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A column-generation-based heuristic algorithm for solving operating theater planning problem under stochastic demand and surgery cancellation risk

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ABSTRACT

This paper investigated an operating theater allocation problem with uncertain surgery duration and emergency demand. Under the consideration of surgery cancellation, a stochastic model was developed to minimize the total expected operating cost. A trade-off was sought between the total cost of opening operating rooms and the total overtime due to the overbooking of an operating theater. The sample average approximation method was used to transform the stochastic model into a deterministic one. A column-generation-based heuristic (CGBH) algorithm was developed to solve the integer programming problem. The performance of the CGBH algorithm was tested by solving randomly generated instances with given distributions. Multiple heuristic rules for branching were developed and compared from the perspectives of solution quality and efficiency. Numerical results indicated that high surgery cancellation risk helps to reduce the operating costs of hospitals and improve the OR efficiency but results in patients' dissatisfaction, and vice versa. This provides management insights for hospital manager to balance the operating costs and patients' satisfaction. The CGBH algorithm performed as well as the CPLEX in the solution quality for small-scale problems. This algorithm can obtain solutions within a 5% gap of the lower bound obtained by the linear problem for large-scale problems that cannot be solved by CPLEX.

1. Introduction

The sixth census indicates that China has stepped into an aging population society, which will increase the health care demand in the next 40 years. The growing demand has caused a great deal of concern for health care system. One of the major challenges in hospitals is how to improve the processes related to surgical cases (Oostrum, 2009). Operating room (OR) management is challenged to address the conflicting objectives of low operating costs, high quality of the surgery, low surgery cancellation risk and high efficiency. There are many uncertainties involved in surgery processes, such as the surgery duration, emergency arrivals and unstable physical conditions related to an individual in the surgery process, making it more difficult for effective operating room management. Therefore, OR management is a complex task, and an excellent management strategy should have high efficiency and be robust to the inherent variability and uncertainty.

The main purpose of this paper is to develop a robust method with high efficiency to solve the surgery planning problem by considering surgery duration uncertainty and emergency arrival in a day-care facility. To achieve this purpose, the author has investigated several AAA hospitals in China and identified the bottleneck problems those hospitals are facing. A trade-off is sought between the regular OR opening costs and overtime costs, high efficiency and low cancellation risk, which provides the motivation for this paper.

Operating rooms have been estimated to generate more than 40% of the total revenues and consume more than 9% of the annual budget in hospitals (Bowers and Mould, 2005), making them the greatest revenue source, as well as the highest cost department. For these reasons, the planning and scheduling of ORs has been widely addressed (Lamiri et al., 2008a) and minimizing the operating cost of operating rooms is a widely used objective (Cardoen et al., 2010). The objective function of the OR planning and scheduling models usually consists of two parts: the regular opening cost for each OR and the overtime cost. Min and Yih (2010) addressed a surgery scheduling problem by considering the different patients' priorities to obtain the trade-off between the costs for overtime and for surgery postponement. Cardoen et al. (2009) developed a column generation method to solve the

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surgical case sequencing problem in a day-care facility, which was a multi-criteria objective function that included minimizing the recovery overtime cost, the peak use of recovery beds, and the violation of various patient and surgeon preferences as specified in the issue. Jebali et al. (2006) presented a two-stage approach for elective surgery scheduling which consists of assigning surgical operations to operating rooms and sequencing the assigned operations. Lamiri et al. (2008b) developed a stochastic model with the objective of minimizing the sum of the elective patient related costs and the overtime costs of the ORs with a solution method combining Monte Carlo simulation with Mixed Integer Programming being proposed to solve the OR planning issue.

The literature on emergency care received little attention as compared to that for elective patients. This is because emergency care contains so many inherent uncertainties, and it is particularly hard to accurately forecast the surgery demand for emergency arrivals. Emergency patients should be promptly scheduled for a surgery start within two hours after their arrival to insure their safety (Cardoen et al., 2010; Ben Bachouch et al., 2012), while elective-surgery can be delayed. Previous research related to emergency surgery mainly focuses on two aspects; they are emergency demand estimation based on historical data, and reserve surgery capacity for emergencies. Essen et al. (2012) considered the case that emergency surgeries are scheduled in one of the elective operating rooms and immediately started when an ongoing elective surgery had finished. They developed several exact and heuristic solution methods to minimize the waiting time for emergency patients. Adan et al. (2011) considered the intensive care units and nursing hour resources in an elective and emergency patients' allocation problem. To address the deviation between patients actually arriving and those expected, some scheduled elective patients may be canceled and emergency patients may be sent to other hospitals. Wullink et al. (2007) examined whether it is preferable to reserve a dedicated operating room or to reserve some capacity in all elective operating rooms to improve the responsiveness to emergencies. Using discrete-event simulation, they found that the responsiveness, the amount of overtime and the overall operating room utilization significantly improved when the reserved capacity was spread over multiple operating rooms. This paper focuses on both the elective and emergency patients. We reserve some emergency capacity in each operating theater under different scenarios. If the capacity reserved for emergency surgeries is not enough, this may result in overtime costs, even with the cancellation of already planned elective patients. However, devoting too much bandwidth to emergency surgeries will increase the operating cost and waiting time for patients. Therefore, the surgery cancellation constraint is introduced to address the trade-off between the duration reserved for emergencies and the operating room efficiency.

Surgery cancellation is a general phenomenon in the operating theater (Saremi et al., 2013). A certain rate of surgery cancellation is allowable because it can increase the OR utilization rate and decrease the operating cost and waiting time for patients. However, a rate of surgery cancellation that is too high will have some negative effects; for instance, the additional cost of rescheduling and the potential losses resulting from the dissatisfaction of patients and surgeons. Therefore, taking surgery cancellation into account in OR planning is an interesting and important research issue to address for actual cases. To the author's knowledge, very little research has been conducted regarding surgery cancellation. Adan et al. (2011) proposed some cancellation rules under different scenarios for emergency and elective patients and used simulations to obtain the scheduling results. Kim and Horowitz (2002) developed a simulation model to reduce the number of canceled elective surgeries that result from ICU bed shortages without significantly worsening the waiting times of other patients who are seeking admission to the ICU. Shylo et al. (2013) used a chance-constrained model of overtime for OR scheduling. Surgery cancellations result from the uncertainty of surgery duration, which is related to the complexity of the surgery process and physical condition of the individual. In this paper, we introduce the definition of cancellation risk as it depends on the possibility of the surgery plan to exceed the maximum capacities of an operating room. Each OR has its regular open period, such as from 8 a.m. to 4 p.m. When the surgery tasks allocated to one OR exceed the regular open period, overtime will occur. The availability of overtime is not infinite, normally 90–150 min according to regular practice. Beyond an OR's maximum open period, a surgery would be canceled, as shown in Fig. 1. Thus, the cancellation risk for a surgical plan is defined as the possibility of surgeries allocated to one OR exceeding the maximum capacity. Surgery cancellations result from the uncertainty of surgery durations with regards to the maximum overtime. That is to say, when some surgeries assigned to an OR require more operating time than predicted(e.g., worst case), they will delay the completion time of the surgeries over the maximum opening period, and leading to surgery cancellations.

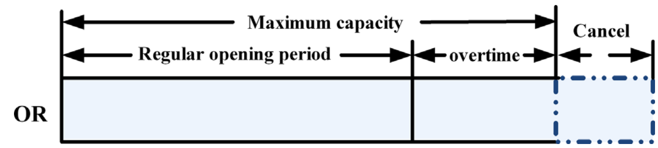

Fig. 1. The condition of surgery cancellation.

This paper addresses an operating room allocation problem by considering the uncertainty of surgery durations, emergency demands and surgery cancellation in a daily schedule. The number of patients on the list to be treated is given and it assumes that the surgery ability is enough for the patients in the waiting list. That is to say, the total capacity of the operating rooms, including overtime, is enough on average to serve the patients. We formulate a stochastic model for the multi-OR allocation problem to decide the number of open ORs and which OR to assign to which patient. To simplify the model, the sampling average approximation method is used to transform it into a deterministic optimization problem. We develop a column-generation-based algorithm and perform a series of experiments to test the method under a given distribution of surgery duration and emergency demand.

The contribution of this paper can be summarized as follows: (i) to make surgery scheduling more reasonable and feasible in practice, the risk for surgery cancellation is considered in the proposed stochastic model for solving the operating room allocation problem under stochastic demand, (ii) some managerial insights on the relationship between surgery cancellation risk and the operating costs, which are related to the number of open ORs, are observed from numerical experiments, (iii) a heuristic algorithm combined with column generation is developed; the algorithm can obtain the solutions of the same quality as CPLEX for small-scale problems with a much shorter run time and obtains solutions in less than a 5% gap of the lower bounds for large-scale problems which cannot be solved by CPLEX within reasonable time.

The remainder of this paper is organized as follows. Section 2 provides the formulation of the operating room allocation problem under cancellation risk (ORAP-CR) and proposes a stochastic model. A sampling average approximation method is used to simplify the problem and the formulation of cancellation risk for a surgery plan is discussed. Section 3 proposes a set partitioning formulation for the ORAP-CR planning problem and the column generation-based approach is presented. We also discuss the design of the sub-problem and some other strategies for algorithms. Numerical experiments are conducted and discussed in Section 4. Finally, the conclusions and future research are presented in the last section.