16
7	262 (87)	25	213 (82)	6	432 (181)	10	254 (75)	5	291 (102)	5
8	351 (124)	9					549 (203)	6		

(*Continued*)

Cat. = category; SD = standard deviation; Freq. = frequency.

Sample sizes: General surgery 31,209, gynecological surgery 10,163, plastic surgery 14,318, ear–nose–throat surgery 17,103, orthopedic surgery 11,859, urology 11,876, trauma 8385, ophthalmology surgery 9801, neurosurgery 10,370, and oral surgery 2608. Surgical cases were classified based on their expected duration. Surgical cases for which no prediction of the case duration was available are grouped in Category 1.

[a] Mean and standard deviation (SD) are given in minutes.

Table 3. Fixed Weekly Block Plan for the Inpatient Operating Room Department of Erasmus Medical Center with 16 Operating Rooms

Specialty	Mon	Tue	Wed	Thu	Fri
	No. of operating rooms per day of the week				
General surgery	3	3	3	3	3
Gynecological surgery	1	1	1	1	1
Oral surgery	1	1	1	1	1
Ear–nose–throat surgery	2	2	2	1	2
Neurosurgery	2	2	2	2	2
Trauma	1	1	0	1	1
Ophthalmology	1	1	1	1	1
Orthopedic surgery	1	1	2	1	2
Plastic surgery	2	2	2	2	1
Urology	2	2	2	2	2

In our study, waiting lists were generated based on different surgical case categories representing each department's case mix (Table 2). Subsequently, a First-Fit algorithm simultaneously selected and scheduled surgical cases for the period of 1 wk which, in practice, is done approximately 2 wk before the date of surgery. This algorithm scheduled next cases only if the previous surgical case had been scheduled and if the algorithm concluded that it was impossible to fit the previous case into any of the available OR blocks. If the case did not fit in any of the available blocks, it was placed back on the waiting list. The algorithm terminates once it reaches the end of the waiting list. Note that for scheduling of cases the mean duration was used and that no planned overtime was allowed, as prescribed by the Erasmus MC rules. The resulting surgical case schedules comprised surgical cases, planned slack, and unused OR capacity (Fig. 1).

Planned Slack and the Portfolio Effect

The financial world deals with uncertainty by using the portfolio effect. This ensures that the expected return of a stock portfolio is less vulnerable to fluctuations on the stock market. The term "portfolio effect" then indicates that portfolio risk decreases with increasing diversity, as measured by the absence of correlation (covariance) between portfolio components (16). We earlier found application of the portfolio effect to surgical case scheduling to be successful in increasing OR efficiency, since it reduces the required amount of planned slack, given an accepted risk of overtime (11). The approach clustered surgical cases with similar variability in the same OR block, assuming these to be uncorrelated.

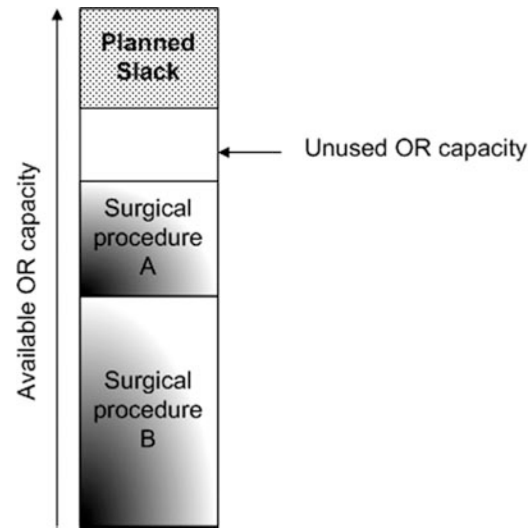

Figure 1. Graphical representation of a surgical case schedule, which typically includes various surgical cases, planned slack, and unused operating room time.

We illustrate the portfolio effect applied to surgical case scheduling by the following example: Consider two OR blocks, both of which have two surgical cases scheduled. One case with (mean, standard deviation) = (100, 10) and one case with (mean, standard deviation) = (100, 50) (Fig. 2) (all values are given in

Table 2. Continued

Urology Mean (SD)	Urology Freq. (%)	Trauma Mean (SD)	Trauma Freq. (%)	Ophthalmology Mean (SD)	Ophthalmology Freq. (%)	Neurosurgery Mean (SD)	Neurosurgery Freq. (%)	Oral surgery Mean (SD)	Oral surgery Freq. (%)
121 (68)	3	100 (68)	7	83 (46)	1	192 (165)	8	97 (37)	1
59 (30)	5	62 (23)	22	46 (14)	35	113 (41)	17	87 (29)	44
74 (26)	30	81 (30)	32	60 (22)	42	171 (62)	14	130 (43)	44
102 (49)	15	122 (38)	20	95 (30)	17	255 (62)	28	238 (87)	11
152 (49)	17	176 (92)	19	127 (34)	5	324 (73)	12		
230 (68)	21					492 (177)	21		
385 (123)	8								

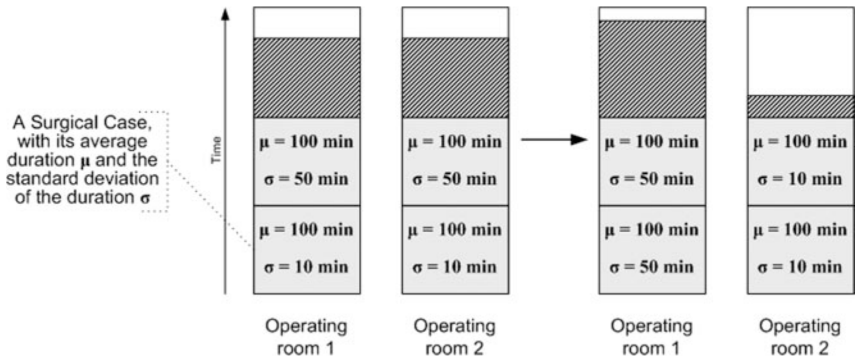

Figure 2. Example of planned slack reduction as a result of the portfolio effect. The sum of the shaded areas in the two operating room blocks on the left exceeds that in the two operating room blocks on the right.

Table 4. Description of Scenarios Representing Various Flexibility Levels

Scenario	Interdepartmental flexibility	Flexibility over the week
1	OR block consists of surgical cases of a single department	Rescheduling on the same day
2	OR block consists of surgical cases of a single department	Rescheduling within the same week
3	OR block consists of surgical cases of a department within one unit	Rescheduling on the same day

See Table 1 for the clustering of surgical departments in organizational units. The flexibility is applied to the construction of surgical schedules 2 wk in advance.
OR = operating room.

minutes). We assumed that case durations are described by a normal distribution function. In this example, we now compared this situation (the left side of Fig. 2) with the situation in which surgical cases with similar variance are clustered. In the first situation, the standard deviation of total duration is the same for both OR blocks: $\sqrt{}(50^2 + 10^2) = 51.0$ min. The total planned slack for the two blocks is thus 102.0β min, where β is a risk factor to deal with risk of overtime. Since the sum of the durations follows a normal distribution the following holds: P (mean + β·standard deviation) $\leq$ accepted risk of overtime, such that given a certain accepted risk of overtime the risk factor can be calculated. In the second situation, the total planned slack is: $(\sqrt{}(50^2 + 50^2) + \sqrt{}(10^2 + 10^2))\beta = 84.9\beta$ min. This means a 17.1β min reduction in the total required planned slack time, and thus an equal increase in available capacity. This portfolio profit will increase with higher variability of the cases concerned. This example illustrates that rescheduling a surgical case can reduce the extent of planned slack.

Organizational Barriers

We constructed three scenarios to investigate the impact of lowering organizational barriers imposed by block planning (Table 4). The scenarios are graded as to interdepartmental flexibility (i.e., scheduling cases of different departments in the same OR on 1 day) and flexibility of rescheduling surgical cases between days of the week compared with the current situation. Rescheduling of surgical cases throughout the week does not affect patients, since they have not yet been scheduled.

In this study, we assumed application of the scenarios directly after the construction of the surgical case schedules, approximately 2 wk before the actual execution of the schedule (Fig. 3). This enables OR departments to take necessary steps to ensure feasibility; for example regarding material logistics, ranging from specific surgical material to complete navigation system for complex craniotomy surgery. Surgical departments are responsible for the scheduling of semiurgent or add-on elective patients who need an operation on a day for which a surgical case schedule is already set. For this purpose, departments may schedule cases without assigning a patient to it, or by canceling one or more of the elective cases. Emergency patients are operated on within the reserved OR time as described earlier.

Advanced Mathematical Algorithms

Application of the different scenarios to a surgical case schedule implied rescheduling of surgical cases according to the organizational flexibility of the scenario under consideration. A bin-packing algorithm, based on work of Hans et al. (11), who used RBRS, did the rescheduling of the surgical schedules given the scenarios. Figure 4 shows how rescheduling surgical cases saves OR time. The objective of the algorithm is to minimize planned slack by exploiting the portfolio effect and the required number of OR blocks. RBRS procedures start with removing all cases of the existing surgical schedule to a list. Then, RBRS iteratively schedules a random surgical case from the list until all cases are scheduled. The drawing probability of each of the cases is based on the case's Best Fit suitability. This randomized procedure gives a new solution (a "surgical case") every time it is executed. We stopped the algorithm after generating a preset number of 1500 surgical case schedules. The generated schedules were evaluated on the objective criterion (amount of free OR capacity) and the best schedule was saved (11). The algorithm was coded in the Borland Delphi computer language (Cupertino, USA).

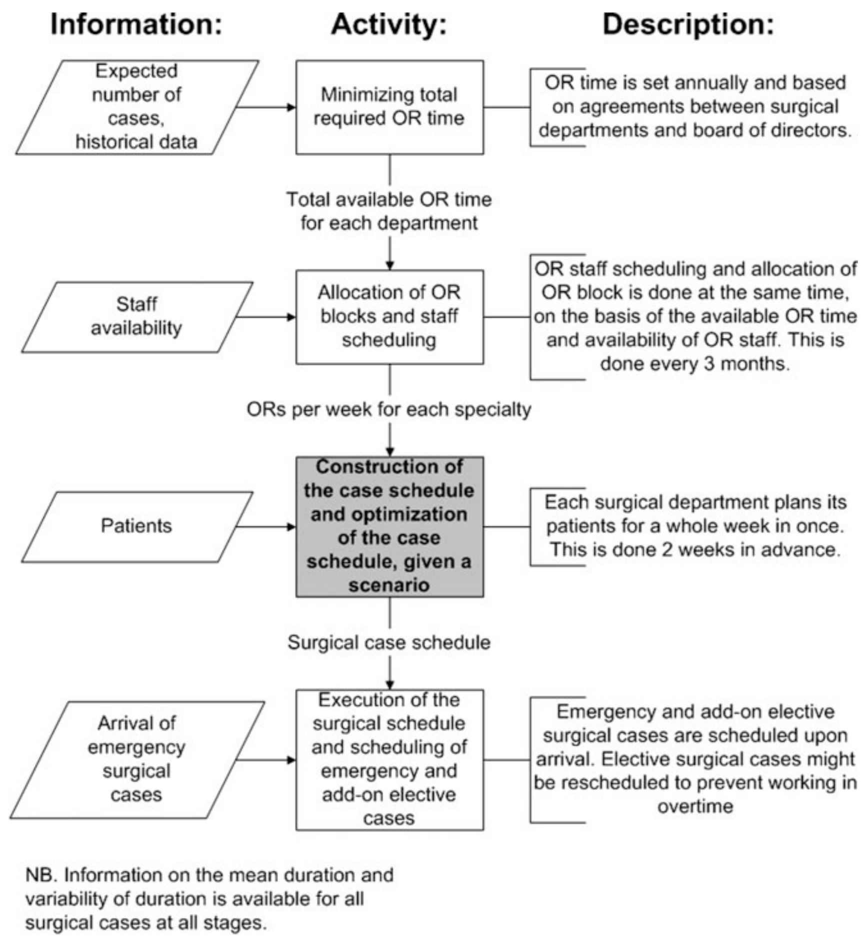

Figure 3. Positioning of the operating room scheduling process. The focus of this paper is on scheduling surgical cases approximately 2 wk in advance, methodology for scheduling add-on and elective cases is beyond the scope of this paper and therefore not explicitly described in the figure.

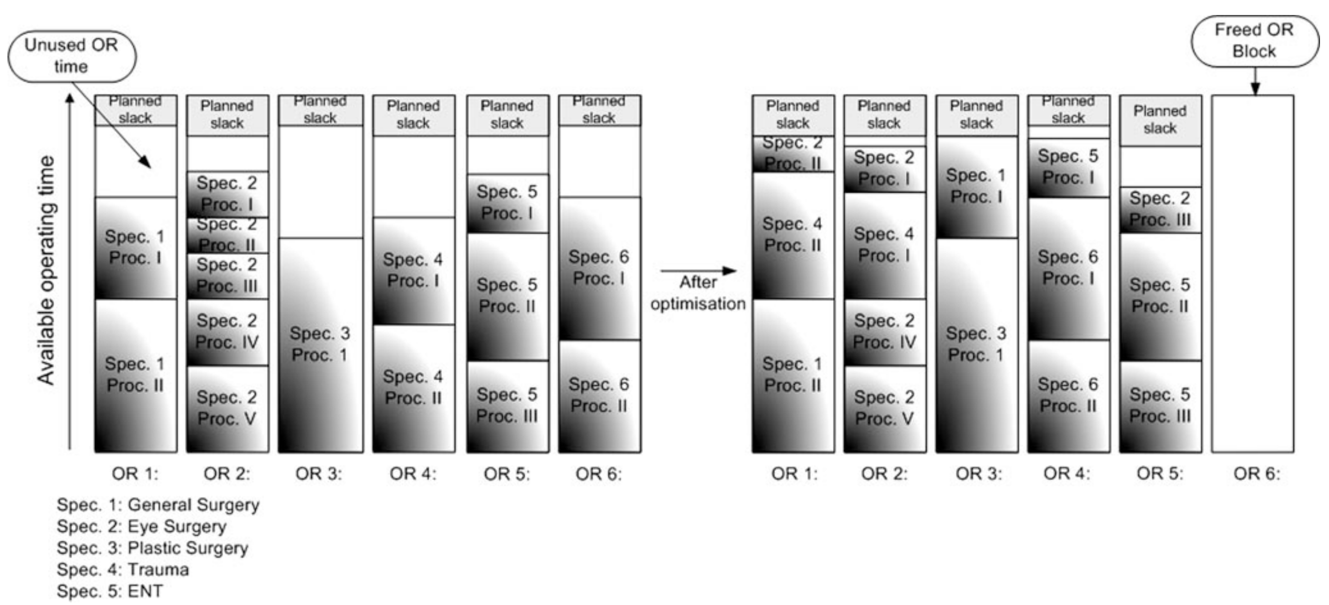

Figure 4. Example of creating a free operating room block by reallocating surgical cases.

Experimental Design

The Erasmus MC's main inpatient department considered using the news-vendor approach of Strum et al. (3). Subsequently, we investigated the benefits of the RBRS that exploited the portfolio effect and relaxation of the organizational constraints. To this aim, the surgical case scheduled created by the RBRS algorithm was compared with the surgical schedules constructed by the First-Fit approach. The RBRS algorithm was compared with the Best Fit algorithm (7) to assess the performance of advanced mathematical algorithms over available and simpler heuristic techniques.

Table 5. Operating Room Performance

	Mean (min)	Standard deviation (min)	Proportion (%)
Under-utilization	59	68	52
Over-utilization	40	94	47

Measures are based on 30 consecutive months from January 1, 2004 onwards.

Table 6. Operating Room (OR) Utilization Rates

	Current situation Mean ± SE (%)	Scenario 1 Mean ± SE (%)	Scenario 2 Mean ± SE (%)	Scenario 3 Mean ± SE (%)
First Fit case schedule	77.4 ± 0.2			
RBRS algorithm		77.5 ± 0.2	81.9 ± 0.2	78.8 ± 0.2
Best Fit Descending		77.4 ± 0.2	81.2 ± 0.2	78.2 ± 0.2
RBRS algorithm versus Best Fit Descending		0.1 (−0.5 to 0.6)[a]	0.7 (0.2 to 1.2)[a]	0.6 (0.1 to 1.0)[a]

Utilization is defined as the ratio between the total amount of elective surgical cases and the total allocated OR capacity. SE = standard error. Mean and 95% confidence interval (CI) of differences between Regret-Based Random Sampling (RBRS) algorithm and Best Fit Descending in the three scenarios are examined by a paired *t*-distribution.
[a] Mean (95% CI) (%).

We performed a robustness analysis on the influence of unpredictability of case duration on OR utilization, wherein the unpredictability was represented by the standard deviation of case duration. The influence of number of ORs within an OR department on OR utilization was investigated as well. Both analyses were performed for each of the three flexibility scenarios. The outcome measures of this study are OR utilization and the number of freed OR blocks, so-called "freed ORs." OR utilization was defined as the ratio between the total duration of elective surgical cases and the total staffed OR capacity per week. Hence, it is similar to what is known in the literature as "raw OR utilization" (17).

RESULTS

Applying the news-vendor approach of Strum et al. (3) did not lead to improved efficiency. With staffing costs determined by the allocated capacity and overtime by a relative cost ratio of 1.5 and increasing the block times with 15 min, it even decreased efficiency (Table 5). Therefore, new ways to increase OR efficiency were explored, as described in the previous section.

Increased flexibility in the three scenarios increased the number of freed OR blocks (Table 6). Eventually, this resulted in an improved utilization rate of 4.5% points (95% confidence interval 4.0%–5.0%). Both the Best Fit Descending heuristic and the RBRS algorithm improved utilization. The latter, more advanced, algorithm significantly out-performed the first heuristic by 0.7% point in Scenario 2 (95% confidence interval 0.2%–1.2%). Applying either the RBRS algorithm or the Best Fit Descending did not significantly improve the initial surgical schedules when combined with Scenario 1 (i.e., blocks consists of surgical cases of a single department and cases are rescheduled on the day). No significant difference was measured between the Best Fit Descending heuristic and the RBRS algorithm in Scenario 1 (Table 6).

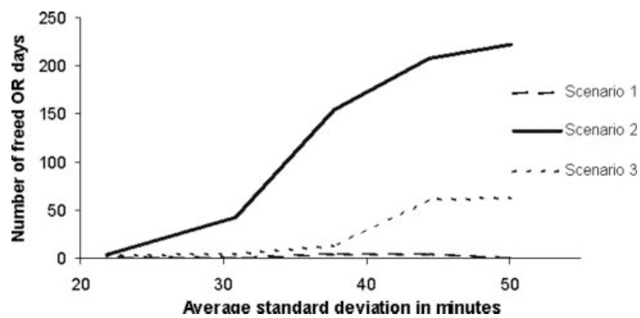

Figure 5. Graphic representation of the number of freed operating room blocks in Erasmus Medical Center when the Regret-Based Random Sampling algorithm is applied in combination with the three scenarios in which the standard deviation of case duration is varied.

Number of freed OR blocks, and hence OR utilization, increased relative to the standard deviation of case duration within one department (Fig. 5). The RBRS algorithm and the portfolio effect did not significantly improve the original schedule in Scenario 1, regardless of the standard deviation in the patient mix. Furthermore, in Scenarios 2 and 3, the benefits of the RBRS algorithm increased with the standard deviation of case duration.

Figure 6 shows the association between number of ORs and OR utilization rate expressed in number of freed OR days for the three scenarios. The findings shows that if more flexibility would be achievable, benefits progressively increase with the number of cases performed daily relatively to the available hours provided.

DISCUSSION

The study showed how to improve OR efficiency by combining advanced mathematical and financial techniques with the lowering of organizational barriers. The combination facilitates OR departments to improve OR efficiency when current methods will no

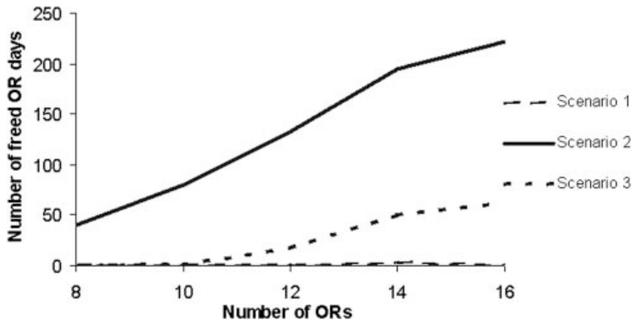

Figure 6. Graphic representation of the number of freed operating room blocks when the Regret-Based Random Sampling algorithm is used in combination with the three scenarios for operating room departments of various sizes.

longer benefit (3,7). The method is applicable in hospitals that set their surgical case schedules approximately 2 wk in advance, and potentially improves OR utilization by 4.5%. Improved efficiency implies that more operations can be performed at the same OR capacity or that less OR capacity is needed for the same number of operations. We also showed that potential benefits vary for different OR departments, depending on the uncertainty in case duration and number of ORs within one OR department. Absolute measures of this study are difficult to compare with results from other studies because Erasmus MC uses a specific method of reserving OR time in surgical schedules.

The algorithms used aimed to free OR blocks, because capacity that was previously allocated in these blocks is not accounted for while calculating the utilization rate. This is true for all OR departments that have sufficient flexibility in their staff scheduling to allow changes approximately 2 wk in advance.

We assumed in the analysis that surgical case durations show normal distribution. Other studies have shown that a lognormal distribution is a better approximation of the real duration (18). Calculation of planned slack, which is required to simulate the portfolio effect, requires a closed form probability distribution. This is not the case for a lognormal distribution, and this is why we have opted for a normal distribution, which may modestly influence the outcomes. Since the amount of planned slack is similarly calculated for the RBRS algorithm compared with that for the Best Fit heuristic, we do not expect that the assumption influences the calculated outcomes.

Many hospital use information technology systems to actually schedule their surgical cases in the available blocks. The mathematical techniques presented in this paper can easily be incorporated in such information technology systems, permitting planners to actually use the mathematical algorithms. Using the techniques addressed in this paper, and given a flexibility scenario agreed upon beforehand, the set of cases planned by the different departments in their blocks is collectively optimized after surgeons have set their patients' surgery dates. After optimization, each department can match its surgeon and bed planning with the new, more efficient, case schedule.

Lowering organizational barriers might have some negative effects and will require a more flexible attitude of surgical departments and individual surgeons. First, allowing various surgical departments to use the same OR may result in longer waiting times for surgeons. Second, surgeons may be scheduled in various ORs on the same day. Third, having surgeons operate on different days in the week requires adjustment of their other tasks, especially in hospitals where surgeons are highly specialized and where cases cannot be interchanged among surgeons. All these issues should be carefully addressed and weighed against the efficiency increase. The essential consideration, we believe, is that the drawbacks for a surgical department can be compensated for by the huge amount of extra OR capacity, which can be used to shorten the waiting list and earn more money.

Another aspect of implementation of the techniques is the required additional flexibility of the ORs. Each OR has to be uniformly equipped so that all surgical departments may operate in it. The efficiency increase achieved by the proposed method would justify the investment to equip all ORs generically.

Each hospital can choose a flexibility scenario that matches its requirements. Even more scenarios can be made to show benefits of even lower organizational barriers. The potential benefits can be calculated by comparing the current case scheduling strategy, in this paper represented by a first-fit algorithm, and the future situation in which the portfolio effect and bin-packing techniques have been applied and organizational constraints have been relieved. This paper provides a tool for any hospital type to make their own trade-off between flexibility and higher utilization of OR capacity.

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