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Discrete Optimization

Surgical scheduling with simultaneous employment of specialised human resources

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ABSTRACT

Surgical scheduling is a challenging problem faced by hospital managers. It is subject to a wide range of constraints depending upon the particular situation within any given hospital. We deal with the simultaneous employment of specialised human resources, which must be assigned to surgeries according to their skills as well as the time windows of the staff. A particular feature is that they can be assigned to two surgeries simultaneously if the rooms are compatible. The objective is to maximise the use of the operating rooms. We propose an integer model and integer programming based heuristics to address the problem. Computational experiments were conducted on a number of scenarios inspired by real data to cover different practical problem solving situations. Numerical results show that relaxations provide tight upper bounds, and relax-and-fix heuristics are successful in finding optimal or near optimal solutions.

1. Introduction

Operating room management has been recognised as a main source of income for hospitals. It is important to improve performance by using surgical resources as efficiently and effective as possible. It has been reported in the literature that the operating theatre is one of the most critical and costly functional areas in a hospital (Guinet & Chaabane, 2003). It represents a bottleneck in many hospitals and it consumes a significant amount of a hospital's annual budget because it typically utilises the most expensive resources. See, for instance, the recent surveys by Cardoen, Demeulemeester, and Beliën (2010), Guerriero and Guido (2011), May, Spangler, Strum, and Vargas (2011) and Rais and Viana (2011). As in other service sectors, the decision process comprises different decision levels – from capacity and facility planning to detailed scheduling.

In this paper, we concentrate on the detailed surgical scheduling of elective patients on a daily basis. Elective patients are those for whom the surgery is not completely unexpected and can be planned in advance. Broadly speaking, surgical scheduling consists of the selection of surgical interventions to be performed in each available operating room along with dates, starting times and the allocation of required resources. Surgical scheduling problems are very hard to solve, and different optimisation modelling approaches have been proposed in the literature to face different situations. Meskens, Duvivier, and Hanset (2013) observed from visits to several hospitals that problems are specific to each institution. Indeed, as also noted by other authors, for instance, Cardoen et al. (2010); Riise and Burke (2011), each hospital has its own established practices reflecting specific constraints related to both human and material facets. These specific constraints may vary from medical staff availabilities (e.g., regular working hours or surgeon preferences) and patient priorities (e.g., children or diabetics) to operating room versatilities and the limited capacity of human and material resources (e.g., number of nurses, auxiliary staff, medical instruments, recovery beds or places in intensive care unities).

We deal with surgical scheduling in a hospital in Brazil. The hospital has 14 non-identical operating rooms dedicated to elective interventions – some are multifunctional, some have particular medical devices installed that cannot be moved, and some are restricted in size. Each surgeon has a set of patients, so that each operation has to be carried out by a specific surgeon. However, decisions assigning surgeries to operating rooms is part of the problem, and scheduling starting times are subject to surgeries and surgeon's time windows,

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among other constraints. Time windows may capture patient priorities in terms of time of the day that interventions must occur, e.g., children should be operated upon early in the morning (Riise & Burke, 2011) or there should be later starts for out-of-town patients (Vijayakumar, Parikh, Scott, Barnes, & Gallimore, 2013). There are also medical staff preferences, which can be viewed as an attempt to improve working conditions (Roland, di Martinelly, Riane, & Pochet, 2010). The problem is also constrained by limited shared resources. We may have surgery requirements on renewable and/or nonrenewable resources, a characteristic already observed in the case studied by Roland et al. (2010). Renewable resources (human or material) are those allocated to a surgery strictly for its duration, like nurses or auxiliary staff and medical equipment. On the other hand, nonrenewable resources are those allocated to a surgery for the entire day, in our case places in the intensive care utility.

A particular feature of our case study is the simultaneous employment of specialised human resources. Anaesthetists, for instance, are identified due to specialities, training skills and availabilities. An anaesthetist has his/her own time windows. Each surgery is associated with a subset of anaesthetists able to perform that intervention. An anaesthetist can perform more than one intervention simultaneously depending upon the room in which the surgeries are taking place. Thus, the simultaneous employment of specialised human resources is constrained by room compatibilities. This leads to another decision to be made jointly with assigning and scheduling surgeries, as anaesthetists must be assigned and scheduled according to surgery requirements and subject to room compatibilities and to their own time windows. The objective is to maximise the use of the operating rooms. In fact, recent surveys list a number of objectives studied in the literature including minimisation of costs or makespan, and maximisation of throughput or utilisation (Cardoen et al., 2010; Guerriero & Guido, 2011; May et al., 2011). In our case, the manager of the hospital where the study was conducted suggested the maximisation of the utilisation of the operating rooms.

We propose an integer programming formulation to model the particular surgical scheduling problem in hand. Preliminary computational experiments have shown that the linear relaxation of the proposed model could provide good upper bounds to the optimal solution values. Based on these early experiments, we decided to develop integer programming-based heuristics to obtain high quality feasible solutions with a posteriori performance guarantees. The heuristics in the first step draw from relaxation candidate assignments of surgeries to rooms and periods, and then in the second step they address a reduced model to obtain feasibility. We test the proposed approaches on a variety of scenarios inspired from real data. Computational results show that it is possible to find optimal or near optimal solutions for most of the instances.

The paper is structured as follows. In the next section, we present a literature review which is focused on deterministic models for surgical scheduling. In Section 3, we formulate the integer programming model. We describe, in Section 4, the integer programming-based heuristics. In Section 5, we report on computational experiments on real-based instances, and in the last section we draw concluding remarks.

2. Literature review

Many modelling studies aimed at using surgical rooms efficiently have been motivated by practical considerations and goals. Ozkarahan (2000) proposed a goal programming model to assign surgeries to operating rooms under a policy of reserving blocks of operating room time for surgical specialties or authorised surgeons. Marcon, Kharraja, and Simonnet (2003) adapted the multiple knapsack model to assign surgeries to operating rooms optimising measures related to the risk of no realisation. Some authors have investigated applications based on bin-packing to select surgeries that make efficient use of available operating room time, see Dexter, Macario, and Traub (1999), Dexter and Traub (2002), Dexter, Traub, and Macario (2003), Hans, Wullink, van Houdenhoven, and Kazemier (2008), van Houdenhoven, van Oostrum, Hans, Wullink, and Kazemier (2007). Guinet and Chaabane (2003) proposed a model to assign surgeries to operating rooms over a horizon of one or two weeks subject to time and capacity constraints. Santibáñez, Begen, and Atkins (2007) also dealt with time and constraints to manage a set of hospitals as a single system.

Jebali, Hadj Alouane, and Ladet (2006) addressed the daily scheduling of a surgical centre with an assignment model of surgeries to operating rooms, taking into account capacity constraints such as opening duration and overtime of operating rooms, the working time of surgeons, and the number of beds in the intensive care unit. The objective is to minimise the costs associated to keeping patients waiting, and to minimise undertime and overtime. Then, sequencing is modelled as a two-stage hybrid flow shop where the first stage is represented by surgical rooms and the second stage by recovering beds. Analogies to scheduling problems more often found in industrial applications were also exploited by Pham and Klinkert (2008). The authors introduced an extension of the job shop with blocking to model the patient flow comprising preoperative, perioperative and postoperative stages.

Hierarchical approaches in three stages have been proposed (Ogulata & Erol, 2003; Testi, Tanfani, & Torre, 2007). Ogulata and Erol (2003) developed models to select, in the first stage, patients from a candidate list. In the second stage, they are assigned to surgical groups, and, in the final stage, operating rooms are determined independently for each group. Testi et al. (2007) developed models to distribute operating room time among surgical groups, and then to build a cyclic timetable that determines the surgical unit associated with each block of operating room time. The last stage is performed by simulation. Testi and Tanfani (2009) proposed a model to assign both patient and surgical sub-speciality to operating rooms and days within a planning horizon.

Augusto, Xie, and Perdomo (2008) developed a Lagrangian relaxation to a patient flow problem considering the transfer from the ward to the operating room, the surgery, and the transfer to the recovery bed. The model defines starting times for the different tasks in order to minimise completion times subject to capacity constraints. The same authors (Augusto, Xie, & Perdomo, 2010) addressed the impact of allowing patient recovery in the operating room when no recovery bed is available. Marques, Captivo, and Pato (2012) proposed a model to schedule elective surgeries on a weekly time horizon with the objective of maximising the operating rooms occupancy. The authors considered different surgery priority levels, surgery time windows, and operating time limits.

In recent years, some authors have developed branch-and-price approaches (Cardoen, Demeulemeester, & Beliën, 2009b; Fei, Chu, Meskens, & Artiba, 2008). Fei et al. (2008) focused on surgical cases assignment to operating rooms. The model takes into consideration the room's opening time and surgical deadlines to plan one week minimising undertime and overtime costs. The master problem partitions surgeries into days, whereas the subproblem deals with opening duration constraints to find an improving column. This approach was extended by Fei, Meskens, and Chu (2010) to consider daily scheduling performed by a hybrid genetic algorithm. Cardoen et al. (2009b) developed a branch-and-price approach over a multi-objective model proposed by the same authors (Cardoen, Demeulemeester, & Beliën, 2009a). The model decides which surgeries to start in each slot of each period, restricted to operating rooms and starting ranges that have been previously defined. Other constraints include the availabilities of medical instruments and recovering areas and additional cleaning due to particular infection concerns. A column represents all surgeries sequenced for a specific surgeon, and the pricing problem is addressed by dynamic programming.

Roland et al. (2010) proposed a model dealing with different aspects of human and material resource management. Resource