Optimization modeling of hospital operating room planning using a logistic perspective

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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 analyze hospital surgical suit with focus on operating room planning and we suggest optimization modeling to support allocation of key resources. 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 logistic chain. Optimal resource allocation giving different objectives according to patient perspective, staff perspective, costs etc. under different system settings (e.g. principals for operating room allocation and amount of stand-by personnel) is proposed. Preliminary results are presented based on case studies from Swedish, both general and university hospitals.
1. Introduction

Hospital surgical suite is an activity where several different resources have to be synchronized in order to achieve efficiency. One of the main interests of optimizing health care is how the allocation of operating room is performed. Operating room planning is a complex task which has to consider many aspects such as surgeon scheduling, operating team scheduling (included anesthetist personnel), patient related information, (i.e. estimated operating time, priority and diagnosis), equipments and surrounding activities like intensive care unit etc. In this paper we suggest optimization modeling to support allocation of key resources for operating room planning. The purpose is to show that this tactical planning method can be a tractable tool for tactical planning within this environment. The case study is based on real data from Swedish hospitals.

Many studies have been conducted in attempt to optimise health care delivery through the last decades [2,9,6]. Scheduling staffs, beds and operating room allocations are common optimisation problems that are studied in this field [8,5,1]. Various approaches including optimisation techniques are used depending on how the problem is formulated and possibly separated into different parts. Earlier research focusing on optimizing the surgical suite, generally propose strategies to minimize monetary costs and to achieve as high patient through-put as possible [3, 4, 7]. 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 included.
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.

2. 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.
  
  General surgery

- Sahlgrenska University Hospital (Universitetssjukhuset)
  
  A university hospital
  
  Thorax surgery
We focus on the Blekinge Hospital and relate our findings to Sahlgrenska University Hospital. Thorax surgery together with neuro surgery etc. are specialties that mostly are located at university hospitals.

2.1 General planning problem in relation to surgery

First of all there are patients with different diagnosis that are planned for operation. These patients are given priorities after medical decisions into three groups;

1. Double priority (operation needed within two weeks.)
2. Single priority
3. No priority

Disturbances of acute operations are not included. With acute operations we mean patients that need immediate operation. The surgical suit is provided with a fixed number of operating rooms. In order to perform an operation there are some general requirements;

- One operating room
- One operating team consisting of (local differences):
  - one nurse anesthetist,
  - one or two operating room nurses and
  - one or two assistant nurses.
- One or several surgeons
- One available anesthetist
Special equipment when necessary (can be located to certain operating rooms which means that some operations have to be performed in certain operating rooms)

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. In order to handle the priority group 1, the final operation schedules usually are made one week at a time. In addition there are typically a queue of patients that can be operated if possible.

Figure 1 illustrates the number of operating rooms available for the general surgery at Blekinge Hospital per day and week.

As described later, the final operating schedule is planned one week ahead and here we can easily obtain an understanding of what resources, according to time slots and operating rooms, are at disposal. Thorax surgery at Sahlgrenska University Hospital in Gothenburg has five operating rooms at disposal.
2.2 Surgery planning at the general surgery clinic

The surgical suit in general surgery is generally shared with other medical specialties like gynecology and orthopedics. This means that the operating teams, more or less, alternate between the specialties. Moreover, the general surgery is internally divided up into teams according to specialty. Below, we can see 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 by all surgeon teams included all surgeons, so-called standard operation. These diagnoses require 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>Patient 1</th>
<th>Patient 2</th>
<th>Patient 3</th>
<th>Patient 4</th>
<th>Patient 5</th>
<th>Patient 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeon 2</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>Surgeon 3</td>
<td>ok</td>
<td></td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon 4</td>
<td>ok</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon 5</td>
<td>ok</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon team 2</td>
<td>Surgeon 6</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ok</td>
</tr>
<tr>
<td>Surgeon 7</td>
<td>ok</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon 8</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon team 3</td>
<td>Surgeon 9</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ok</td>
</tr>
<tr>
<td>Surgeon 10</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ok</td>
</tr>
<tr>
<td>Surgeon 11</td>
<td>ok</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ok</td>
</tr>
</tbody>
</table>

Table 1
Based on historical data, these divisions of surgeon teams have disposal of a fixed number of operating room (included operating team) per week. This is a way of planning which makes the operating room scheduling rather inflexible and is therefore interesting to compare with a more dynamic approach. The scheduling of operations with considerations taken to available resources (surgeons, operating teams, and operating rooms) is, in principal, conducted by a coordinator. The coordinator also has to consider how to distribute resources according to fluctuating patient load with varying priority. In addition, surgeons from general surgery clinics are also scheduled with other duties at ward or consulting-room which complicate the scheduling of the surgeons. The number of planned operations per week is varying between 20 and 30.

2.3 Surgical planning at the thorax surgery clinic

Due to the “complexity” of operations at thorax surgery, the operating teams are specialized and are only working with thorax surgery. Unlike the surgeons at the general surgery, the thorax surgeons are not as much occupied with other duties. This is explained by the fact that there are usually other physicians (cardiologists) that are responsible for the medical examination and rehabilitation. This enhances the availability of the thorax surgeons considerably compared to the general surgeon and simplifies the surgeon schedule mapping the operating room schedule. Though the divisions of teams are employed in the same way at the thorax surgery and the principals for teams related to patients and diagnosis, illustrated in Table are valid for the thorax surgery as well. A fixed number of 5-6 operations per day are scheduled at the thorax surgery. The operation
times are generally longer than in the general surgery and one operation per operating room and day are normally scheduled.

2.4 Summary

Comparing the two strategies for operating room scheduling, we see the scheduling problem at the general surgery is dealing with more aspects than in the thorax surgery, at least when delimiting focus on the operating room planning. Therefore, the identified key resources and decisions presented in the next section are more important to the general surgery but are also relevant for the thorax surgery.

3. Problem formulation

3.1 Scheduling priorities and tactical decisions.

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.

- *Available surgeons.*

This is one of the key resources due to the central role surgeons are playing. In addition, all the duties that have to be scheduled for the surgeons are more or less connected, e.g. if surgeons are scheduled with ample time for receiving patients at consulting-room, the
direct effect is more patients waiting for operations. In order to account for the additional
duties for surgeons (e.g. consulting, education etc.), we are specifying when surgeons are
available for surgery.

-Operating room and operating team

Operating rooms is another key resource which is limited by time. An operating room is
allocated to an operating team. In order to meet requirements from surrounding activities
like decreased staff at ward during weekends, we have extended the available operating
room time in the beginning of the week

-Objective

The objective of the operating room planning is to operate 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 a
patient. In this approach, cost is stated different for patients with different priorities.

3.2 Optimization Model

The model presented below represents the patient scheduling and resource allocation
presented above. Each patient is given a cost which is based on priority and the
associated time the patient has been waiting for an operation and without loss of
generality other factors might also be used to determine this cost. Also, the patients are
associated with an estimated operating time according to what kind of operation and
severity. This estimated time could also be associated with surgeon, but are not included
here.
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 \( t \).
\( b_k \)  Parameter of how many operating rooms a surgeon team is allowed to allocate in the same time slot.
\( c_j \)  Cost of not operating patient \( j \).
\( d_{jl} \)  1 if surgeon \( l \) is qualified to operate 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.

Variables:

\( o_{kmt} \)  1 if surgeon team \( k \) allocates operating room \( m \) in time slot \( t \), 0 otherwise (binary).
\( s_j \)  1 if patient \( j \) is not operated, 0 otherwise (binary).
\( x_{lmt} \) 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).

\[
\text{minimize } z = \sum_{j \in J} c_j s_j
\]

subject to:

1. Capacity limit:

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

2. Connection between patient diagnosis/operation type, surgeon available and surgeon team:

\[
y_{jmt} \leq \sum_{l \in L} d_{ji} \cdot f_l \cdot x_{lmt} \quad \forall j, m, t
\]

3. Patient can only be operated once. Also if operation of patient \( j \) does not occur, a cost is paid. The cost is related to patient priority and patient waiting time:
\[ \sum_{m \in M} \sum_{t \in T} y_{jmt} = 1 - s_j \quad \forall j, s_j \in \{0,1\} \]

4. Constraints for how many operating rooms a surgeon team is allowed to occupy at the same time.

\[ \sum_{m \in M} o_{kmt} \leq b_k \ast z_{kt} \quad \forall k, t \]

5. Restrict operating days in series for surgeon teams.

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

6. Restrict the surgeon to one operating room per time slot.

\[ \sum_{m \in M} x_{lm} \leq 1, \quad \forall l, t \]

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

\[ \sum_{k \in K} o_{kmt} \leq 1 \quad \forall m, t \]

8. An operating room is restricted to surgeons from one surgeon team in a time slot.
4. Scenarios and preliminary results

4.1 Input data

In order to conduct as relevant scenarios as possible, we use input data based on statistics mainly from Blekinge Hospital, but also Sahlgrenska University Hospital. The scenarios represent one week of operating room planning.

Operation and operating time

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). Operating times are based on mean values plus 45 minutes of set-up time (also mean value).

Surgeons and teams

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 composition of surgeon teams are similar at Sahlgrenska University Hospital. The individual schedules for each surgeon, 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.
For comparison we have chosen to have the individual schedules and surgeon teams allocation of operating room in a more preliminary state. We let two of the three surgeons always to be available for surgery. Also we change the fixed allocation of the operating rooms to be flexible but still keeping requirements of not having a surgeon team operating on two subsequent days etc.

*Operating room and time available*

The number of operating rooms considered is three, as in Blekinge Hospital, and the time slots are calculated four full-time days (Monday-Thursday) and one half day (Friday).

*Costs*

The cost parameters 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 true patient cost parameters.

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 represents a mix of medical priority, time waited and economical aspects and is, as described in the model section, included when the patient is not operated. Expect for the subsequent described aspects, the scenarios use the same system settings for optimization.

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

1. Fixed operating room allocation of surgeon teams verses no fixed room allocation.
2. Extended operating time available.

4.2 Aspects of surgeon team and operating room allocation

As described in section 2.2, the surgeon teams at Blekinge Hospital 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. This static division is for comparison removed from our model, instead we use a more dynamic approach, of restriction. 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 this we keep the advantages of having the surgeon free from operative duties the day after having operated in order to be accessible to the post operative patients. Constraint 5 from the model describes the restriction of surgeon teams not allowed to operate on two subsequent days. For other scenarios, as described, we have changed that constraint to only concern surgeons;

Constraint $5 \ z_{k(t-1)} + z_{kr} \leq 1$ is changed into constraint $\sum_{m \in M} (x_{lm(t-1)} + x_{lm}) \leq 1$. We name the static operating room allocation strategy as default.

4.3 Operating time available

As a starting point we use time available for each room, default time, as described in Table 2 below;

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>
<th>Friday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room 1</td>
<td>350min</td>
<td>350min</td>
<td>300min</td>
<td>300min</td>
<td>200min</td>
</tr>
<tr>
<td>Room 2</td>
<td>300min</td>
<td>300min</td>
<td>300min</td>
<td>300min</td>
<td>200min</td>
</tr>
<tr>
<td>Room 3</td>
<td>300min</td>
<td>300min</td>
<td>300min</td>
<td>300min</td>
<td>200min</td>
</tr>
</tbody>
</table>

Table 2

On Mondays and Tuesdays room 1 is assigned more time compared to the other rooms which represent potential shifts, over time or flex time. This “over time” is for half of the scenarios increased into 450 minutes to illustrate the effects of extended operating time available. No considerations to availability of staff and beds are taken.

4.4 Fixed operations

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, for the scenarios which are not default, we have constructed 6 fixed operations per week distributed among all surgeon teams. This entails
increased validity to our, rather dynamic approach, and allows us to compare our proposal to the existing system (here; default scenarios) of operating room planning.

4.5 Results

We have used 4 sets of data input to represent the cost parameter when optimizing. In Table 3 we can first see the minimized costs from the default scenarios. The total compiled cost results indicate that using a more dynamic operating room planning model is more cost-efficient than the default case.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Minimized cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Default operating time</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Fixed team allocation (Default)</td>
<td>157 173</td>
</tr>
<tr>
<td>&quot;Team operating on two subsequent days&quot; - restriction</td>
<td>132 149 150 100</td>
</tr>
<tr>
<td>&quot;Surgeon operating on two subsequent days&quot; - restriction</td>
<td>121 149* 150* 84*</td>
</tr>
</tbody>
</table>

Table 3

In the table the asterisk denote 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.
5. Conclusion

Although this experiment only shows preliminary results, we can rather quickly perceive distinctions about earlier mentioned characteristics, i.e. aspects of handling the static room allocation (as in the default case) or giving the scheduling a more dynamic approach as in this model. Moreover has the scenarios of extended operating time indicated a price to flexibility of staff. This brings us very interesting issues to continue to deal with and further research in these directions will be carried out. Operating room planning is a complex task that commits several mutually influencing resources. In this paper we have chosen to delimit the resources included to get a direct connection to operating room planning. This research will be complemented with further investigations on the effects of surrounding activities (see section 3.1). The use of more representative cost parameters will, of course, refine the results and our intention is to put more focus on this value in the future.

6. Acknowledgements

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7. References


