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A new heuristic algorithm for the operating room scheduling problem ☆

Ya Liu [a,b,*], Chengbin Chu [b,c], Kanliang Wang [d]

[a] LAMIH, University of Valenciennes, 59313 Le Mont-Houy, France
[b] LGI, Ecole Centrale Paris, 92295 Chatenay-Malabry, France
[c] School of Economics and Management, Tongji University, 200092 Shanghai, China
[d] Department of Management Science and Engineering School of Business, Renmin University of China, 59 Zhongguancun Street, 100872 Beijing, China

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ABSTRACT

Due to the great importance of operating rooms in hospitals, this paper studies an operating room scheduling problem with open scheduling strategy. According to this strategy, no time slot is reserved for a particular surgeon. The surgeons can use all available time slots. Based on Fei et al.'s model which is considered to be close to reality, we develop a heuristic algorithm to solve it. The idea of this heuristic algorithm is from dynamic programming by aggregating states to avoid the explosion of the number of states. The objective of this paper is to design an operating program to maximize the operating rooms' use efficiency and minimize the overtime cost. Computational results show that our algorithm is efficient, especially for large size instances where our algorithm always finds feasible solutions while the algorithm of Fei et al. does not.

1. Introduction

Medical system is facing a state of change. For patients, as the population aging in many countries, the number of patients is increasing rapidly. Regarding the technical constraints and human resource constraints in hospitals, a large part of patients cannot be processed immediately. The longer they wait, the less satisfied they are. Whereas on another side, hospitals, especially public ones, suffer from a great amount of budget deficit. They seek to increase the medical service efficiency and decrease the medical service cost in order to balance the budget.

Litvak and Long (2000) pointed out that the operating theater can be seen as the engine of a hospital. Many other resources like anesthetists and patient beds highly depend on the operating room planning. The control of operating rooms becomes more and more important in the decade years. But in reality, the operating rooms, as key resources, often lead to a great time waste. Weinbroum, Ekstein, and Ezri (2003) investigated 10 operating rooms in a medical center and found that the waste time reached 15% of the total time. So, appropriate scheduling of operations and matching patient requirements with operating rooms and surgeons, in order to increase the efficiency of the operating rooms, are significant research topics in medical care.

In the past decade, researchers focused on the operating room scheduling problems from both modeling and algorithmic points of view. Fei, Chu, and Meskens (2008) used a heuristic method based on column generation to minimize the total cost of operations. Kuo, Schroeder, Mahaffey, and Bollinger (2003) considered the availability of surgeons and the operating room opening hours as constraints, established a linear programming model and solved it by Excel software. Marcon, Kharraja, and Simonnet (2001) proposed an integer linear programming model, solved by Cplex software. Dexter, Macario, Traub, Hopwood, and Lubarsky (1999) used computer simulation to model operating room scheduling to find an optimal scheduling strategy to maximize the use of operating room block time. Kharraja, Chaabane, and Marcon (2004) realized the minimum makespan of operating rooms. Sier, Tobin, and McGurk (1997) took into account more constraints, like the patients' age, the patients' priority, the operations' allocation rule. The obtained mathematical model is nonlinear.

With respect to its great significance for both patients and hospitals, there is quite little research on operating room management. In this paper, we focus on Fei et al.'s models (Fei, Chu, Meskens, & Artiba, 2008; Fei, Meskens, & Chu, 2010). These models are close to the reality and consider both block scheduling and open scheduling strategies. As block scheduling is a special case of open scheduling, we study only the open scheduling model and develop a heuristic algorithm. This algorithm comes from the dynamic programming idea by aggregating states to avoid the explosion of the number of states. This idea was successfully applied by Chu and Antonio (1999) to solve a one-dimensional cutting stock problem. In general, it keeps a global view of the overall

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* Corresponding author at: LAMIH, University of Valenciennes, 59313 Le Mont-Houy, France.
E-mail address: liuya.utt@gmail.com (Y. Liu).

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optimization problem, in contrast to other myopic methods where the solution is constructed very locally in a step-by-step manner. This algorithm can also be used in meta-heuristics or branch-and-bound procedures to generate one of the initial solutions.

The paper is organized as follows. Section 2 describes the open scheduling strategy. Section 3 presents the general method. Section 4 states the detailed procedure for solving subproblem. Section 5 gives a numerical example. Section 6 reports computational results to evaluate the performance of this algorithm. zSection 7 concludes the paper.

2. Description of open scheduling strategy

Before describing the open scheduling strategy, the definition of "time slot" should be illustrated. In Fei et al.'s instances, the planning period is five work days (one week), and there are six operating rooms in the hospital. Because of some technical and human constraints, not all the operating rooms can be opened each day. Instead, the operating rooms are open during certain time periods. For instance, operating room 1 may be open on Monday from 9:00 to 12:00, and each opening period of an operating room is called a time slot. So, a given time slot specifies the day and the concerned operating room. For the sake of simplicity, the objective of the operating room scheduling problem is to allocate operations to the time slots available to maximize the time slots' use efficiency and minimize the overtime cost. In the models considered by Fei et al. the objective function is expressed by minimizing the total cost of under-utilization of time slots and overtime of time slots.

Open scheduling strategy consists of assigning operations corresponding to each given surgeon into time slots. All the surgeons are considered. Operations that should be performed by different surgeons can be assigned to the same time slot. For example, in Fig. 1, some operations corresponding to surgeons 1 and 3 are assigned to time slot 2. No operation can be scheduled after its deadline and the total operating time of the operations assigned to a time slot cannot exceed its maximum opening hours (the sum of its regular opening hours and overtime). For security reasons, overtime is limited. Each surgeon's working hours cannot exceed his/her maximum working hours allowed per day. The mathematical formulation for open scheduling strategy is defined in Fei et al. (2010).

3. The general method

The core problem for the open scheduling strategy is to assign operations to the time slots available in a planning horizon while respecting all constraints to maximize the time slots' use efficiency and minimize the overtime cost. It can be formulated as a set partitioning problem representing the same model described in Fei et al. (2010). Our objective is to partition the set of operations to be performed into subsets and assign a time slot to each subset to optimize the objective function.

Let N be the number of operations to be arranged, and n the number of time slots available. Any set of operations (respectively time slots) can be represented by an N-vector B (respectively n-vector C) whose ith entry is equal to 1 if operation (time slot) i belongs to the set, and 0 otherwise. Any subset B' of B is also an N-vector and we write $B' \leqslant B$ to denote the fact that any entry of B' is less than or equal to the corresponding entry of B. Similarly, we have $C' \leqslant C$ for any subset C' of C. The sets of all operations to be performed and time slots available are respectively expressed by B_0 and C_0 in which all entries are equal to 1. The problem is how to partition B_0 into subsets, and which time slot in C_0 is distributed to each subset to optimize the objective function.

Therefore, this operating room scheduling problem with open scheduling strategy can be reformulated based on the classic dynamic programming idea. We define $\gamma(B,C)$ as the minimum cost of assigning the operations in B to the time slots available in C. It represents the total cost of underutilization or overtime of these time slots. Then the following recursive equation holds:

$$\gamma(B, C) = \min_{B' \lneqq B, |C - C'| = 1} \{\gamma(B', C') + h(B - B', C - C')\} \tag{1}$$

where $h(B - B', C - C')$ is the cost of assigning the operations in $B - B'$ to a *single* time slot represented by $C - C'$. Of course, if an operation in $B - B'$ whose deadline is earlier than the day corresponding to the time slot represented by $C - C'$, $h(B - B', C - C')$ is set to $+\infty$, without loss of generality. In this relation, $B' \lneqq B$ requires that $B' \leqslant B$ but $B' \neq B$. In other words, each entry of B' should be less than or equal to the corresponding entry of B but at least one inequality should be strict. By the definition, we have $\gamma(0,0) = 0$, which provides the boundary condition. In this formulation, an optimal solution is given by (B_0, C^*) where $\gamma(B_0, C^*) = \min_{C' \leqslant C_0} \gamma(B_0, C')$, since all the operations have to be performed.

The considered problem is a kind of set partitioning problem. All the set partitioning problems can be considered as partitioning a given set of activities into subsets and allocating a resource to each subset. A subset of activities and the resource allocated form a patten. Such a pattern incurs a cost. The objective is to minimize the total cost of the selected patterns so that each activity is involved in exactly one pattern and each resource is involved in at most one selected pattern. Details are referred to Liu (2009). In

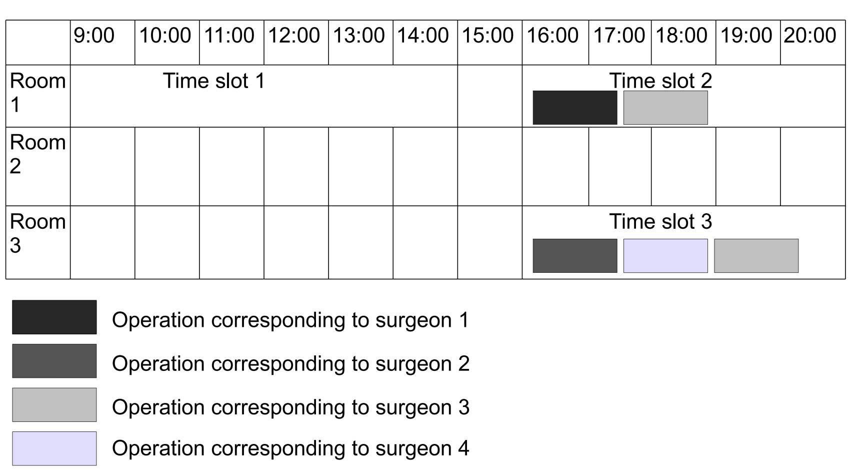

Fig. 1. Open scheduling strategy.