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A two level metaheuristic for the operating room scheduling and assignment problem

Roberto Aringhieri [a,*], Paolo Landa [b], Patrick Soriano [c], Elena Tànfani [b], Angela Testi [b]

[a] Department of Computer Science, University of Torino, Italy
[b] Department of Economics and Business Studies, University of Genova, Italy
[c] Department of Management Sciences and CIRRELT, HEC Montréal, Canada

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ABSTRACT

Given a surgery department comprising several specialties that share a fixed number of operating rooms and post-surgery beds, we study the joint operating room (OR) planning and advanced scheduling problem. More specifically, we consider the problem of determining, over a one week planning horizon, the allocation of OR time blocks to specialties together with the subsets of patients to be scheduled within each time block. The aim of this paper is to extend and generalize existing approaches for the joint OR planning and scheduling problem. First, by allowing schedules that include patients requiring weekend stay beds which was not the case previously. Second, by tackling simultaneously both the OR planning and patient scheduling decision levels, instead of taking them into account in successive phases. To achieve this, we exploit the inherent hierarchy between the two decision levels, i.e., the fact that the assignment decisions of OR time blocks to surgical specialties directly affect those regarding the scheduling of patients, but not the reverse. The objective function used in this study is an extension of an existing one. It seeks to optimize both patient utility (by reducing waiting time costs) and hospital utility (by reducing production costs measured in terms of the number of weekend stay beds required by the surgery planning). 0–1 linear programming formulations exploiting the stated hierarchy are proposed and used to derive a formal proof that the problem is NP-hard. A two level metaheuristic is then developed for solving the problem and its effectiveness is demonstrated through extensive numerical experiments carried out on a large set of instances based on real data.

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1. Introduction and literature review

Operating Rooms (ORs) planning is a critical activity with important financial impacts for most hospital setting. In addition, demand for surgery very often overwhelms supply therefore causing long waiting times for patients and reducing their quality of life [1]. This is particularly true in publicly funded health care systems such as those found in Italy, in the province of Québec in Canada and many other settings. One of the main questions health care system planners and administrators are faced with when planning ORs is how can demand and supply meet, i.e., how should the available OR capacity be allocated in order to improve efficiency and productivity and how can efficiency be attained and measured. The review of the operations research and management science scientific literature clearly reveals an increasing interest of researchers towards OR planning and scheduling problems [2,3].

Researchers frequently distinguish between strategic (long term), tactical (medium term) and operational (short term) decisions in order to better characterize their planning or scheduling problem even if there are no clear and universally accepted definitions of these three decision levels [2]. In the following, we concentrate our analysis on the OR planning and scheduling problem at both the tactical and operational levels under the block scheduling or closed block planning paradigm. When planning with this paradigm, each specialty is assigned a number of OR time blocks (usually with homogeneous block lengths of half-day or full day) for each planning period, typically a week to two weeks. Each specialty then schedules their surgical cases within these time blocks [4].

The OR planning and scheduling problem under the block scheduling approach can be viewed as being made up of three phases corresponding to three decision levels [5]. In the first phase,

* Corresponding author.
E-mail addresses: roberto.aringhieri@unito.it (R. Aringhieri), paolo.landa@unige.it (P. Landa), patrick.soriano@hec.ca (P. Soriano), etanfani@economia.unige.it (E. Tànfani), testi@economia.unige.it (A. Testi).

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the problem addressed is that of determining, at a strategic level, the number and type of ORs available, the hours of operation of the ORs and how overall OR capacity is to be divided among surgical specialties, individual surgeons or groups [6–10]. Then, a cyclic timetable, often referred to as the "Master Surgical Schedule" (MSS), is constructed on a medium term horizon to define the specific assignment of OR blocks to specialties. The MSS must of course be updated whenever the total amount of OR time changes or when the make-up of some specialties changes. This can occur not only as a response to long-term changes in the overall OR capacity or fluctuations in staffing, but also in response to seasonal fluctuations in demand [11–17]. The last phase, which may be called "surgery process scheduling", is generally separated into two sub-problems referred to as "advance scheduling" and "allocation scheduling" [18]. The first sub-problem consists in assigning a specific surgery and OR time block to each patient over the planning horizon, which can range from one week to one month [19–25]. Given this advanced schedule, the second sub-problem then determines the precise sequence of surgical procedures and the allocation of resources for each OR time block and day combination [26–31] in order to implement it as efficiently as possible.

As evidenced by the references listed here-above, the vast majority of papers found in the literature only consider one decision level at a time. Approaches dealing with more than one planning level simultaneously are quite rare. Among these, Jebali et al. [32] use a two-phase approach to deal with both the advance scheduling and allocation scheduling problems and propose a 0–1 linear programming model aimed at minimizing OR overtime and under-time costs as well as hospitalization costs related to the number of days patients are kept in the hospital waiting for an operation or procedure. Testi et al. [5] present a hierarchical three-phase approach to determine operating theater schedules. First, integer programming models are developed in order to divide the available OR time among the different surgical specialties. Then they formulate a master surgery scheduling problem in order to assign a specific operating room and day of the planning horizon to the OR time blocks of each specialty. Finally, a discrete-event simulation model is used to evaluate the decisions concerning patients date, OR and time assignments. Tànfani and Testi [33] propose a 0–1 linear programming model to simultaneously address the decisions involved in the three phases of the OR planning and scheduling problem described above, excluding only the most strategic ones dealing with the number and type of the ORs and their operating hours. The objective of the model consists in minimizing a societal cost function that combines the patients' waiting time since referral and urgency status. The solution approach is based on a sequential heuristic. First, a subset of suitable patients is selected using heuristic rules. Then OR time blocks to which the selected subset of patients could be assigned considering their expected length of stay (LOS) are identified (i.e., time blocks in the schedule such that the patient would not require to stay hospitalized during the weekend). Finally, a reduced version of the 0–1 linear programming model is solved. In that version, the patients and the OR blocks not selected in the previous two steps are excluded from consideration. The main limitation of this approach is that the decisions taken in the first two steps are not re-evaluated and therefore no interaction between them is considered nor any tradeoff investigated. In Choi and Wilhelm [34], they include in the analysis the problem of determining the duration of time blocks reserved to each surgery sub-specialty and their sequencing, referred as Block Surgical Schedule (BSS). A newsvendor-based model has been developed to solve the BSS with the aim of minimizing the total expected lateness and earliness costs. Agnetis et al. [35] proposed a decomposition approach to solve MSS and assigning patients to available OR blocks. The solution of the two problems being done in sequence. The performance of the approach has been evaluated on a large set of real based instances and the solutions compared with those obtained by an exact integrated approach.

In this paper, we deal with the joint master surgical schedule and advanced scheduling problem but with the aim of extending and generalizing existing approaches as well as proposing more efficient solution methodologies. We assume that all strategic level decisions are given as input data, including the number of OR time blocks assigned to each specialty weekly. This responds to a real practical issue faced by surgery departments since these strategic decisions are generally the result of a long and complex negotiation process involving the different surgical specialties and the hospital administration. They are therefore not easily changed on a short-term horizon. The first generalization consists in developing a modeling and solution approach which simultaneously considers both the OR planning and patient scheduling decision levels instead of taking them into account separately. This increases significantly the potential quality of the resulting schedules but, of course, at the expense of a significant increase in the difficulty for solving the problem. To achieve this generalization, we exploit the inherent hierarchy between the two decision levels, i.e., the fact that the assignment decisions of OR time blocks to surgical specialties directly affect those regarding the scheduling of patients, but not the reverse. The type of schedules considered here is also more general with respect to the tactical and operational level decisions than the ones produced in Tànfani and Testi [33] because it allows schedules in which patients may require weekend stay beds. Here, weekend stay beds are modeled as an additional limited resource that can be used but not exceeded. Finally, we adopt the idea proposed in Tànfani and Testi [33] of using societal costs as the objective function but extending it to incorporate both patient utility (by reducing waiting time costs) and hospital utility (by reducing production costs measured in terms of the number of weekend stay beds required by the surgery planning). 0–1 linear programming formulations exploiting the stated hierarchy are proposed and used to derive a formal proof that the problem is NP-hard.

As reported in Aringhieri et al. [36], health care optimization problems are challenging, often requiring the adoption of unconventional solution methodologies. The solution approach proposed herein belongs to this family. It is a tabu search algorithm (see, e.g., [37,38]) in which the main idea is to iterate the search between the two decision levels in such a way as to globally improve the solution. Its effectiveness is demonstrated through extensive numerical experiments carried out on a large set of instances based on real data.

The paper is organized as follows. Section 2 describes in more details the problem under investigation. Section 3 introduces 0–1 formulations and presents a formal proof of complexity. The proposed solution algorithm is described in Section 4. Computational results highlighting the effectiveness of the two level approach as well as comparisons between the solutions produced by the metaheuristic and optimal ones are reported in Section 5. Concluding remarks and further research directions close the paper.

2. Problem definition and notation

Given a set of surgical specialties, a list of patients waiting to be operated on for each specialty and a number of OR time blocks to be assigned to each specialty, we face the problem of determining for a given planning horizon of one week: (1) the cyclic timetable that gives for each day of the planning horizon the assignment of specific OR time blocks to specialties, referred to as the *Master Surgical Schedule Problem* (MSSP); and (2) the surgery date and operating room assigned to each patient selected to be operated

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