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Multi-period and multi-resource operating room scheduling under uncertainty: A case study

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ABSTRACT

Efficient planning and scheduling is essential for timely treatment of patients and improving the quality of operating room services and activities. In the present study, attempts are made to investigate a multi-period and multi-resource operating room integrated planning and scheduling problem under uncertainty. To this end, a mixed integer linear programming model has been developed for minimizing the tardiness in surgeries, overtime and idle time. Constraints related to human resources, equipment, as well as beds in pre-operative holding unit, recovery unit, ward and intensive care unit are taken into consideration. The durations of surgeries and recoveries are assumed uncertain, and a robust optimization approach has been used to manage the uncertainty. Due to the complexity of the model and the inability to solve large-scale problems, a metaheuristic method based on the genetic algorithm and a constructive heuristic approach have been proposed. After setting the parameters of the solution approaches using the Taguchi method, numerical experiments are performed based on various instances, and the results obtained from solving the mathematical model are compared to the results of the proposed metaheuristic and heuristic approaches. The results indicate that the proposed methods have a very good performance and the heuristic approach outperforms the genetic approach because the objective function of the proposed constructive heuristic is on average, about 19% better than the objective function of the genetic approach. A case study is also conducted in a hospital. The results obtained from the comparison of the proposed approaches with the hospital scheduling show that overtime and idle time are significantly improved in the proposed approaches.

1. Introduction

Hospitals are one of the fundamental elements of the healthcare industry. They consist of several units, such as a pharmacy, operating room, recovery unit, blood bank, laboratory, and radiology. Operating room is one of the most important and expensive units, and besides, it is a bottleneck resource (Landa, Aringhieri, Soriano, Tànfani, & Testi, 2016). Today, healthcare organizations are under pressure to offer surgical services at the lowest possible cost, and are facing challenges such as limited budgets, increasing waiting lists and aging populations at the same time (Molina-Pariente, Fernandez-Viagas, & Framinan, 2015). The demands for surgery are usually more than its supply, and this gives rise to long waiting times for patients and leads to reduced quality of services and dissatisfaction (Aringhieri, Landa, Soriano, Tànfani, & Testi, 2015). It is estimated that 60–70% of hospital admissions will require operating rooms (Van Essen, Hans, Hurink, & Oversberg, 2012). Operating rooms are very expensive. Surgical costs usually account for more than 40% of hospital costs (Denton, Viapiano, & Vogl, 2007). On the other hand, surgeries account for about 67% of hospital revenues. Of course, surgeries don't provide any revenue in many public hospitals in different countries (Saadouli, Jerbi, Dammak, Masmoudi, & Bouaziz, 2015).

Inattention to effective management and planning leads to delays, postponement of surgeries, withdrawal of patients, overtime, and eventually loss of revenue and decline in quality of treatment (Vancroonenburg, Smet, & Berghe, 2015). Timely treatment and increased efficiency and productivity in hospitals and operating rooms require proper management. Operating room planning and scheduling is one of the important aspects of operating room management which represents an application of optimization in the field of healthcare.

Operating room scheduling is associated with specific complexities due to the inherent uncertainties, various constraints and the presence of different beneficiaries. This issue has been one of the challenging research topics in the recent decades and years (Landa et al., 2016).

Different resources must be considered for proper scheduling and planning of operating theaters. Operating rooms, human resources

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(including surgeons, nurses, anesthesiologists, technicians, etc.), surgical equipment and tools, beds needed in preoperative holding unit (PHU), post-anesthesia care unit (PACU), intensive care unit (ICU) and ward are the resources that should be accessible and coordinated (Pham and Klinkert, 2008; Xiang, Yin, & Lim, 2015). According to Weinbroum, Ekstein, and Ezri (2003), the most important factors in waste of time in operating rooms are: lack of access to operating rooms 32%, lack of access to nurses 20%, lack of beds in the post-anesthetic care unit 10% and lack of access to specialist surgeon 4.7%. Therefore, about 70% of the waste of times in the operating rooms can be attributed to lack of coordination between resources and inaccessibility of them. Jonnalagadda, Walrond, Hariharan, Walrond, and Prasad (2005) found that the most important reasons for cancellation or delays in surgical procedures in developing countries include the lack of access to beds in the recovery unit (15%), problems in PHU (13%) and the lack of access to nurses (11%). These items demonstrate the importance of the downstream resources.

As mentioned before, operating room scheduling is associated with various uncertainties. The most important of which are uncertainty of the duration of surgery, postoperative length of stay, and arrival of emergency patients. Uncertainty of the surgery and post-operative length of stay has a direct effect on scheduling efficiency. The arrival of emergency patients (in case the resources for elective and emergency patients are not independent) causes disruptions in the plans. Uncertainty of the surgery duration can lead to overtime. Also, uncertainty in the length of stay in the recovery unit, intensive care unit, or ward may lead to cancellation of surgeries due to the shortage of beds (Neyshabouri and Berg, 2017).

Decisions made for management and planning of operating theaters are usually divided into three hierarchical levels: strategic, tactical, and operational. These items are fully described in the review articles in this area (Cardoen, Demeulemeester, & Beliën, 2010; Guerriero & Guido, 2011; May, Spangler, Strum, & Vargas, 2011) and we skip explaining them here. In the present paper, we focus on the operational level. Operating room scheduling at the operational level generally includes two main steps: the advance scheduling and allocation scheduling. The first step involves selection of patients from the waiting lists and assignment of specific date and operating room to them during the planning horizon. The second step provides a precise sequence of surgical procedures (determining start and finish times), along with allocation of resources to each patient. The former case is sometimes called operating room planning, and the latter is sometimes called operating room scheduling. In the literature, these two steps are presented as simultaneous (integrated) or hierarchical. Hierarchical scheduling reduces the quality of the acquired schedules due to the interdependence of the advance scheduling and allocation scheduling (Cardoen, Demeulemeester, & Beliën, 2009). Therefore, the interest in integrated planning and scheduling is increasing among researchers (Molina-Pariente et al., 2015; Roland, Di Martinelly, Riane, & Pochet, 2010; Van Huele and Vanhoucke, 2014). In this paper, an integrated approach has been used.

Many researchers distinguish between three management policies for the planning and scheduling of the operating rooms. Guerriero and Guido (2011) describe these three types of management policies including open, block, and modified block policies. In the block strategy, a set of time blocks are allocated to specific surgical specialties. In open strategy, time blocks do not belong to certain surgical groups and surgical procedures are planned based on the requests of surgeons. Open strategy performs significantly better than block strategy (Fei, Chu, Meskens, & Artiba, 2008; Van Huele and Vanhoucke, 2014). The modified block strategy is similar to the block strategy, except that some time blocks remain open in the schedule in order to provide more flexibility.

In this paper, the multi-period operating room planning and scheduling problem is studied with a comprehensive view of resources. Constraints on the number and availability of resources related to the surgical processes before and after surgery, including human resources (surgeons, anesthesiologists and nurses), beds of recovery unit, intensive care unit and ward as well as the required equipment and tools are taken into account. The uncertainty in the duration of surgery, recovery, and post-operative length of stay are also taken into consideration. Scheduling is done for elective patients under open scheduling strategy. A mixed integer linear programming model (MILP) has been developed and three criteria are considered for optimization: Idle time and overtime are considered as criteria based on hospital point of view, while the tardiness in surgery is a criterion based on patient point of view. Due to the complexity of the problem, a constructive heuristic (CH) algorithm and a hybrid genetic algorithm (GA) are proposed to solve medium-scale and large-scale problems. A case study is also conducted to investigate the efficiency of the mathematical model and the proposed algorithms in real conditions. The contributions of this paper are as follows:

- Developing a new mixed integer linear programming (MILP) model for multi-period integrated operating room planning and scheduling.
- Considering different units in the operating theater, including the PHU, the operating rooms, PACU, the intensive care unit and the ward.
- Providing a comprehensive view on the resources needed at the operating theater, including human resources, equipment and beds, and consideration of the limited number and availability of them for the first time.
- Considering uncertainty in the duration of surgery and recovery and using a robust optimization approach to manage uncertainty. Also, paying attention to the uncertainty in post-surgery length of stay.
- Proposing a new constructive heuristic algorithm for solving the problem.
- Implementing experimental analysis to compare the proposed approaches.

The remainder of this paper is classified as follows: Section 2 provides a review of relevant literature. Section 3 describes the problem and provides the mathematical model. Section 4 explains the proposed solution methods. Section 5 presents the computational results and analysis. A case study is presented in Section 6. Finally, Section 7 concludes and summarizes the study.

2. Literature review

Operating room planning and scheduling has been the subject of extensive studies. Review papers conducted by Cardoen et al. (2010), Guerriero and Guido (2011) and May et al. (2011) provide comprehensive literature review in this field. Accordingly, here we will review studies that are directly related to the subject of this article.

In the context of deterministic operating room scheduling, Jebali, Alouane, and Ladet (2006) introduced a two-stage approach consisting of sequencing and allocation for operating room scheduling. The authors proposed two mixed integer programming models. Constraints on resources such as surgeons, equipment and beds of recovery and intensive care units were taken into account. Roland et al. (2010) investigated the multi-period operating room planning and scheduling under the open scheduling strategy. They provided a mixed integer programming model. Constraints on access to renewable resources (including nurses, surgeons and some tools and equipment), as well as non-renewable resources (materials and some tools) were included in the problem, but the constraints of other units of the operating theater, such as the recovery unit, were not considered. The authors used genetic algorithm to solve the model. In a similar study, Silva, de Souza, Saldanha, and Burke (2015) studied the operating room scheduling with consideration of the similar factors, but on a daily basis. In their problem, a specialist human resource can simultaneously participate in