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A variable neighborhood search algorithm for the surgery tactical planning problem

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ABSTRACT

We address the tactical planning problem of surgeries that consists in building an admission plan of patients over a medium-term horizon planning so as to minimize over and under utilization of several resources such as operating theaters, beds and nursing care, compared with their target level of utilization. The problem is formulated as a mixed integer linear program for which exact solution methods fail to find an optimal solution in a reasonable execution time. We develop a Variable Neighborhood Search algorithm and show its ability to provide high quality solutions in short computational running times compared with CPLEX for numerous real-sized instances based on the surgery planning problem in a Dutch cardiothoracic center. Furthermore, with few parameters' settings and low computational memory requirements, this approach may easily be implemented in a decision support system for hospitals.

1. Introduction

As in many organizations, decision making in hospitals occurs at three main levels: strategic, tactical and operational. Strategic decisions involve capacity planning decisions that allocate surgical specialities to operating-theater (OT) days for the long-term, often a year [1–3]. At the operational level, the problem is to schedule surgeries on a daily basis where patients are first assigned to days and surgery slots [4] or [5] and then sequenced for a given day [6] or [7,8].

In between the strategic and the operational levels lies the less tangible tactical level as hospital managers, submerged with real-time operational issues, are often inclined to solve problems at hand. They also claim for more capacity, a drastic strategic measure whereas a tactical allocation of available resources may be more effective and cheaper [9]. Such a tactical allocation problem is referred to the Master Surgery Schedule (MSS) problem and consists in allocating blocks of resource time (e.g. OT or nursing hours) to specialities and/or patient categories over a horizon length lying between the strategic and the operational horizon (e.g. a month).

A lot of tactical planning models focus on a single resource, the operating theater, as an increasing number of surgical procedures are now safely performed on an outpatient basis (recent surveys include [10–12]). However some surgeries like brain tumor resection or cardiothoracic surgery procedures often imply a stay in the Intensive Care Unit (ICU) post surgery. For these surgeries, it is now widely recognized that integration of downstream resources such as beds or nursing care in ICUs leads to a better overall performance [3,13–15]. Thus, in addition to OT, some models to build MSSs include other resources such as nurses [16] or beds [17] or beds in the ICU and multiple general wards [18]. Adan et al. [14] consider cardiothoracic surgeries divided into several categories where the problem – which is under the scope of this paper – is to determine the number of patients in each category to be operated on for each day of the horizon. Four resources are included: OT, beds and nurses in the ICU and beds in the Medium Care Unit (MCU). This problem is formulated as a mixed integer linear program that can be solved to optimality with branch and bound algorithms. However, pitfalls of exact solving methods involve too long solution time. In Adan et al. [14] or Adan et al. [19] where emergencies were considered, several instances have been solved using CPLEX that failed to reach an optimal solution even after 24 h of running time. Obviously, taking into account multiple resources increases the problem complexity and a need for heuristic solution methods arises. As such, simulated annealing is used in Beliën et al. [17] and Fügener et al. [18]. Among local search techniques is the Variable Neighborhood Search (VNS) proposed by Mladenovic and Hansen in the late 1990s [20]. As this approach changes the neighborhood during the search, it is very successful compared to other local search techniques for solving many combinatorial problems from different areas [21]. Despite its

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effectiveness, the use of VNS to solve complex problems in health care delivery systems is limited to the nurse rostering problem [22,23].

In this paper we explore the potential of VNS to solve the tactical planning problem with multiple resources for cardiothoracic surgeries as formulated by Adan et al. [14] and also used in Adan et al. [19] and Dellaert et al. [24]. A solution to this problem is a tactical plan specifying for each day of a 28-day horizon (a month), the number of patients in each category to be operated on. Surgery of patients implies a consumption of the four resources for which capacity must not be exceeded. The objective function to minimize is a weighted sum of over and under utilization of the four resources compared with their target level of utilization. In our VNS, starting from an empty tactical plan, an initial solution is randomly generated using an insertion mechanism of patients on each day of the 4-week horizon. The neighborhood structure relies on the application of several local search operators on a feasible tactical plan, like swapping patients from different categories planned on two different days or shifting a single patient to another surgery day. The shaking procedure follows a ruin-reconstruct mechanism with deletion and subsequent addition of a variable number of patients in the current solution. Test results show that our algorithm outperforms CPLEX in most cases.

The remainder of this paper is organized as follows. Section 2 describes the tactical planning problem in detail. Section 3 presents the proposed VNS approach. Section 4 provides the computational study and discusses the results. Conclusions and suggestions for future research are given in Section 5.

2. Problem description

The problem is based on the functioning of the Thorax Center Rotterdam described in Adan et al. [14], where four critical resources are considered: operating theater hours (OT), number of beds in the ICU (IC), nursing hours in the ICU (NH) and number of beds in the MCU (MC). Patients are grouped in several categories that are homogeneous in terms of resource consumption. The patient flow in the Thorax Center is depicted in Fig. 1. Some categories of patients are admitted to the Medium Care Unit (MCU) one day before surgery. Each patient category is associated with a deterministic operation duration, based on average observed values. After surgery, patients are transferred to the ICU where they benefit from specialized nursing care. The nursing hours required for each patient category on each post-operative day are deterministic. After recovery, patients may stay in the MCU for a few days. Lengths of stay in the ICU and in the MCU are probabilistic, with different distributions for each category. Thus, a patient undergoing surgery on a given day consumes OT hours on that day, and has an expected consumption of bed and nursing hours in the ICU for a number of subsequent days corresponding to its length of stay in this unit. After the stay in the ICU, the patient has an expected consumption of bed in the MCU.

A feasible tactical plan thus specifies for each day of a 28-day horizon the number of patients in each category to be operated on, such that the consumption of each resource on any day does not exceed the daily resource capacity. Furthermore, the total number of patients in each category planned for surgery over the whole horizon must be equal to the target throughput of patients which is set to the average number of surgeries observed in the past (over a same horizon length). The objective function is a weighted sum of over and under utilization of resources compared with their target level of utilization which is usually set to 80% of the capacity. The reason for using target deviations rather than cost relies on the fact that capacity allocation has been decided at the strategic level, so at the tactical level capacity is roughly fixed with a small variation margin though. Furthermore, target deviation is recognized as an important performance measure, besides waiting time and sojourn time in the hospital before treatment [25].

The mathematical formulation we use here was first given by Adan et al. [14] and then adapted to emergency cases in Adan et al. [19]. It was also used in Dellaert et al. [24]. We adopt the notation and definitions in Table 1.

Formally, the objective is to determine the values of variables $\{x_{c,t}\}$ satisfying a number of constraints and for which the daily expected utilization of each resource deviates as little as possible from the daily target. The objective function to be minimized can be written as

$$\sum_{r\in\{\mathrm{OT,IC,NH,MC}\}} \alpha_r \sum_{t=1}^{T} (o_{r,t} + u_{r,t}), \tag{1}$$

Relative weights α_r assigned to the resources were derived from gross values of weights g_r as follows:

$$\alpha_r = \frac{g_r / \sum_{j=1}^{T} A_{r,j}}{\sum_{r\in\{\mathrm{OT,IC,MC,NH}\}} \left(g_r / \sum_{j=1}^{T} A_{r,j}\right)}, \tag{2}$$

with values for g_r decided by the stakeholders of the hospital, depending upon the degree of flexibility of each resource with the following rank: $g_{\mathrm{IC}} > g_{\mathrm{OT}} > g_{\mathrm{NH}} > g_{\mathrm{MC}}$.

Thus, finding an extra bed in the ICU was assessed as more difficult than calling for an additional surgeon. Beds in the MCU were considered as the most flexible resource since some patients can be discharged earlier than planned after surgery or may be sent to another hospital in order to free some beds. Nurses in the ICU were considered as a more flexible resource than surgeons, but less flexible than beds in the MCU. In our simulation experiment (Section 4), we make these weights varying.

For the sake of simplicity, we let $q_{r,t}$ be the expected consumption of resource r on day t. For all resources and periods, the expected consumption must not exceed the available capacity and over and under utilizations are auxiliary variables expressed as deviations between consumption and target level of utilization. Formally, the following constraints must hold

$$\begin{cases} q_{r,t} \le K_{r,t} \\ -u_{r,t} \le q_{r,t} - A_{r,t} \le o_{r,t} \end{cases}, \quad r \in \{\mathrm{OT, IC, MC, NH}\}; \quad t = 1, \ldots, T. \tag{3}$$

The formulation of expected resources consumption is provided in Table 2 where we used the convention that subscript $t - j$ in

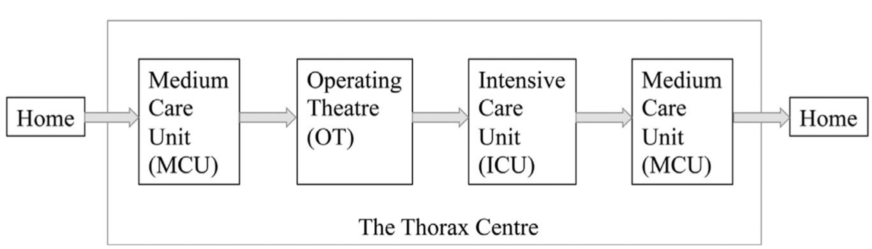

Fig. 1. The flow of elective patients in the Thorax Center.