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An ant colony optimization approach for solving an operating room surgery scheduling problem ☆

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ABSTRACT

Operating room surgery scheduling deals with determining operation start times of surgeries on hand and allocating the required resources to the scheduled surgeries, considering several constraints to ensure a complete surgery flow, the resource availability, and specialties and qualifications of human resources. This task plays a crucial role in providing timely treatments for the patients while ensuring the balance in the hospital's resource utilization. By observing similarities between operating room surgery scheduling and a multi-resource constraint flexible job shop scheduling problem (FJSSP) in manufacturing, this article proposes an Ant Colony Optimization (ACO) approach to efficiently solve such surgery scheduling problems based on the knowledge gained in FJSSP. Numerical experiments are performed on five surgery test cases with different problem sizes and resource availability. The performance of the ACO algorithm was compared against schedules generated by a discrete event system simulation model built in SIMIO on five test cases. The results showed a superior performance of ACO in makespan, overtime, and the variation coefficient of working time.

1. Introduction

One of the main challenges in health care systems in recent years is to deliver high quality service under limited available resources. With the increase of aging population, social demands for surgical service have been constantly increased (Etzioni, Liu, Maggard, & Ko, 2003). As a vital hospital component, the operating room (OR) division accounts for approximately more than 40% of a hospital's total revenues and expenses (Denton, Viapiano, & Vogl, 2007). Hence, it is essential to improve patient flow and optimize OR management in order to provide timely treatments for the patients and to maximize utilization of the available resources. As a required step, surgery scheduling plays a crucial role in the OR management.

OR surgery scheduling determines the operation start time of every surgery to be performed in different surgical groups, as well as the resources assigned to each surgery over a schedule period. The overall surgery process involves several activities before (pre-operative/surgery), during (peri-operative/surgery) and after (post-operative/surgery) an actual surgical procedure. Fig. 1 illustrates these three stages as well as the required resources. The resources required to perform a surgery comprises of personnel (surgeons, anesthetists, nurses, etc.), facilities (specialized equipment, pre-operative holding units (PHUs), multiple operating rooms, post anesthesia care units (PACUs), and intensive care units (ICUs)). Other factors such as personnel shifts and qualifications, different surgical specialties (SSs) and priorities for services also need to be taken into account. Furthermore, many hospitals utilize open scheduling and the ORs are no longer assigned to specific departments, which makes the surgery scheduling problem even more complex. Therefore, researchers made attempts to develop decision support systems for efficient surgery scheduling so as (1) to maximize the operating room efficiency, (2) to increase the number of daily performed operations, and (3) to realize an appropriate resource allocation using various optimization approaches (Blake & Carter, 1997; Guerriero & Guido, 2011; Przasnyski, 1986).

A number of reviews on OR surgery scheduling have been reported in the past (Blake & Carter, 1997; Przasnyski, 1986; Cardoen, Demeulemeester, & Beliën, 2010; Erdogan & Denton, 2010; Guerriero & Guido, 2011; May, Spangler, Strum, & Vargas, 2011). Cardoen et al. (2010) surveyed the related manuscripts published since year 2000, and provided detailed classifications based on surgery durations (deterministic or stochastic), patient arrivals (elective and non-elective), and operations research methodology. Erdogan and Denton (2010) further limited the review scope on

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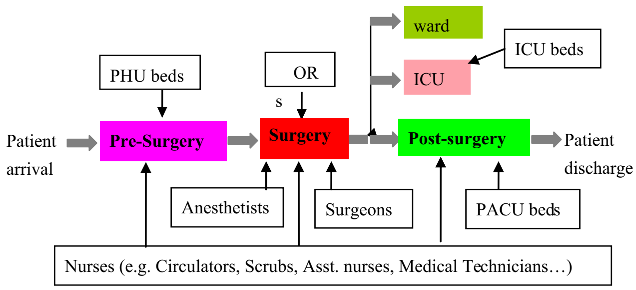

Fig. 1. Stages and resources in OR management.

the type of Operational Research methodology used for daily scheduling and categorized the literature in Queuing models, Simulation, Optimization and Heuristic Methods. Guerriero and Guido (2011) underlined the major developments which emerged throughout the years of Operational Research in management of operating room and grouped the research contributions based on different decision levels, such as strategic, tactical, operational and mixed decision level. According to the classification by Guerriero and Guido (2011), our research article belongs to the mixed decision level (integrating planning and scheduling) because we consider the open scheduling strategy. A typical surgical case scheduling problem in the operational level or the mixed decision level generally covers two sub-problems: advanced scheduling (patients are assigned to operating rooms, also known as OR planning) and allocation scheduling (surgeries are sequenced adequately). It is evident that the two sub-problems are generally formulated as separate combinatorial optimization models. The problem becomes even more difficult when several different surgery specialties are considered in the models and all types of available resources for all three surgery stages. Unlike most published papers in this field, our approach handles both the advanced and allocation scheduling problems simultaneously and provides an ACO approach to solve such a computationally challenging problem. Based on our knowledge, there has been little to no research on ACO applications in healthcare field, especially in surgery scheduling.

The rest of the paper is organized as follows. In Section 2, we provide a sum of the recent surgery scheduling literatures that are most relevant to our work. In Section 3, the scheduling environment we consider is outlined and a formal problem statement is given. Section 4 introduces an ACO algorithm for solving the surgery scheduling problem, and presents the details of our approach. Section 5 provides the computational experiments to validate and evaluate our approach. We close our paper in Section 6 with summary and suggestions for future research.

2. Literature review

Given the ever increasing demand in the healthcare industry and the fact that the OR management accounts for approximately 40% of a hospital's budget, a great deal of efforts have been made to improve surgery scheduling. Because literature on OR surgery is vast, we intend to focus this section on literature that is most relevant to our problem, i.e. surgery scheduling dealing with both advanced and allocation scheduling and/or adopting the open scheduling strategy. Furthermore, we limit the scope of this review to papers on optimization models and their solution methods.

Guinet and Chaabane (2003) addressed the advanced and allocation scheduling separately. The advanced scheduling was represented as an assignment model with the objective of minimizing patient waiting time. The allocation scheduling was described as two-stage, no-wait hybrid flow-shop problem with the objective of minimizing makespan. They considered resource capacity such as open hours and availability of surgeons, and surgery's time-window (release and due data) constraints. Although the recovery stage is considered in their work, they assumed that there are sufficient numbers of recovery beds at all time. Jebali, Hadjalouane, and Ladet (2006) proposed a MIP model for advanced scheduling with the same objective as Guinet and Chaabane (2003) and a two-stage hybrid flow shop model with the objective of minimizing total overtime (OT). Their work considered the recovery bed availability as additional constraints. Fei, Meskens, and Chu (2010) also separately solved a weekly operating theatre planning and scheduling problem. The advanced scheduling problem, to give the date of surgery for each patient, is formulated as a multi-objective (maximizing utilization, minimizing cost of OT and idle time in surgery) mathematical model, considering the availability of operating rooms and surgeons. It is solved by a column-generation-based heuristic (CGBH) procedure. Then, a daily scheduling problem is devised to determine the sequence of operations in each operating room, taking into account the availability of recovery beds. Considering the problem as a two-stage hybrid flow-shop problem, it is solved by a hybrid genetic algorithm (HGA). Roland et al. (2006, 2010) handled the advanced and allocation scheduling in a united way by proposing a resource constrained project scheduling model and solved it by a Genetic Algorithm. The resources considered in their work included surgeons, anesthetists and nurses. However, PACU and PHU bed's availability are not considered. Pham and Klinkert (2008) proposed a job-shop scheduling model and emphasized the resources needed in the pre-operative, peri-operative and post-operative stage among the operation process. The medical staff constraint mentioned in their model is described as resource modes, i.e. surgeons and nurses are combined as several fixed teams modes. Augusto, Xie, and Perdomo (2010) modeled surgery scheduling under the open scheduling strategy as a four-stage flow-shop scheduling problem, further involving the preoperative stage and the transporting stage comparing to the previous 2-stage flow-shop model. Moreover, this work investigated the impact of allowing patient recovery in the operating room when a recovery bed is not available, which made the model quite closer to the flow of the actual surgery procedure. The resources considered in their model included transporters, ORs and recovery beds, while other personnel resources (i.e. surgeons, nurses, etc.) constraints were ignored. The works (Testi & Tànfani, 2009, Tànfani & Testi, 2010) formulated a binary IP model to address the OR planning and scheduling problem which is to determine the assignment of wards and ORs during a given planning horizon, together with the subset of patients to be operated on each day. Different resource constraints associated with operating block time length, maximum allowable OR overtime, patient length of stay (LOS), available OR equipments, number of surgeons, number of wards and ICU beds, are considered. Testi and Tànfani (2009) evaluated the impact of their proposed binary IP model on welfare implications taking a patient perspective. Tànfani and Testi (2010) however, the objective is to maximize the overall societal benefit, i.e., improving both patient satisfaction by reducing weighted waiting times and hospital efficiency by reducing costs. A heuristic procedure was developed to solve real large instances. Chaabane, Meskens, Guinet, and Laurent (2008) only tackled the operating theatre planning problem by introducing two methods under open scheduling. They proposed a mixed LP model to build a master surgery schedule (MSS): a time block (TB) is assigned to each surgery specialty (SS) every day, taking into account the requests changing from one week to another and the SS's availability. The first method aimed to minimize the gap between the total supply and the weekly requests of the SSs. The second method was to minimize the costs of surgical cases which depend on the OT cost and the patient waiting time. Denton et al. (2007) developed a two-stage stochastic MIP model for a daily scheduling of single OR first, and then it was extended to a two-stage stochastic MILP