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A short-term operating room surgery scheduling problem integrating multiple nurses roster constraints

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ABSTRACT

Objectives: Operating room (OR) surgery scheduling determines the individual surgery's operation start time and assigns the required resources to each surgery over a schedule period, considering several constraints related to a complete surgery flow and the multiple resources involved. This task plays a decisive role in providing timely treatments for the patients while balancing hospital resource utilization. The originality of the present study is to integrate the surgery scheduling problem with real-life nurse roster constraints such as their role, specialty, qualification and availability. This article proposes a mathematical model and an ant colony optimization (ACO) approach to efficiently solve such surgery scheduling problems.

Method: A modified ACO algorithm with a two-level ant graph model is developed to solve such combinatorial optimization problems because of its computational complexity. The outer ant graph represents surgeries, while the inner graph is a dynamic resource graph. Three types of pheromones, i.e. sequence-related, surgery-related, and resource-related pheromone, fitting for a two-level model are defined. The iteration-best and feasible update strategy and local pheromone update rules are adopted to emphasize the information related to the good solution in makespan, and the balanced utilization of resources as well. The performance of the proposed ACO algorithm is then evaluated using the test cases from (1) the published literature data with complete nurse roster constraints, and 2) the real data collected from a hospital in China.

Results: The scheduling results using the proposed ACO approach are compared with the test case from both the literature and the real life hospital scheduling. Comparison results with the literature shows that the proposed ACO approach has (1) an 1.5-h reduction in end time; (2) a reduction in variation of resources' working time, i.e. 25% for ORs, 50% for nurses in shift 1 and 86% for nurses in shift 2; (3) an 0.25 h reduction in individual maximum overtime (OT); and (4) an 42% reduction in the total OT of nurses. Comparison results with the real 10-workday hospital scheduling further show the advantage of the ACO in several measurements. Instead of assigning all surgeries by a surgeon to only one OR and the same nurses by traditional manual approach in hospital, ACO realizes a more balanced surgery arrangement by assigning the surgeries to different ORs and nurses. It eventually leads to shortening the end time within the confidential interval of [7.4%, 24.6%] with 95% confidence level.

Conclusion: The ACO approach proposed in this paper efficiently solves the surgery scheduling problem with daily nurse roster while providing a shortened end time and relatively balanced resource allocations. It also supports the advantage of integrating the surgery scheduling with the nurse scheduling and the efficiency of systematic optimization considering a complete three-stage surgery flow and resources involved.

1. Introduction

Surgeries are critical processes in hospital operation, not only because of their direct impact on patients' health but also because of their high relevance to a hospital's total revenues and expenses. At the moment, hospitals around the world are facing a trend of increasing demand for surgeries due to the aging population [1], and the prevailing nurse shortage problem [2]. Hence, it has been a challenge for operating room (OR) management to deliver timely and high quality surgery services to patients with limited resources in recent years. In this context, it is essential to provide an efficient decision making strategy for OR management.

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Much OR management focuses on the surgery scheduling and resource management. Surgery scheduling (also called OR scheduling) determines the time sequencing of an individual surgery in different surgical specialties and the resources assigned to it over a scheduling period. It is used to satisfy the patient's demand for timely treatments and to maximize the OR's resource utilization. On the other hand, resource management in OR needs to focus on the nurse roster as nursing services play an important role in hospital's operating budget [3,4]. For medical and operation research literature, both the surgery and nurse scheduling problems have been studied independently and are solved separately. There usually exists a sequence in OR decisions, i.e. firstly surgery sequencing decision and then nurse scheduling decision. We are thinking of why surgery scheduling and nurse scheduling have to be separately done. Why not try to integrate these two decisions together in short term OR management?

Current literature on a daily or weekly surgery scheduling problem can be classified into two categories. The first category can be called "surgery-based OR scheduling" in which a schedule is provided to assign resources for the intra-operative activities only (OR and surgeon scheduling) while ignoring all other resources. The second category can be called "comprehensive OR scheduling" where a schedule is designed considering all resources for all three stages, i.e. the pre-operative stage, the intra-operative stage and the post-operative stage. Most of the currently available comprehensive OR scheduling research, especially operations research type of articles, usually treats the resources as homogenous entities for simplification. However, in an actual OR management, there exists vast differences in individual nurse attributes such as skill set, qualification, shift preferences, contractual agreements, to name a few. Furthermore, surgeries also have constraints on the qualification and skills of nurses. Oversimplifying nurses by considering them as homogeneous entities may result in a surgery schedule that may not even be feasible in practice. Scheduling a surgery without considering the nurse roster constraints on that day may lead to an inability of securing qualified nurses to support pre-scheduled surgery cases. OR management then has to either arrange OT hours for the qualified nurses on-duty or call for part-time qualified nurses as temporary replacement, which will increase the OR operation cost and will create an inefficient management of operating rooms. Recently, OR management has been coping with a growing problem in the shortage of registered OR nurses, which continues to hamper the effective delivery of the scheduled surgery service. Hence, it is of vital importance that surgery scheduling should be carefully optimized by integrating both surgery scheduling and daily nurse roster constraints.

The research presented in this paper aims to solve a surgery scheduling problem for an operating suite with multiple operating rooms, taking into account of the real life nurse roster constraints such as skill/specialty, job qualification, level, shift, and contractual agreements. A mathematical model is proposed to describe such a complicated surgery scheduling problem, and an ACO approach is developed to solve it. As to our knowledge, there has been little, if any, research on the surgery scheduling problem that integrates real life nurse roster constraints.

The rest of the paper is organized as follows. In Section 2, a summary of the literature review on recent surgery scheduling problem is presented. In Section 3, the integrated scheduling problem is outlined and a formal problem statement is given. In Section 4, we introduce an ACO algorithm to solve the integrating surgery scheduling problem and present the detailed mechanisms. In Section 5, the proposed ACO approach is evaluated with the test cases using the literature data and the real-life hospital scheduling data. Section 6 summarizes the current study work and suggestions for future research.

2. Literature review

Given the ever increasing demand in the healthcare industry, a great deal of efforts has been invested in improving OR management. This section reviews the state of art surgery scheduling (or OR scheduling) and nurse scheduling (or nurse rostering).

The surgery scheduling problem has been a widely studied topic and there exists a vast amount of literature in the medical and operation research communities. Reviews about OR planning and scheduling have been reported by several researchers recent years [5–8]. They provide detailed classifications of papers based on the types of problems, operations research methodology, and decision levels. We limit our literature review specifically on the short-term surgery scheduling problem (daily or weekly) as it is directly related to the scope of this paper.

According to the literature, earlier work on the surgery scheduling research was mostly concentrated on the activities and resources associated with the intra-operative stage only in the operating room [9–11]. The developed models are often applicable to small size problems with a limited number of constraints including surgery demand and OR capacity.

Surgery scheduling problems are then further extended to take into account multiple resources that are involved during the entire process of surgery flow: before, during, and after surgery. More realistic constraints on surgery flow and multiple resources were added to the models. Some researchers have treated the surgery scheduling problem as a "two-stage no wait hybrid flow-shop" problem with the operating rooms as the first stage and the recovery room as the second stage [12,13]. However, human resources, except surgeons, are always considered available in their works. Fei et al. [14] further improved the hybrid flow-shop model by taking into account the availability of recovery beds, and proposed a hybrid genetic algorithm (HGA) to solve such daily surgery scheduling problems. Augusto et al. [15] 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 it to the previous two-stage flow-shop model. However, all of the above research ignored the qualifications and skills of human resources. Pham and Klinkert [16] proposed a job-shop scheduling model and emphasized the resources (such as transporters, ORs and recovery beds) needed in the three stages (i.e. pre-operative, intra-operative and post-operative stage) in the operation process. The medical staff constraint in their model is described as resource modes, in which each mode consists of a surgical team with surgeon(s) and nurses. An individual surgery has its own required mode to make the solution closer to the actual surgical procedure. Our pilot research [17,18] represented the surgery scheduling problem as an extended multi-resource constrained flexible job-shop scheduling problem and proposed a modified ant colony algorithm to solve it. The multiple resources covered include all major resources involved in a complete surgery stages. However, the resources like ORs, nurses, anesthetists, and beds in different surgery stages are all considered as homogeneous. As it has been surfaced by reviewing these papers, the short-term surgery scheduling problem, in most research, has simplified the resources (especially workforce resources) required in surgery as homogeneous. Few surgery scheduling research takes into account the constraints on the nurse roster, such as specialty, skill level, qualification and shift, which are very common in actual OR management in the hospitals.

Given the ever increasing labor costs and the fact that the nursing staff accounts for a substantial portion of an OR's budget [19], another scheduling problem, called nurse scheduling (or nurse rostering), has especially been proposed for resource management in OR, mainly dealing with the nurse related constraints. The surgery demand (a set of resources for a surgery to be performed)