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Comparing resource balancing criteria in master surgical scheduling: A combined optimisation-simulation approach

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ABSTRACT

This study compares three different scheduling policies in the Master Surgical Scheduling context with respect to three performance criteria: efficiency, i.e. the capability of scheduling a large number of surgeries; balancing, i.e. the capability to distribute workload fairly among the resources involved in surgical activities; and robustness, i.e. the capability to prevent schedule disruptions caused by variability of surgical time and length of stay. We develop a mixed-integer programming model and compare three objective functions, each corresponding to a different scheduling policy. All the policies maximise the number of scheduled surgeries and balance the utilisation of post-surgical beds and operating rooms. However, they implement a different balancing criterion. To assess the robustness of the schedules produced by the optimisation model, we used a discrete event simulation model that samples surgical times and length of stay from a probability distribution and keeps track of schedule disruptions that may occur. The work is based on real data from the Meyer University Children's Hospital in Florence. It comprises an experimental campaign that extends to 27 hospital settings and uses both empirical and theoretical probability distributions. Overall, the study reveals that none of the investigated policies allows superior performance in terms of efficiency, balancing and robustness to be achieved concurrently. However, depending on the hospital management's priorities and needs, it is always possible to identify a policy that allows for a reasonable trade-off among these performance criteria. In addition, the study reveals the causal mechanisms that, under certain circumstances, make certain balancing criteria perform better than the others.

1. Introduction

The operating theatre (OT) is one of the most critical functional areas in a hospital. It drives almost 70% of the hospital's admissions and determines most of its costs (Denton et al., 2007). Improving the OT performance, thus, represents a strategic objective for a growing number of hospitals. In this regard, hospital managers have widely recognised that the performance of the OT largely depends on the way the surgical activities are scheduled (Litvak and Long, 2000, Guinet and Chaabane, 2003). This challenging topic has encouraged the development of a significant number of mathematical models that support the surgical planning and scheduling process (Cardoen et al., 2010, Guerriero and Guido, 2011, May et al., 2011, Dobrzykowski et al., 2014).

In the literature, such a process is considered to entail three stages i.e., *case mix planning*, *master surgical scheduling* (MSS) and *patients scheduling*, where the output of the upstream stage is the input of the downstream one (Beliën and Demeulemeester, 2007).

In the *case mix planning* stage, each specialty (e.g. urology, orthopaedic surgery, etc.) is assigned with a *total* OR time, which is usually expressed in terms of sessions per week/month. The *master surgical scheduling* stage, instead, consists in producing a timetable (the MSS) where a specialty is assigned to each OR session for each day of the planning horizon. Finally, in the *patients scheduling* stage, patients who have to undergo surgery are selected and sequenced within each session of the MSS.

This study focuses on the second stage, i.e. the MSS problem. Coherently with Banditori et al. (2013, 2014), in this study we consider a situation where the *case mix planning*, has already been performed and we address the problem of determining: (i) the specialty (or specialties) to assign to each operating room (OR) and session of each day of the planning horizon; (ii) the number and

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type of surgeries that should be performed in each OR session (van Oostrum et al., 2008). Such a plan serves as an input for the *patient scheduling* stage. Solving a MSS problem has been proven to be extremely complex. Indeed, it requires taking into account many resources (ORs, post-surgical beds, surgical teams, ICU) and dealing with the randomness of surgical times (ST) and patients' length of stay (LoS) (Cardoen et al., 2010, Guerriero and Guido, 2011). In addition, it necessitates to take into consideration the conflicting priorities of different stakeholders, e.g. hospital managers, surgeons, nurses, patients (Glouberman and Mintzberg, 2001, Marcon et al., 2003).

In general, to fulfil the expectations of these stakeholders a MSS should be *efficient* (Cardoen et al., 2010, Guerriero and Guido, 2011), *balanced* (Litvak and Long, 2000) and *robust* (Banditori et al., 2013, 2014). In fact, it should allow for the increase of revenues and for the reduction of waiting times by maximising the number of patients scheduled (*efficiency*). In addition, it should determine a fair allocation of the workload among the people (doctors, nurses, etc.) working in the OT and in the post-surgical wards (*balancing*). Finally, it should prevent schedule disruptions, i.e. it should prevent OR overtime and/or bed overbooking that are usually caused by the variability of both ST and LoS (*robustness*).

This study is based on a combined optimisation-simulation approach and has the following twofold aim:

i. Compare three different scheduling policies and identify the one that under given operational conditions allows for the trade-off between efficiency, balancing and robustness best fitting the hospital priorities and its needs, and
ii. explain *why* in certain conditions certain scheduling policies are superior to the others.

All the investigated policies aim to maximise the number of scheduled surgeries and to balance the utilisation of both post-surgical beds (hereafter beds) and ORs. However, these policies adopt different balancing criteria. The first policy (hereafter referred to as minMax) minimises the maximum daily utilisation of beds and ORs. The second one (hereafter referred to as minRng), instead, minimises the range between the maximum and minimum utilisation of these resources. Finally, the third policy (hereafter referred to as minOvrn), minimises the *overrun*, i.e. the positive deviation between the actual resource utilisations and target utilisation values.

In this study, we develop a mixed-integer programming (MIP) model, which is based on the models presented in Banditori et al. (2013, 2014) and compare three alternative objective functions.

Each objective function corresponds to one of the aforementioned scheduling policies. The model variables and constraints do not vary across policies. We assume that the cases in a hospital's waiting list can be classified into homogeneous surgery groups that are based on the resources (e.g. ORs, beds) that they are expected to require. Hence, the model produces a solution (the MSS) indicating the number of cases to treat and the surgery group these cases must belong to for each day of the planning horizon, for each OR, and for each session of the day. Such a solution also has to satisfy Quality of Service (QoS) requisites, i.e. it should allow the desired case-mix and the desired level of OR utilisation to be obtained.

The MIP model assumes deterministic values for the parameters ST and LoS. Thus, to assess the impact that the variability of these parameters has on the MSS robustness, we use a discrete-event simulation model. Such a model samples the values of ST and LoS from suitable probability distributions. By combining optimisation and simulation, we are able to calculate the overtime and the overbooking that would emerge as a consequence of the implementation of a given MSS.

The underlying conjecture of this study is that, in general, if the daily utilisation profiles of ORs and beds are nicely balanced, there should be some idle resources to absorb the unexpected peaks caused by ST and LoS variability (Beliën et al., 2009). In other terms, a higher balancing should lead to a higher robustness, especially when average resource utilisation is high. However, resource balancing can be achieved by using different scheduling policies, where each policy allows for the scheduling of a different number of surgeries (efficiency). In this study, the trade-off between efficiency, balancing and robustness is empirically investigated.

The main contribution of this work is to offer fresh insights into the relationship between efficiency, balancing and robustness in the surgical scheduling field, and to provide a thorough assessment of the pros and cons associated with the utilisation of three alternative scheduling policies. This work is based on real data from the Meyer University Children's Hospital (hereinafter Meyer Hospital) a leading Italian hospital. Starting from this data, we create 26 additional "realistic" hospital settings, thus to compare the scheduling policies in different scenarios. Moreover, to increase the external validity of our findings, the schedules produced in the optimisation phase have been simulated using both empirical distributions and theoretical (lognormal) distributions, for both ST and LoS.

The major findings of our work are as follows:

(i) A scheduling policy that allows achieving for a given hospital setting, superior performances in terms of efficiency *and* balancing *and* robustness, does not exist;
(ii) in general, when the focus is on efficiency, the best policy is the one that minimises the resources utilisation range (minRng). This policy allows for the containment of the overtime and for a good balancing of both beds and ORs. On the contrary, when the focus is on how to avoid overbooking, other policies (minMax, minOvrn) should be preferred.
(iii) These results are consistent across different distributional models.

Another important contribution of this study is to explain the causal mechanisms that make some scheduling policies outperform the others.

The empirical results of this work are organised in (Tables 5–12) that can help managers in choosing the scheduling policies that best fit their own hospital settings and priorities.

The remainder of the paper is organised as follows: in Section 2, we provide a review of the literature. In Section 3, we present the characteristics of the addressed MSS problem. In Section 4, we describe the optimisation and simulation models. In Section 5, we illustrate the experimental campaign we have carried out, whose results are presented in Section 6. Subsequently, in Section 7, we draw the conclusions and outline the direction of our future research efforts.

2. Literature review

Balancing/levelling issues emerge from different fields of application, i.e. machine scheduling (Sen et al., 1995, Caramia and Dell'olmo, 2003), crew scheduling (Cappanera and Scutellà, 2011), project scheduling (Neumann and Zimmermann, 1999), surgical scheduling (Banditori et al. 2014) and have been the object of a large number of contributions.

In this review, we primarily focus on works studying the workload balancing problem in the MSS context, i.e. the problem of equally distributing a certain workload among a given set of resources (e.g. beds, ORs). The papers reviewed here are analysed