



# Patient mix optimisation in hospital admission planning: a case study

Patient mix  
optimisation

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**Abstract** Admissions planning decides on the number of patients admitted for a specialty each day, but also on the mix of patients admitted. Within a specialty different categories of patients can be distinguished on behalf of their requirement of resources. The type of resources required for an admission may involve beds, operating theatre capacity, nursing capacity and intensive care beds. The mix of patients is, therefore, an important decision variable for the hospital to manage the workload of the inflow of patients. In this paper we will consider the following planning problem: how can a hospital generate an admission profile for a specialty, given a target patient throughput and utilization of resources, while satisfying given restrictions? For this planning problem, we will develop an integer linear programming model, that has been tested in a pilot setting in a hospital. The paper includes an analysis of the planning problem, a description of the model developed, an application of a specialty orthopaedics, and a discussion of the results obtained.

## Introduction

Patients can enter a hospital in three ways: as an outpatient after a referral from a general practitioner, as an emergency patient in case of immediate need of specialist treatment and as an inpatient. Inpatient admissions can be distinguished into two types: scheduled and non-scheduled. Scheduled inpatient admissions, also called elective patients, are selected from a waiting list or are given an appointment for an admission date. Non-scheduled inpatient admissions, also called emergency admissions, concern patients that are immediately admitted, as a consequence of a medical decision by a specialist at the outpatient department or at the emergency department. Sometimes also urgent admissions (treatment at a short notice) are distinguished but these patients – depending on the way they are handled – can be included in our approach as scheduled or non-scheduled. In this paper we will concentrate on scheduled inpatient admissions.

Admissions planning decides on the number of patients admitted for a specialty each day, but also on the mix of patients admitted. Within a specialty

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different categories of patients can be distinguished on behalf of their requirement of resources. The type of resources required for an admission may involve beds, operating theatre capacity (in case of a surgical specialty), nursing capacity and intensive care (IC) beds. Other resources involved could regard diagnostic departments (e.g. radiology, laboratory) but these will not be considered in this paper as their workload is also influenced by outpatients. The mix of admissions is, therefore, an important decision variable for the hospital to manage the workload of the inflow of inpatients. The current way of dealing with this issue is based on experience of planners rather than on a formal procedure. Often the only focus is the operating theatre capacity, because it is important that this resource is used to its maximum capacity. Admission planning in such a case boils down to operating theatre planning, as the other resources involved are not considered. Currently, there is no tool available to evaluate the patient admission profile (i.e. the number and the mix of patients to be admitted) on their consequences for the combined resources involved.

The literature on admission planning and patient classification is rather extensive; see Gemmel and Van Dierdonck (1999) for a recent state of the art on admission planning. Though many studies are concerned with scheduling of admissions and resources, developing policies for admission profiling at aggregate level based on the mix of different categories of patients within a specialty has not been investigated much before. Patient classification studies and patient mix studies are mostly used for marketing and finance purpose (see, for instance, Barnes and Krinsky, 1999) and not so much for patient flow planning.

In this paper we consider the following planning problem: how can a hospital generate a patient admission profile for a specialty, given targets for patient throughput and utilization of the resources while satisfying given restrictions? The following sections will further elaborate on the planning problem by positioning it in a framework for production control of hospitals. The next section describes the integer linear programming model that has been developed for this planning problem. The penultimate section will discuss the application of this model for orthopaedics in a pilot-hospital. The final section reflects on our contribution to this planning problem, by formulating conclusions and recommendations for further research.

### **Patient mix optimisation within the context of hospital production control**

In this section we position the planning problem in a framework for production control. This framework has been introduced by Groot *et al.* (1993) to describe the different planning levels required for hospital production planning (see Table I).

To guarantee that decisions at a lower level of control are taken and executed within the boundaries set at a higher level, a control function needs to be implemented. This function measures the performance on a predefined set of

Type of decision	Decision makers	Framework level	Horizon	Patient mix optimisation
What is the future direction of the hospital?	Top management	Strategic planning	2-5 years	<div>447</div> <div>Table I. Production control decisions in a hospital</div>
What will be the development of hospital activities in the next year?	Top management	Main patient flow planning	1-2 years	
How are resources allocated to specialties or departments? (lump sum allocation)	Top and middle management	Capacity allocation	months-1 year	
How are capacities scheduled in time? (time-phased allocation)	Middle management	Capacity scheduling	weeks-months	
Which patient is treated at what time?	Planning officers	Operational management	days-weeks	

performance indicators. This set of performance indicators must be constructed in such a way that decisions can be evaluated and deviations from targets set can be explained. Using horizontal and vertical control loops in combination with the levels of production control described above, the production control framework can be further elaborated (see Groot *et al.*, 1993). For the follow-up development of this framework, see Vissers *et al.* (2001).

The framework allows for positioning of different contributions to the planning problem addressed in this paper. At strategic level decisions are taken as to whether the categories of patients distinguished for admission planning fit in the profile of the hospital, and are not in conflict with arrangements with other hospitals. At main patient flow planning decisions are taken about the annual patient volumes and the service level. At this level hospital management negotiates with the purchasers of health care (i.e. in The Netherlands health care insurance organisations) about the number of patients to be treated for the next year and the amount of money the hospital gets for these treatments. Essentially, at this stage the level of service that can be provided with the available amount of money is also preset, as this is the result of a trade-off between service and utilization of resources. The next two levels are responsible for defining the amount of capacity necessary to perform the service (capacity allocation) and for taking care that allocated capacity is available at the right time to avoid capacity loss (capacity scheduling). Owing to the many dependencies there is a danger of suboptimisation and introduction of peaks and troughs in the workload of departments if requirements for capacity co-ordination are not taken into account. Hospitals that do not deal well with the decision making at these intermediate levels may lose capacity due to the way services are organised. The lowest level of the framework focuses on operational management and day-to-day planning.

In the previous section we formulated the following planning problem: how can a hospital generate a patient admission profile for a specialty, given different resource requirements for patient categories, targets for patient throughput and utilization of the resources while satisfying given restrictions? We can now relate the different steps in the planning problem to the framework discussed above:

- The relevance of patient categories, distinguished in the planning problem, is part of the hospital strategic planning.
- Throughput refers to the the annual patient volume that is agreed upon at main patient flow planning level.
- Amount of resources available to a specialty refers to the level of capacity allocation, where annual patient throughputs are translated into capacity allocations; also at this level decisions are taken to set beds apart or reserve beds for emergency admissions.
- Utilisation of resources refers to the level of capacity scheduling, taking into account the dependencies between resources and the time-phased resource requirements of patient categories.

Therefore, we can conclude that the issue of the patient mix can be positioned at the level of capacity scheduling of the framework for hospital production control.

The decision about an optimal patient mix for admission planning of a specialty is part of the fine-tuning at this level to avoid loss of capacity. The optimal patient mix will depend on the characteristics of the patient categories and the amount of resources, made available to the specialty concerned. The outcome will be an admission profile that describes the number of patients and the mix of admitted patients for each day in the planning period, and that has been evaluated on the projected levels of occupancy of the different resources involved. This admission profile can be used as a guideline at the operational level of planning. When admission planning uses the admission profiles as a target mix to be filled in with daily admissions, one may expect results similar to the projections.

### **The model**

In this section we translate the planning problem into a mathematical model in the form of an integer linear program (ILP). In the following two subsections we describe the various factors that are relevant to the planning problem and the mathematical model will be formulated.

#### *Relevant factors*

It will be clear from the discussion in the previous sections that the following factors play an important role in the planning problem:

- (1) *Planning period.* This is the complete time period (typically several months or a year) over which the admittance of patients has to be planned.
- (2) *Patient categories.* There is usually such a wide variety of patients that they need to be categorised – apart from a medical grouping – for planning purposes to make the planning problem more manageable. Patients are in this paper categorised according to their workload for the resources. Patients in the same category have a similar length of stay and require on average the same amount of nursing and operating theatre time.
- (3) *Resources.* The resources considered are beds, IC beds, operating theatres and nursing staff. These are the most important resources that are directly influenced by the inflow of inpatients.
- (4) *Available capacity of the resources.* The bed and IC bed capacity are the total number of beds available to the specialty at the wards and IC unit, respectively. The operating theatre capacity is the total operating time available per day. Nursing workload is measured in terms of a point system that allows for differences in nursing requirements for a patient depending on the stage of the admission; the nursing capacity in terms of full-time equivalents can be translated into the number of points that is available per day. Typically, the availability of resources varies over the planning period, and the capacities will be allocated in a cyclic (e.g. weekly) pattern.
- (5) *Planning cycle.* Since the capacities are allocated cyclically, it is natural to also consider cyclic admission patterns. On one hand, the cycle length should not be too short, because then patients with a low admission occurrence cannot be included in the admission cycle. On the other hand, a long cycle length results in a planning problem that is computationally too big to handle. In practice, the cycle length (i.e. the frequency in which sessions are organized) typically varies from one week to four weeks.
- (6) *Admission profile.* The admission profile describes the inflow of patients, i.e. the number and mix of patients admitted on each day within the planning cycle.
- (7) *Target patient through-put.* The target number of patients that should be admitted within the planning cycle. Of course, this number can be easily deduced from the target number of patients set for the whole planning period.
- (8) *Target utilization of the resources.* This is the desired utilization (or occupancy rate) of the resources on each day of the planning cycle. It should be realised as close as possible.

- (9) *Restrictions on admission profiles.* An admission profile realising the target throughput and resource utilization may still be unacceptable for the specialty for a number of reasons. These reasons include:
- the specialty may want to fix the number of patients from a specific category admitted at a specific day in the admission cycle.
  - the number of patients from a certain combination of categories who can be nursed (or operated) on a single day is limited.

These options will be treated as additional restrictions for admission profiles.

This completes the description of the relevant factors. Clearly, the important decision variable is the admission profile, and the planning problem can now be reformulated as follows: find an admission profile for a given planning cycle such that the desired target utilization of the resources is realised as close as possible, while satisfying the target patient throughput and restrictions.

#### *Mathematical model*

In this subsection we translate the planning problem into a mathematical model. Let  $T$  denote the length (in days) of the planning cycle, and let  $M$  denote the number of patient categories. The patients are categorised according to their workloads for the resources. To describe the workloads of patients from category  $i, i = 1, \dots, M$ , we introduce the following variables:

$b_i$  = number of days that a patient from category  $i$  stays in the hospital and needs a bed;

$p_i$  = number of pre-operative days for a patient from category  $i$ ;

$c_i$  = number of days that a patient from category  $i$  needs an IC bed;

$o_i$  = the operation time (in minutes) for a patient from category  $i$ ;

$n_{it}$  = the nursing workload (in points) for a patient from category  $i$  on day  $t$  of his stay in the hospital, where  $t$  runs from 1 to  $b_i$ .

On each day of his stay in the hospital a patient needs a nursing bed at the wards. Here we assume that a nursing bed is also reserved while the patient is in the IC unit. The number of IC-days are counted with the day of operation as starting point. Typically, the nursing workload is high on the day of operation, after which it gradually diminishes. The workload variables are illustrated in Figure 1. Finally, the target throughput of patient category  $i$  over the planning cycle is denoted by  $THR_i$ .

It is convenient to number the resources, operating theatre, nursing, beds and IC beds, from 1 to 4. For resource  $r, r = 1, \dots, 4$ , we then introduce the following quantities:

$C_{rt}$  = available capacity of resource  $r$  on day  $t$  of the planning cycle;

$U_{rt}$  = target utilization of resource  $r$  on day  $t$  of the planning cycle.

The important decision variables in the planning problem are the number and mix of patients admitted on each day of the planning cycle. Let  $X_{it}$  denote the number of patients from category  $i$  admitted on day  $t$  of the planning cycle. Clearly,  $X_{it}$  is a nonnegative integer. Thus:

$$X_{it} \in \{0, 1, 2, \dots\}, \quad i = 1, \dots, M, \quad t = 1, \dots, T,$$

and they should satisfy the target patient throughput, i.e:

$$\sum_{t=1}^T X_{it} = THR_i, \quad i = 1, \dots, M.$$

We now want to find  $X_{it}$  values, for which the absolute deviation of the realized and target utilization of the resources is minimized. For this problem we introduce the auxiliary variables  $V_{rtk}$  satisfying:

$$V_{rtk} \geq 0, \quad r = 1, \dots, 4, \quad t = 1, \dots, T, \quad k = 1, 2, :$$

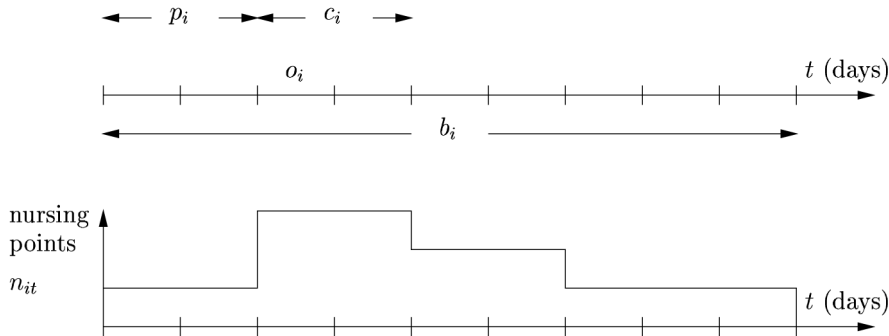
and formulate linear constraints forcing these variables to be equal to the absolute deviation of the realized and target utilization. Below we first explain this for resource 1, i.e. the operating theatre. Since patients of category  $i$  are operated after being  $p_i$  days in the hospital, the realized utilization of the operating theatre on day  $t$  is equal to:

$$\sum_{i=1}^M o_i X_{it-p_i}.$$

Here we adopt the convention that subscript  $t$  in  $X_{it}$  should be read modulo  $T$  (so, e.g.  $X_{iT+1} = X_{i1}$ ). Hence, if we require that:

$$\sum_{i=1}^M o_i X_{it-p_i} \leq U_{1t} + V_{1t1}, \quad t = 1, \dots, T, \quad (1)$$

$$\sum_{i=1}^M o_i X_{it-p_i} \geq U_{1t} - V_{1t2}, \quad t = 1, \dots, T, \quad (2)$$



**Note:**  $b_i = 9$  days,  $p_i = 2$  days and  $c_i = 2$  days

**Figure 1.**  
The nursing workload  
function  $n_{it}$  and the  
different stages of the  
admission over time for  
patients from category  $i$

and minimize the sum:

$$\sum_{t=1}^T (V_{1t1} + V_{1t2}),$$

then it is readily verified that the minimum is realized for:

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$$V_{1t1} = \max \left( \sum_{i=1}^M o_i X_{it-p_i} - U_{1t}, 0 \right), \quad V_{1t2} = \max \left( U_{1,t} - \sum_{i=1}^M o_i X_{it-p_i}, 0 \right).$$

So, indeed,  $V_{1t1} + V_{1t2}$  is equal to the absolute deviation of the realized and target utilization of the operating theatre on day  $t$  of the planning cycle.

For the other resources we formulate constraints similar to equations (1) and (2). That is, for nursing staff, beds and IC beds we subsequently obtain:

$$\begin{aligned} \sum_{i=1}^M \sum_{d=1}^{b_i} n_{id} X_{it-d+1} &\leq U_{2t} + V_{2t1}, & t = 1, \dots, T, \\ \sum_{i=1}^M \sum_{d=1}^{b_i} n_{id} X_{it-d+1} &\geq U_{2t} - V_{2t2}, & t = 1, \dots, T, \\ \sum_{i=1}^M \sum_{d=1}^{b_i} X_{it-d+1} &\leq U_{3t} + V_{3t1}, & t = 1, \dots, T, \\ \sum_{i=1}^M \sum_{d=1}^{b_i} X_{it-d+1} &\geq U_{3t} - V_{3t2}, & t = 1, \dots, T, \\ \sum_{i=1}^M \sum_{d=1}^{c_i} X_{it-p_i-d+1} &\leq U_{4t} + V_{4t1}, & t = 1, \dots, T, \\ \sum_{i=1}^M \sum_{d=1}^{c_i} X_{it-p_i-d+1} &\geq U_{4t} - V_{4t2}, & t = 1, \dots, T. \end{aligned}$$

The realized utilization of the resources may, of course, not exceed the available capacity. Thus:

$$U_{rt} + V_{rt1} \leq C_{rt}, \quad r = 1, \dots, 4, \quad t = 1, \dots, T.$$

Then, minimizing the absolute deviation of the realized and target utilization of the resources amounts to minimizing the sum:

$$\sum_{r=1}^4 w_r \sum_{t=1}^T (V_{rt1} + V_{rt2}). \quad (3)$$

In this sum, the absolute deviation of the utilization of resource  $r$  is weighted with coefficient  $w_r$ , defined as:



$$w_r = \frac{a_r}{\sum_{t=1}^T U_{rt}}.$$

where  $a_r$  is some nonnegative number. The coefficients  $w_r$  are introduced (i) to make the sum dimensionless (i.e. independent of the units used) and (ii) to control the relative importance of the resources (by means of  $a_r$ ).

Finally, we have to take into account the restrictions on admission profiles mentioned in the previous section. The first restriction just means that we fix certain variables  $X_{it}$  to prescribed values. For the second restriction we introduce  $B$  indicating the maximum number of patients from categories  $i \in S$  that can be nursed on a single day, where  $S$  is a subset of  $\{1, \dots, M\}$ . Then, the second restriction translates to:

$$\sum_{i \in S} \sum_{d=1}^{b_i} X_{it-d+1} \leq B, \quad t = 1, \dots, T.$$

Summarizing, our planning problem can be formulated as the following ILP:

$$\min \sum_{r=1}^4 w_r \sum_{t=1}^T (V_{rt1} + V_{rt2})$$

subject to:

$$\begin{aligned} \sum_{t=1}^T X_{it} &= THR_i, i = 1, \dots, M, \\ U_{1t} - V_{1t2} &\leq \sum_{i=1}^M o_i X_{it-p_i} \leq U_{1t} + V_{1t1}, & t = 1, \dots, T, \\ U_{2t} - V_{2t2} &\leq \sum_{i=1}^M \sum_{d=1}^{b_i} n_{id} X_{it-d+1} \leq U_{2t} + V_{2t1}, & t = 1, \dots, T, \\ U_{3t} - V_{3t2} &\leq \sum_{i=1}^M \sum_{d=1}^{b_i} X_{it-d+1} \leq U_{3t} + V_{3t1}, & t = 1, \dots, T, \\ U_{4t} - V_{4t2} &\leq \sum_{i=1}^M \sum_{d=1}^{c_i} X_{it-p_i-d+1} \leq U_{4t} + V_{4t1}, & t = 1, \dots, T, \\ \sum_{i \in S} \sum_{d=1}^{b_i} X_{it-d+1} &\leq B, & t = 1, \dots, T, \\ U_{rt} + V_{rt1} &\leq C_{rt}, & r = 1, \dots, 4, \quad t = 1, \dots, T, \\ V_{rt1} &\geq 0, \quad V_{rt2} \geq 0, & r = 1, \dots, 4, \quad t = 1, \dots, T, \\ X_{it} &\in \{0, 1, 2, \dots\}, & i = 1, \dots, M, \quad t = 1, \dots, T. \end{aligned} \tag{4}$$

### *Solution approach*

To solve equation (4) we used the solver MOMIP. This is an optimization solver for middle-sized mixed integer programming problems, based on the branch-and-bound algorithm. It has been developed by W. Ogryczak and K. Zorychta from the International Institute for Applied Systems Analysis (IIASA)[1]. A nice feature of this solver is that it allows the user to control the computation time (by limiting the number of nodes examined), of course, without guarantee to find the optimal solution. In the application presented in the next section we bounded the computational effort for each scenario, and always found a good (but maybe not optimal) solution in a few minutes computer time on an ordinary PC. The model has been implemented in a decision support system.

### **Application**

The model has been applied to the specialty of orthopaedics in a general hospital setting. In a separate paper we have illustrated the process of applying the model for this planning problem and the managerial context. Here, we concentrate on illustrating the model. We will first discuss the input of the model, then show some analyses to illustrate the correct working of the model, and finally discuss results of the application of the model to orthopaedics.

### *Input*

In this section the input of the model will be discussed, using data of orthopaedics in a medium-sized general hospital with 450 beds and four orthopaedic surgeons.

*Patient inflow and throughput.* In 1998 about 760 inpatients were admitted and 700 day-cases. About 20 per cent of the inpatients were admitted as emergencies (and thus not included in this study), while the remaining were admitted on an elective basis using a waiting list. Day-cases are always elective admissions. The average length of stay of inpatients (exclusive day-cases) is 12.4 days. In total 11 categories of patients are distinguished in the inflow of orthopaedics; these categories were meaningful for the admissions planning department and the orthopaedic surgeons, but have also different resource requirements.

Based on the actual admissions per week, we will use the inflow of week 12 in 1998 as a representative inflow pattern, but also use an average inflow pattern, based on the annual output. Table II provides information on the number of admissions per category of patients in the sample week and the average week.

*Demand requirements.* The patient categories can be characterised on a number of features, such as length of stay, nursing workload, day and duration of operation, and use of IC-beds. These features are given in Table III. The nursing workload profile is expressed in number of days with *Z* workload (five points), number of days with *M* workload (two points) and number of days with *L* workload (1 point). For example, the workload in Figure 1 would be expressed as *L2Z2M2L3*. The workload points refer to the amount of nursing work to be done for a patient category, based for instance on the San

Patient category	Patient mix week 12	Patient mix average
1	14	13
2	2	1
3	0	1
4	1	2
5	0	1
6	0	1
7	1	2
8	3	1
9	2	2
10	1	1
11	2	1
Total	26	26

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**Table II.**  
Number of admissions  
per category of  
patients in the sample  
week and the average  
week

Patient category	Length of stay (days)	Nursing workload	Day of operation	Operation duration (min.)	IC-days
1	1	L1	1	20	0
2	1	M1	1	30	0
3	2	M1L1	1	38	0
4	3	M2L1	1	40	0
5	4	M2L2	1	50	0
6	5	M3L2	1	46	0
7	9	Z4M4L1	2	77	0
8	14	Z6M6L2	2	70	0
9	18	Z6M8L4	2	80	0
10	24	Z24	2	120	1
11	29	Z29	2	92	0

**Table III.**  
Characteristics per  
category of patients

Joaquin system. Day of operation = 1 implies that the patient is operated on the day of admission. IC days are counted from the day of operation as reference point.

*Available resources.* Orthopaedics has 28 beds allocated at the ward, including beds for short-stay and day-surgery. The four orthopaedic surgeons have each day operating theatre sessions, in total six hours a day. There are about 12 full-time equivalent nurses available for the ward, but nursing capacity is expressed in terms of nursing points. On Wednesday one IC-bed is reserved for elective admissions from category 10. Table IV summarises the available resources for orthopaedics.

As one can see, the availability of resources is less during the weekend. During the weekend there is no operating theatre capacity available and no IC-beds; also there are no short-stay beds available and the nursing staff is less.

*Capacity load factors and resource importance.* The different resources each have a target occupancy level, which defines the level of occupancy that reflects a realistic target workload. This can be different during the weekend. Table V provides information on the target occupancy level for each type of resource.

The above-mentioned data are required to describe the production system of the specialty. The extra input required for the mathematical model is the weight function for the optimization, and information on restrictions imposed on the planning problem.

Table VI gives the weights  $a_r$  used to reflect the relative importance of the different resources involved, according to the participants in the hospital. The weight range used is the following: 0 = ignore, 1 = not important, 2 = barely important, 3 = medium importance, 4 = important, 5 = very important.

As one can see, operating theatres and IC-bed use are considered here as very important, bed use is considered as important, and nursing workload is considered as of medium importance. The weights chosen are in this case a subjective reflection of the relative importance in the eyes of the participants involved. An alternative, more objective approach would have been to make the weights dependent on historical data, for instance on the frequency of resources to act as bottleneck.

*Restrictions.* In reality many restrictions can play a role that will make it difficult to realize a feasible admission profile. We will illustrate this feature of

**Table IV.**  
Available resources for  
orthopaedics

Day of the week	Operating theatre (min.)	Nursing (points)	Beds (number)	IC-beds (number)
Monday	360	80	28	0
Tuesday	360	80	28	0
Wednesday	360	80	28	1
Thursday	360	80	28	0
Friday	360	80	28	0
Saturday	0	70	20	0
Sunday	0	70	20	0

**Table V.**  
Target occupancy  
levels per type of  
resource

Day no.	Operating theatres (%)	Nursing (%)	Beds (%)	IC-beds (%)
1	85	95	90	0
2	85	95	90	0
3	85	95	90	100
4	85	95	90	0
5	85	95	90	0
6	0	95	80	0
7	0	95	80	0

**Table VI.**  
Relative weights per  
type of resource

Resource type	Weight
Operating theatres	5
Nursing	3
Beds	4
IC-beds	5

the model with two examples of restrictions in the case of orthopaedics. The first restriction that plays a role in the planning problem is that category 6 patients, having a length of stay of five days, need to be admitted on Monday in order to have them discharged before the weekend. Furthermore, the number of category 1 patients is limited to six patients a day from Monday to Friday, in order to avoid a concentration of day-surgery patients (leading to extra handling for the nurses) on one day.

### *Sensitivity analysis*

This section contains results produced by the model to illustrate the model's behaviour on the use of the weighting function for the relative importance of the different resources. The outcomes provide evidence that the model indeed does what it should do.

We will start with the current setting for the weighting function provided in Table VI, and use the average weekly throughput of patients in Table II. The other parameters are set according to the settings in the current situation described before. Clearly, we are looking for a weekly admission profile. The output of the model for the current setting is shown in Table VII (utilization figures) and Table VIII (admission profile). The numbers between parenthesis indicate the relative weights used.

Day no.	Operating theatres (5)		Nursing (3)		Beds (4)		IC-beds (5)	
	Target	Realized	Target	Realized	Target	Realized	Target	Realized
1	306	293	76	76	25	25	0	0
2	306	272	76	77	25	25	0	0
3	306	200	76	76	25	22	1	1
4	306	90	76	76	25	23	0	0
5	306	245	76	75	25	25	0	0
6	0	0	66	64	16	16	0	0
7	0	0	66	65	16	16	0	0

**Table VII.**  
Model output for the  
current setting

Day no. category	1	2	3	4	5	6	7
1	4	3	0	1	5	0	0
2	0	0	0	0	1	0	0
3	0	0	0	0	1	0	0
4	1	1	0	0	0	0	0
5	1	0	0	0	0	0	0
6	1	0	0	0	0	0	0
7	0	0	0	1	0	0	1
8	0	0	1	0	0	0	0
9	1	1	0	0	0	0	0
10	0	1	0	0	0	0	0
11	1	0	0	0	0	0	0

**Table VIII.**  
Admission profile for  
current setting

As can be seen from Table VII, operating theatre utilization shows the least performance due to an over-capacity that is made available to orthopaedics. The use of beds follows the target line reasonably well and the nursing workload and the IC-use are according to the target lines. The score of the solution, based on the objective function given by (3), is 1.561. This score quantifies the quality of the solution, and therefore, it can be used to compare different solutions. The weekly admission profile suggested by the model is shown in Table VIII.

As can be seen from Table VIII, the restrictions regarding patient categories 1 and 6 have been dealt with properly. Also, the category 10 patient is admitted on Tuesday to be in need of an IC-bed on Wednesday.

Suppose we reduce the operating theatre resources to find a better fit between demand for and supply of resources. Table IX shows the results in case we reduce the operating theatre resources available to orthopaedics to 260 minutes a day. Taking into account the target occupancy level of 85 per cent, the target capacity then becomes 221 minutes.

Table IX shows that the reduced operating theatre capacity is sufficient to handle the demand, and the occupancy lines follow the target lines reasonably well. The objective function score of this solution is 0.530. This shows that the deviations from the target lines in Table IX are less than the deviations in Table VII.

Suppose we change the weight function, focusing on optimizing one resource type, say operating theatres; we give operating theatres' capacity a maximum weight of 5 and the other resources a minimum weight of 1. Table X shows the results of this change in the parameter setting of the weight function.

As can be seen from Table X, the use of operating theatre capacity has improved (smaller sum of differences) and the use of beds and nursing workload have slightly worsened; the use of the IC-beds is unaltered. Though the changes are small compared to the results in Table IX, the direction of the changes follows, nonetheless, the setting of the weights.

Results

Focusing on the contribution of mathematical model to the planning problem of orthopaedics, we will illustrate this with output of the model for the following situations:

Day no.	Operating theatres (5)		Nursing (3)		Beds (4)		IC-beds (5)	
	Target	Realized	Target	Realized	Target	Realized	Target	Realized
1	221	243	76	73	25	22	0	0
2	221	220	76	77	25	24	0	0
3	221	200	76	78	25	23	1	1
4	221	227	76	77	25	25	0	0
5	221	210	76	74	25	25	0	0
6	0	0	66	64	16	16	0	0
7	0	0	66	64	16	17	0	0

**Table IX.**  
Model output for the current setting with reduced operating theatre capacity

- What if we use the programme of week 12, the sample week, in combination with the original settings?
- What is an adequate availability of resources for the average week programme?

We first evaluate the feasibility of the programme of week 12 (see Table II). The total number of patients is the same as for the average week programme, but there is a substitution towards patient categories requiring more resources (categories 8 and 11). Using the model for this inflow of patients results in no feasible admission profile found within the restrictions defined for the planning problem. Looking at Table VII, one may suspect that the nursing capacity and the bed capacity have acted as bottlenecks obstructing a feasible admission profile, and not the operating theatre capacity. The conclusion is that the programme of week 12, though the number of patients is adequate, has a mix of patients that does not fit within the capacity constraints for orthopaedics. Probably, the orthopaedic surgeons have only considered the operating theatre capacity, when deciding the week programme, and not bed and nursing capacity.

So, the first decision orthopaedics has to make is the week programme that reflects the maximum number and mix of patients that can be admitted as elective patients, given the capacity constraints. This can be calculated from the target volumes at annual level, given the number of weeks operating theatres are available to orthopaedics. Perhaps it is necessary to make different week programmes for each season, but in total it has to result in the annual target volumes.

Suppose we use the average week programme as given in Table II, how many resources do we need then to adequately fit the demand of resources? We follow a stepwise procedure. First we observe in Table IX that operating theatre capacity is on average at the target level, so further reduction will not be wise. The only resource worthwhile to consider is the bed capacity. By reducing the bed capacity during the week to 27 beds, we arrive at the results shown in Table XI.

Clearly, there are different answers possible to the question put forward concerning the amount of resources that would adequately fit to the demand required for the average week programme, but the solution presented does

Day no.	Operating theatres (5)		Nursing (1)		Beds (1)		IC-beds (1)	
	Target	Realized	Target	Realized	Target	Realized	Target	Realized
1	221	206	76	69	25	21	0	0
2	221	222	76	76	25	25	0	0
3	221	220	76	79	25	24	1	1
4	221	232	76	80	25	24	0	0
5	221	220	76	78	25	25	0	0
6	0	0	66	65	16	16	0	0
7	0	0	66	62	16	17	0	0

**Table X.**  
Model output with  
maximum weight for  
operating theatre use

show good results. The objective function produces a score of 0.206. This is a better fit compared to the fit in Table IX with a score of 0.530.

Up to now we only considered flat lines, with a shift of level during the weekend. One step further would be to consider solutions with a different amount of resources allocated within the days of the week. Suppose we increase the operating theatre capacity in the beginning of the week, decrease the operating theatre capacity at the end of the week, and also make some changes to the bed resources available at the end of the week. See Table XII for the allocations used per day, and the results.

As can be seen from Table XII, by allocating more operating theatre resources and bed resources in the beginning of the week but increasing the number of beds available during the weekend, we seem to get a better fit between demand and supply. The objective function score is 0.235, showing, however, that this solution is slightly worse than the one in Table XI. As both scores are almost equal one could say that both solutions are resulting in a similar performance. The amount of resources used in Table XII is similar to that in Table XI: the amount of operating theatre capacity used is nearly the same, the nursing capacity is better and the number of beds used is slightly worse. Perhaps a similar approach to the allocation of nursing capacity (following the availability of beds) would result in a small improvement in the use of nursing capacity. The day-dependent allocation makes it possible to reflect better the resource demands caused by the short-stay policy followed for many orthopaedic patients. On the other hand, the fixed allocation is perhaps

**Table XI.**  
Finding the proper  
allocation of resources

Day no.	Operating theatres (5)		Nursing (3)		Beds (4)		IC-beds (5)	
	Target	Realized	Target	Realized	Target	Realized	Target	Realized
1	221	216	76	77	24	24	0	0
2	221	227	76	75	24	23	0	0
3	221	220	76	77	24	24	1	1
4	221	217	76	79	24	24	0	0
5	221	220	76	74	24	24	0	0
6	0	0	66	66	16	17	0	0
7	0	0	66	61	16	16	0	0

**Table XII.**  
Results for varying  
amounts of allocated  
capacity per day

Day no.	Operating theatres (5)		Nursing (3)		Beds (4)		IC-beds (5)	
	Target	Realized	Target	Realized	Target	Realized	Target	Realized
1	238	238	76	73	24	23	0	0
2	238	235	76	77	24	25	0	0
3	222	217	76	76	24	23	1	1
4	204	200	76	77	22	22	0	0
5	204	210	76	73	22	22	0	0
6	0	0	66	66	18	19	0	0
7	0	0	66	67	18	18	0	0



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more easy to implement, and does not result in a loss of performance, provided that the right level of resources is available.

## Conclusions

Based on the results described in the previous section, we can conclude that the model is able to generate a good admission profile per category. With a good admission profile we mean a profile that results in a small deviation between the realised and the target resource utilization, while the total available capacity of the different resources is not exceeded, the target patient throughput is met and the given restrictions are not violated. We also demonstrated that the model can be used to tune the level of availability of resources to the demand.

A serious limitation of our work is that it excludes the emergency flow. A model with this limitation is, therefore, more supportive for a specialty with a low percentage of emergency (e.g. orthopaedics) than for a specialty with a high percentage of emergency (e.g. general surgery). In a follow-up project we are developing a model that will deal with both flows, the elective and emergency flow. Further research and development is required to develop planning policies for defining reserve capacity for emergency patients, and buffer capacity required to cope with variations in the resource requirements per patient category.

## Web resource

1. <http://www.iiasa.ac.at/Publications/Documents/WP-96-106.pdf>

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