Optimization modelling of hospital operating room planning:
analyzing strategies and problem settings

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Abstract

There is a growing proportion of elderly which increases the demand for health care. As a consequence health care costs are rising and the need for hospital resource planning seems urgent. Different aspects (often conflicting) such as patient demand, clinical need and political ambitions must be considered. In this paper we propose a model for analyzing hospital surgical suite with focus on operating room planning. An optimization model is developed for patient operation scheduling and for key resource allocation. Medical examinations and treatments of patients are performed using a number of resources similar like products are refined in a number of processes in a logistics chain. Optimal resource allocation given different objectives according to patient perspective, staff perspective, costs etc. under different system settings (e.g. principles for operating room allocation and amount of stand-by personnel) is studied. Preliminary results are presented based on case studies from two Swedish hospitals.

Keywords: Hospital; Health Service; Integer Programming; Logistics; Optimization; Scheduling

Introduction

Hospital surgical suite is an activity where several different resources have to be synchronized in order to achieve efficiency. Many studies have been conducted in attempt to optimise health care delivery through the last decades, see comments by Lagergren (1998), Riley (1999) and De Angelis et al (2003). Scheduling staffs, beds and operating room allocations are common optimisation problems that are studied in this field (Beaulieu, 2000, Kua et al, 2003, Ogulata and Erol, 2003). Various approaches including optimisation techniques are used depending on how the problem is formulated and possibly separated into different parts. One of the main interests of optimizing health care is how the allocation of operating room is performed. Previous research focusing on optimizing the surgical suite, generally propose strategies to minimize monetary costs and to achieve as high patient through-put as possible (Lowery, 1992, Hollingsworth, 2003). In this paper, we connect operating room planning mainly to the patient perspective, which is not the typical view of this planning task; also personnel perspectives and financial aspects are considered.

Operating room planning is a complex task which has to consider many aspects such as surgeon scheduling, operating team scheduling (included anaesthetic personnel), patient related information, (i.e. estimated operating time, priority and diagnosis), equipments and surrounding activities like intensive care unit etc. We suggest optimization modelling to support allocation of
key resources for operating room planning. The purpose is to show that this method can serve as a tractable tool for tactical planning within this environment. The case study is based on real data from Swedish hospitals.

In this paper, we first introduce the problem as experienced from two hospitals of different types. Then, an optimization model is suggested and the generation of input-parameters is presented. Different scenarios are created and the result of using the optimization model is presented. Finally, conclusions and directions for future research are outlined.

**Problem description: Operating room planning**

Due to the complexity of operating room planning and the way surgery activity affects and are affected by many processes within hospital, it is a challenge to find out and analyze the parts which primarily influence the surgery activity. In this case study we try to identify primary requirements that form the basis to operating room planning. In order to obtain an understanding of the surgery activity from a general point of view, we have studied two cases at two Swedish hospitals;

- **Blekinge Hospital (Blekingesjukhuset)**
  A medium sized hospital (ca. 420 beds).
  Department of general surgery

- **Sahlgrenska University Hospital (Sahlgrenska Universitetssjukhuset)**
  A university hospital (ca. 2400 beds)
  Department of cardiothoracic surgery

Blekinge Hospital is a medium sized hospital (for hospitals in Sweden) where we study a general surgery department whereas the study at Sahlgrenska University Hospital concerns surgery that is specialized and which are mostly located at university hospitals.

**Surgery planning**

The main problem is to map the list of planned patients into an operating schedule that meets both patient priority and available resources needed for a particular operation while at the same time consider how the total time of care is performed, presuming that the objective is to operate on as many patients as possible. In this context, it is important to state that disturbances of acute operations are not included explicitly in this study. With acute operations we mean patients that need immediate operation. Patients are given different priorities after medical decisions into three groups;

1. Double priority (Operation needed within 2-4 weeks. Local differences)
2. Single priority
3. No priority

The surgical suit is provided with a fixed number of operating rooms. In order to perform an operation there are some general requirements;

- One or several *surgeons*. The surgeon skill must match the type of operation that is planned.
- One *operating room*
- One *operating team* consisting of (local differences):
- one nurse anaesthetist,
- one or two operating room nurses and
- one or two assistant nurses. In our model, we refer the operating team to opening hours at each operating room.
- One available anaesthetist (Not considered in this model)
- Special equipment which might mean that some operations have to be performed in certain operating rooms. (Not considered in this model.)
- Post operative care. There must be beds available at the ICU (Intensive Care Unit) or at the ward.

In order to handle the priority group 1, the final operation schedule, keeping in mind that we in reality are dealing with a rolling horizon, usually are made one week at a time. In addition there are typically queues of patients that can be operated on if possible.

**Department of general surgery**

In general surgery, the surgeons are internally divided up into teams according to specialty. Table 1 shows an example of how the surgeons are grouped into surgeon teams and how diagnosis/patients can be spread among these. Patient 1 represents diagnosis which can be operated on by all surgeon teams included all surgeons, so-called standard operation. Diagnosis represented by patient 2, require surgical operations handled by the surgeons of surgeon team 1. Patient 5 has a diagnosis that requires skills that only surgeon 1 and 2 (working in the same surgeon team) have. Finally, patient 6 has a diagnosis that only can be treated by surgeon 6 and 9, but in contrast to the case of patient 5, the surgeons are working in different teams.

<table>
<thead>
<tr>
<th>Surgeon team 1</th>
<th>Surgeon 1</th>
<th>Surgeon 2</th>
<th>Surgeon 3</th>
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Table 1 Surgeon team and patient diagnosis.

Currently, each surgeon team has a fixed number of operating rooms per week at its disposal. This is, as far as we know, a common planning strategy at many Swedish medium sized hospitals. It is interesting to note how the surgeon teams are allocated to the same number of operating rooms every week with no considerations taken to how the present patient load is distributed among the surgeon teams and the availability of surgeons. In addition, surgeons from general surgery departments are also scheduled with other duties at ward or consulting-room which complicate the scheduling of the surgeons. In order to take surgeon preferences into
account, surgeons must not operate on two subsequent days in order to see patients at ward (operated on the day before) and seeing new patients at consulting-room.

**Department of cardiothoracic surgery**

Due to the “complexity” of operations at cardiothoracic surgery, the operating teams are specialized and are only working with cardiothoracic surgery. Unlike the surgeons at the general surgery, the cardiothoracic surgeons are not as much occupied with other duties. This is explained by the fact that there are usually other physicians (generally cardiologists) than the cardiothoracic surgeon that are responsible for the medical examination and rehabilitation. This enhances the availability of the cardiothoracic surgeons considerably compared to the general surgeons and introduces greater flexibility in the surgeon scheduling. The internal divisions of surgeon teams are employed in the same way as in the general surgery. Also principles of how the division of surgeons are related to different diagnosis, illustrated in Table 1, are utilized in cardiothoracic surgery as well. Central to the cardiothoracic surgery is the ICU (Intensive Care Units) that must have resources of beds and staff to handle the need of post operative care, i.e. patients transferred from the operating room suite. This in turn means that the ward must be able to accept patients transferred from the ICU to prevent restriction of patient through-put.

**Summary**

The operating room scheduling has the same basic principles at both hospitals. Temporary schedules are constructed several weeks in advance while the final schedules are constructed Thursday or Friday the week before. The scheduling is performed manually (without any advanced software support). When comparing the two strategies for operating room scheduling, the surgeon scheduling at the general surgery is dealing with more aspects than in the cardiothoracic surgery. By aspects we mean that individual preferences from the surgeons at the general surgery have to be considered as for example; not operating on two subsequent days. The static operating room allocation used in the case of general surgery is not used in the case of cardiothoracic surgery. The surgeons at the cardiothoracic surgery mostly operate during working hours and are not as much scheduled for other duties as the surgeons at the general surgery. An interesting observation related to the operating room planning that is very much valid for both of the case studies; the importance of available resources at ICU and later at the ward to prevent restriction of patient through-put at operating room suite with associated cancellations of operations. This could be comparable to how products are refined in a number of processes in a logistics chain where resources at the ICU but also at the ward must be available in order to fulfil the requirements to carry through the operating room schedule. This parallel is sharper in the case for Sahlgrenska University Hospital.

**Problem formulation**

Based on the two case studies, we have identified some key resources that we find the most relevant when optimizing operating room planning. Also we have identified some rules related to the identified resources that have to be considered in order to meet additional non-key requirements.
Optimization Model

Indices and Sets:
\( j \) Index for patient set \( J \),
\( k \) Index for surgeon team set \( K \),
\( l \) Index for surgeon set \( L \),
\( m \) Index for operating room set \( M \),
\( t \) Index for time slot set \( T \).

Parameters:
\( a_{mt} \) Available time in surgeon room \( m \) in time slot \( t \) (when time for potential acute operations has been excluded).
\( b_k \) Parameter of how many operating rooms a surgeon team is allowed to allocate in the same time slot.
\( c_j \) Cost of not operating on patient \( j \).
\( d_{jl} \) 1 if surgeon \( l \) is qualified to operate on patient \( j \), 0 otherwise.
\( e_j \) Estimated operating time for patient \( j \).
\( f_{lt} \) 1 if surgeon \( l \) is available on time slot \( t \), 0 otherwise.
\( g_{kl} \) 1 if surgeon \( l \) is included in surgeon team \( k \), 0 otherwise.
\( q_j \) Estimated days of post operative care for patient \( j \).

Variables:
\( o_{kmt} \) 1 if surgeon team \( k \) is allocated to operating room \( m \) in time slot \( t \), 0 otherwise (binary).
\( p_t \) Number of patients transferred from ICU (Intensive Care Unit) in time slot \( t \) (integer).
\( s_j \) 1 if patient \( j \) is not operated on, 0 otherwise (binary).
\( w_t \) Available beds at ICU (Intensive Care Unit) or the ward in time slot \( t \) (integer).
\( x_{lmt} \) 1 if surgeon \( l \) is assigned to operating room \( m \) in time slot \( t \), 0 otherwise (binary).
\( y_{jmt} \) 1 if patient \( j \) is assigned operating room \( m \) in time slot \( t \), 0 otherwise (binary).
\( z_{kt} \) 1 if surgeon team is operating in time slot \( t \), 0 otherwise (binary).

Objective

The objective of the operating room planning is to operate on as many patients as possible with considerations taken to patient priority and presented resources available. In our model we have chosen the objective function of minimizing the cost of not operating on a patient, which, as far as we now, is not the usual way of modelling. The cost parameter is meant to represent an estimation composed of a combination of patient suffering (related to; diagnosis, time waited for operation and medical priority) and public cost (e.g. cost of sickness benefits etc.) and is individual related to the patient. Alternatively, by having the cost parameter only representing one of the composted issues, one cost perspective could be viewed.
Also, at this moment, we take no considerations to the longer term perspective and a rolling horizon, i.e. we are only considering one week of planning.

Minimize \( z = \sum_{j \in J} c_j s_j \)

Subject to:

Patient can only be operated on once. Also if operation of patient \( j \) does not occur for the current week, a cost is paid.

\[
\sum_{m \in M} \sum_{t \in T} y_{jmt} = 1 - s_j \quad \forall j, s_j \in \{0,1\} \tag{1}
\]

Capacity limit, the patients are associated with an estimated operating time according to what kind of operation and severity.

\[
\sum_{j \in J} y_{jmt} e_j \leq a_{mt} \quad \forall m, t \tag{2}
\]

Connection between patient diagnosis/operation types, surgeon available:

\[
y_{jmt} \leq \sum_{l \in L} d_{jl} \cdot f_{lt} \cdot x_{lmt} \quad \forall j, m, t \tag{3}
\]

**Aspects of surgeon team and operating room allocation**

As described above, the surgeon teams at the general surgery are fixed to certain operating rooms and days (time slots) and within these assigned time slots and operating rooms, the surgeons within the surgeon team are distributed. While at the same time studying the case of cardiothoracic surgery, where a dynamic/flexible operating room allocation is employed, we provide alternatives within the optimization model for analysis. To enable a flexible operating room allocation, we set up limitations for, on the one hand; the surgeon teams and on the other hand; the surgeons, to operate on two subsequent days by replacing the fixed operating room allocation with either constraints (4a) or (4b). By this, we keep the restrictions of having the surgeons free from operative duties the day after having operated in order to be accessible to the post operative patients as preferable in the general surgery.

\[
z_{k(t-1)} + z_{k t} \leq 1 \quad \forall k, t, \ t \geq 2 \tag{4a}
\]

\[
\sum_{m \in M} (x_{lm(t-1)} + x_{lmt}) \leq 1. \quad \forall k, t, \ t \geq 2 \tag{4b}
\]
Constraints (5) are related to the choice of implicating constraint (4a) and they limit how many operating rooms a surgeon team is allowed to occupy at the same time.

$$\sum_{m \in M} o_{kmt} \leq b_k \cdot z_{kt} \quad \forall k, t$$  \hspace{1cm} (5)

Constraint ensuring that only one surgeon team is allowed to occupy an operating room in a time slot.

$$\sum_{k \in K} o_{kmt} \leq 1 \quad \forall m, t$$  \hspace{1cm} (6)

Restricting surgeons to only one surgeon team per operating room and time slot:

$$x_{lmt} \leq \sum_{k \in K, t \in T} o_{kmt} \quad \forall l, m, t$$  \hspace{1cm} (7)

Restrict the surgeon to one operating room per time slot.

$$\sum_{m \in M} x_{lmt} \leq 1, \quad \forall l, t$$  \hspace{1cm} (8)

**Model Extension**

One of the main causes to disturbances of operating room planning besides unpredictable events of acute operations is the restriction of patient throughput in either the ICU or the ward. The possibility of including estimated expected post operative care into the optimization model for the operating room planning is therefore interesting. In the following experiment description, constraint (9) and (10) are not included.

Available ICU/Ward-beds

$$w_{(t-1)} + p_t - \sum_{j \in J} \sum_{m \in M} y_{jmnt} = w_t \quad \forall t$$  \hspace{1cm} (9)

Patients transferred from ICU/Ward in time slot $t$.

$$p_t = \sum_{j \in J} \sum_{m \in M} y_{jmnt-q_j} \quad \forall t$$  \hspace{1cm} (10)

We assume that $y_{jmnt-q_j}$ is a given parameter for $t-q_j \leq 0$ (i.e. given by earlier operations)
Operating room scheduling

Based on the two conducted case studies, we analyze the potential of optimization modelling for operation room planning to support allocation of key-resources. However, we focus on the general surgery and have conducted an experiment using the provided model to help analyze static versus dynamic operating room allocation. As pointed out above, there is a difference in this direction between how the allocation of operating rooms and scheduling of surgeon is performed in the two hospitals. The experiment set-up and results are further described below.

Experiment

The main outline of the conducted experiment of scenarios is organized according to;

1. Analysis concerning static allocation of operating rooms compared to dynamic/flexible allocation of the same.
2. Extended opening hours of the operating rooms.

When utilizing static operating room allocation, the surgeon teams allocate the same number of rooms at the same day (time slot) every week. While at the dynamic/flexible approach, employed at the cardiothoracic surgery, the surgeons (not the surgeon teams) allocate the rooms and time slots according to patient load. This fact gave us the idea of allowing for the optimization model to incorporate a choice of the level of flexibility, in order to simulate the dynamic/flexible approach also at the general surgery. We have modelled (see description of optimization model) so that we are free to choose either a static surgeon team allocation, as is utilized in Blekinge Hospital, flexible surgeon team allocation by applying constraint (4a), or the alternative of no team allocation; flexible surgeon allocation by applying constraint (4b), utilized in Sahlgrenska University Hospital. Constraint (9) and (10) are, as earlier mentioned, not applied in this experiment principally because further investigations in how the estimated post operative care can be related to the clinic (patient group).

We use opening hours for each operating room, denoted default time, according to Table 2 below (parameter $a_{mt}$). Then we extend opening hours to 450 minutes on Mondays and Tuesdays in Room 1 to illustrate the effects of potential shifts, over-time or flex-time for the staff (operating room team). No considerations to availability of staff and beds are taken. On Fridays, the time slots are smaller due to staff considerations during week-ends.

<table>
<thead>
<tr>
<th></th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
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<tr>
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Table 2 Default opening hours

In order to conduct as relevant experiment scenarios as possible, we use input data based on statistics from Blekinge Hospital. The scenarios represent one week of operating room planning. The numbers and types of operations that apply for operating room admission in the scenarios are in ratio to operations performed during the last year at Blekinge Hospital. We have chosen the number of 40 patients at each scenario to represent the patient queue. No considerations to seasonal variations are taken, if there are any. The estimated length of time for
each operation, $e_j$, is based on mean values from real data plus 45 minutes of set-up time (also mean value). Also number of surgeons and surgeon teams correspond to the approximately amount of available surgeons during one week at Blekinge Hospital. In this experiment we use 5 surgeon teams with 3 surgeons each. The individual schedules for the surgeons, i.e. what day to operate or to have a day-off and so on, are predetermined which together with the fixed allocation of operating room constitute basis to current operating room scheduling at Blekinge Hospital and is here denoted; default case. To enable flexible room allocation we let the individual surgeon schedules to be in a more preliminary state. This implies that the surgeons are not scheduled for surgery or other duties until the final surgery schedule is set. We let two of the three surgeons always to be available for surgery. The number of operating rooms considered is three, as in Blekinge Hospital, and the time slots representing opening hours per day and room are calculated four full-time days, Monday-Thursday, and one half day, Friday. The opening hours for each room are in reality describing the availability of operating team (not to mix-up with surgeon team). The cost parameters $c_j$ are not based on real cases but are here randomized to represent patient diagnosis and patient waiting time. Our intention is to further develop this value into realistic patient cost parameters.

As described earlier, the surgeons at the general surgery often are responsible for the medical examination of the patients. In several cases this implies the responsible surgeon also to be the operative surgeon, i.e. a combination of patient-surgeon that is fixed. This could also be the case when some operations require special surgical qualifications. Patients with double priority often are contracted diseases with carcinogenic or other problematic characteristics which involve additionally needs. In reality, this means, the surgeon together with the patient wants to decide what day the operation will be performed. To reflect these needs and come as close to the reality as possible, we have constructed 6 fixed operations per week distributed among all surgeon teams, for the scenarios which are not default. This entails increased validity to the suggested dynamic approach, and allows us to compare our proposal to the existing system (here; default scenarios) of operating room planning. We use 40 patients for admission to operating room planning as default. Each patient is assigned a random cost between 1-70 except for 6 patients that are assigned the value of 100 which will represent the patients that are needed to be scheduled within this time frame. This cost is modelled as a penalty to the objective function when the patient is not operated on and represents a mix of medical priority, time waited and economical aspects. Except for the following described aspects, the scenarios use the same system settings for optimization.

Results

We have used 4 sets of data input to represent the patient associated cost parameter when optimizing. In Table 3 we can first see the minimized costs from the default scenarios, i.e. Fixed Allocation. The total computed cost results indicate that using a more dynamic/flexible operating room planning model is more cost-efficient than the default case. The flexible approach implies a general increase in efficiency, i.e. increased patient through-put.
In the table the asterisk denotes there might exist some better solutions since the gap in the branch and bound approach (Cplex 8.1) could not be closed within the time limit of 1000 seconds of CPU-time.

**Conclusion and Future work**

One of the main objectives for this research has been to provide optimization modelling to support analyzing operating room planning. Although this experiment only shows preliminary results, we have demonstrated how optimization modelling can be used for analyzing strategies and different settings with respect to resource allocation. The experiment was conducted in collaboration with two Swedish hospitals which to a certain extent effected the problem formulation. The conclusions have to be interpreted with this in mind, e.g. the amount of flexibility in allocation depends on the organizational structures and might differ between different countries. The results from the experiment are demonstrated to Blekinge Hospital with interested reactions. However, we are aware of that the model is limited and our intention is to expand the model in different directions. For example, further research with experiments, with constraints (9) and (10), considering the logistics to greater extent are already in progress and will soon be reported. We will further study the impact of more representative cost parameter on the results. Also, the left-out aspect of operating room planning under uncertainty, i.e. acute operations and other events, is very relevant and will be considered for future work. Since the size of the operating room allocation problem could be very big, we are looking into additionally optimization techniques such as decomposition for better and faster results.

**Acknowledgements**

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**References**


