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A comprehensive mathematical model for the scheduling problem of the elective patients considering all resources and the capacity of the postoperative care unit: A case study

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Abstract

Surgical theater consists of operating and recovery rooms and includes a major part of the costs and revenues of a hospital. Moreover, the different wards of the surgical theater are in a wide relationship with the other wards of the hospital and influence them. Thus, improving the performance of the surgical theater not only increases its profitability, but also it increases the quality of the provided services in the other wards. Hence, the scheduling of the surgical theater is a crucial and challenging affair. In this study, we present a new and comprehensive model for the daily scheduling of the elective patients by considering all resources as well as the capacity of the postoperative care units. Moreover, we aim to minimize the underutilization and overutilization cost of the operating rooms by considering the other constraints in the surgical theater such as availability of the operating rooms, surgeons, equipment, human resources, and non-renewable resources. Finally, a real-life example is provided to show the applicability of the proposed model and evaluate its performance in comparison with the actual schedule suggested by the operating room manager. The results showed that the proposed model has a better performance in comparison with the actual schedule used in the hospital.

Keywords: Linear mixed integer model; scheduling of elective surgeries; all resources; the postoperative care unit

1. Introduction

Healthcare and hygiene have long been known as a form of the human development. In recent decades, a wave of studies and experimental researches has been performed on the impact of health on the economic development so that some studies like the research of Magerlein and Martin [1] have shown that the role of health and hygiene in the economic development of the countries has not been less than that of education. Thereby, in recent years, the investment and costs in healthcare has been seriously paid attention by the governments and the effects and type of these costs have been investigated by their scientific societies.

Aggressive growth of population and the medical needs of the people as well as increasing and rapid growth of the serving costs have made the way of controlling these costs as the fundamental problem of the healthcare system of the different countries. During the recent years, these health costs have had ascending approach in Iran as a developing country. Thus, regarding to the government's limited resources and growing population in the near future, the health managers will face a lack of resources. One of the main parts of healthcare and hygiene involved a major part of budgets are the hospitals. Hence, it is vital to use appropriate tools in order to efficient management of hospitals.

Given that the surgical theater is the most high-income and expensive ward of a hospital, the decision made in this unit widely influence in the overall performance of the hospital [2]. Of course, the management of the surgical theater is a difficult and complex task due to the existence of conflicting priorities and preferences of their stakeholders[3]and efficient decision-makings may lead to coordination among all surgeries and available resources such as operating rooms, surgeons, beds and nurses and consequently improvement of the performance of the surgery theater. Proper scheduling and planning of surgeries in the surgery theater based on the available resources is one of the methods may lead to the improvement of the surgery theater and decrease its costs. This issue includes allocating resources (operating rooms, surgeons, anesthetists and operating room technicians, equipment, etc.) For the patients and determining the starting time of the surgical operations on one or more resources in series or parallel form.

According to the framework presented by Hans and Nieberg [4] planning and scheduling of the operating rooms is divided into four levels in the managerial approach: long-term (strategic), medium-term (tactical, offline short-term, and online short-term (technical). Several decisions are made at each level and they are classified into four categories based on the proposed framework: medical, planning the resources' capacities, planning and coordination of materials, and the financial planning. Usually in the long-term level, achieving the purposes in long time horizon such as a few years is desired. Planning in medium-term level investigates the use of available resources in shorter timescales. Planning in short-term level investigates a timescale of one or more days more accurately. The offline planning is called to the planning before running the program. Daily scheduling of patients and allocating the required resources such as the operating room, medical equipment and surgeon, sequence of the surgical operations, daily analyses concerning the operating rooms' costs and so on are categorized in the decisions of the offline short-term level. The aim of online short-term planning is to investigate and control the scheduling of the patients and updating the program. The changes occurred in the offline planning due to the happening of the unpredicted events such as the entrance of the emergency patients, changes in the predicted time, etc. are addressed in the online scheduling. In this study, we have investigated the operating room in the offline short-term level.

The aim of this study is to present a comprehensive mixed integer model for the daily scheduling problem of the elective patients in the operating rooms of general surgeries in Baqiyatallah Hospital considering the capacity of the postoperative care units. In the proposed model, we have considered the constraints such as the number and availability of the recovery beds, specialized equipment, non-renewable material, available human resources, and availability of the surgeons and time window of surgeries. The objective is to minimize the cost related to underutilization and overutilization of the operating rooms. Regarding to the comprehensiveness of the proposed model and considering all required resources for conducting a surgery, the presented model in this study can be used as a managerial tool in order to facilitate the decision-making of the hospital managers and optimal use of the resources.

The structure of the study is as following: in section 2, we review some the previous similar studies in this filed, i.e. the planning and scheduling problem of operating rooms. In section 3, the problem is defined and a comprehensive model for scheduling the operating room are addressed. In section 4, the proposed model is assessed by GAMS software and a real example. Finally, the conclusion will be provided in the last section.

2. Literature review

The activities of researchers to study the issues of health field have been started from about 60 years ago; but a significant volume of the conducted researches and studies are related to after the year 2000, so that a half of the literature related to the year 2000 afterwards. In this section, to avoid burbling and direct the reader towards the research subject better, just the papers in the field of scheduling and planning the operating room have been investigated and the literature of the managerial and immense fields have not been reviewed.

The first paper was a review on the scheduling of the surgical operations presented by Magerlein and Martin [1]; they classified the existing papers based on the type of solving technique and divided the time of surgical operations into two sub-stages of the advance scheduling and allocating scheduling. The advance scheduling is the process of determining the day and the operating room of surgical operation for each patient; while the allocating scheduling determines the start time of the surgery in the previous sub-stage. Blake and Carter [5] developed this classification and added a third process to it under the title of the external resources' scheduling in which the reservation and the required resources before and after each surgical operation were determined. Each of these stages was investigated in three levels of strategic, executive, and operative. Moreover, some other review studies were provided by Smith-Daniels, Schweikhart and Smith-Daniels [6] and Yang, Sullivan, Wang and Naidu [7] who investigated the management fields in the strategic and tactical levels of hospital planning, too.

In a review study, using investigating more than 100 researches, Cardoen, Demeulemeester and Beliën [8] have concluded that the major part of papers in the field of scheduling the operating room has been in strategic and nonfunctional level and there have been a few numbers of functional papers. The results of their review showed that in most studies, the optimization of the healthcare systems had been done using research operation and linear planning methods. Integer planning for scheduling problems has been useful when the decision variables have been limited to the integers. The simulation techniques have been used more when there has been uncertainty. In another review study, Bai, Fügener, Schoenfelder and Brunner [9] investigated the conducted studies concerning the scheduling filed of the intensive care unit from different views such as the decision-making horizon, the model type and the solving techniques. Here, we assess some of the papers related to the current study.

Some researchers such as Jebali, Alouane and Ladet [10] and Guinet and Chaabane [11] have addressed the surgeries' scheduling problem as a two-stage flow shop problem; so that they have considered the operating rooms in the first phase and the recovery rooms in the next phase of the problem. Jebali, Alouane and Ladet [10] have considered the two-phase daily planning and scheduling problem of the surgery operations. In the first phase, the surgery assigned to the operating rooms. Then in the second phase, the sequence of the surgeries is determined in each operating room. In addition to the surgical operations, the conducted processes before and after the operation and the constraints related to the existing resources have been considered. Guinet and Chaabane [11] scheduled patients by considering several objectives, including reducing the patients' waiting time, overutilization, and makespan. In their study, all parameters have been considered deterministic; and in the first phase, firstly special days and rooms are allocated to the patients in order to minimize their waiting time. Then, by considering the capacity of the recovery room, scheduling is done so that to minimize the discharging time of the last patient. In both of the previous studies, the limited availability of nurses and anesthetists has not been considered and only the availability of the surgeon has been taken into account in their models.

With the aim of maximizing the efficiency of the operating room, Vijayakumar, Parikh, Scott, Barnes and Gallimore [12] presented a model in which the elective patients are allocated to the operating rooms, days, time slots, and surgeons regarding to their priorities. In their model, they considered the constraints such as the number of available nurses, equipment, and the window time of the surgeons' availability. Molina-Pariente, Fernandez-Viagas and Framinan [13] addressed the planning and scheduling of the operating rooms as a job shop problem. They considered more than one surgeon in the surgical team as well as the experience of the surgery residents at the time of surgeries. Aringhieri, Landa, Soriano, Tànfani and Testi [14] presented a model to allocate surgeons and elective patients to the time slots simultaneously with the aims of minimizing the cost of waiting time of the patients and enhancing the efficiency of hospital. A two-phase meta-heuristic method has been developed to solve this problem. In all three previous studies, the recovery unit after surgery ignored; while Augusto, Xie and Perdomo [15] indicated that considering the recovery unit in the planning and scheduling problem of the operating rooms may generate impossible solutions in the real world, and this indicates the significance of considering the recovery unit.

Min and Yih [16] has also offered a stochastic model to select the number of patients with different priorities in each period. In this model, the duration of the surgical operations and the time of residence in the intensive care unit (ICU) have been considered as stochastic parameters. The patients' priority has been also determined regarding to the doctor's diagnosis and based on three factors of pain, disease progression status, and disability of patients. After that, Jebali and Diabat [17] developed the model of Min and Yih [16] through adding wards to it. Lodi and Tubertini [18] presented a mixed integer model for scheduling the elective patients as well as surgeons. They also considered the preoperative activities in this scheduling. Saadouli, Jerbi, Dammak, Masmoudi and Bouaziz [19] used a three-phase simulation and optimization approach in order to schedule the elective patients and planning the recovery beds. In the first phase, they firstly selected the list of elective patients through using a backpack problem. Then, in the second phase, through a mixed integer model, they allocated the selected elective patients to the operating rooms so that to decrease makespan and the total waiting time of patients. Without considering the limitations related to the human resources and specialized equipment, they determined the sequence of surgeries, according to SPT rule (surgery with shorter time, should be started earlier). Finally, they evaluated the proposed model compared to the real scheduling through the event-based simulation model.

As it is surfaced from reviewing the above-mentioned papers, most papers have not considered the all material resources needed to conduct surgical operations in surgery theater. In addition, most papers have not considered all surgical team personnel in their studies and just have concentrated on the availability of surgeons. Therefore, the main contributions of this study are the simultaneous consideration of all required resources for conducting the surgical operation including surgeons, nurses, anesthetist, specialized equipment, non-renewable material, operating room beds, and recovery beds in a comprehensive and new mathematical modeling framework. This model can be used by the manager of the operating room as a helpful tool.

3. Problem definition and mathematical model

The surgical theater consists of two sections of operating rooms and recovery unit. After the entrance of each patient to the surgical theater, a bed should be allocated to his/her surgery. As well, a surgical team including at least two nurses (scrub and circular), an anesthesiologist and a surgeon should be formed for conducting the operation. Regarding to the specialty class of each surgery, they require specialized equipment which their availability should be assured during the surgery. It should be noted that because of safety and comfort of patients, a time window is determined for conducting their surgery. After surgery, the patients will occupy a bed in the recovery room or intensive care unit according to his/her conditions and the type of the conducted surgery. If each resource in each stage of conducting the surgical operation will not be available, the surgery may be cancelled or delayed which consequently lead to efficiency reduction and dissatisfaction of the stakeholders (patient, surgeon, operating room manager, etc.). This clearly shows the significance and the necessity of simultaneous considering of the mentioned cases in the planning and scheduling problem of the patients that has been taken into account in this study.

3.1. The model

In this section, we have presented a comprehensive linear mathematical model for the planning and scheduling problem of patients in the surgical ward of Baqiatallah Hospital in Tehran through considering all effective resources in conducting surgeries. According to this mathematical model, we should determine that which each surgery assignment to operating rooms and its starting times.

The assumptions considered in the problem are as follows:

- All patients are prepared for surgery at the beginning of the time horizon.
- The time of surgery operations has been considered deterministic and is equal to the average time for that surgery based on historical data.
- The operating rooms are opened and closed in certain time unless there is overtime, i.e. the operating room has to conduct surgery after the regular opening hours.
- The overutilization hours of the operating room cannot be more than a certain limit.
- Surgeries are not interrupted during an operation.
- The surgeon of each surgery operation is previously determined.
- No surgeon is allowed to participate in the surgery of more than one patient.
- Each hour is divided into 30-minute slots.

First, we will define the indices, parameters and decision variables of the problem as table (1), and then, we will present the proposed model.

Table 1- Indices, parameters, and decision variables.

Indices	Descriptions
m:	Operating room index $m \epsilon \{1,2,\dots,M\}$
t:	Index of time slots $t \epsilon \{1,2,\dots.H,\dots,T\}$
T':	The total number of opening periods PACU
s:	Surgeries index $s \epsilon \{1,2,\dots.,S\}$
c:	Surgeons index $c \epsilon \{1,2,\dots.,C\}$
S_c:	The set of surgeries under the responsibility of surgeon c
Parameters	**Descriptions**
cu^m:	The underutilization cost of each unit of operating room *m*
co^m:	The overutilization cost of each unit of operating room *m*
G:	A large amount
H:	The total number of time slots until the end of the regular working hours of the operating room
$A(c,t)$:	If the surgeon c is available in time slot *t*, it takes one, otherwise zero
R_s^e:	The number of renewable resources *e* required for the surgery *s*
A_t^e:	The number of the renewable resources *e* in the time slot *t*
a_s^v:	The required time for recovery of the surgery *s* in PACU
Re^v:	The total amount of the non-renewable resources
$dPACU(s)$:	The required time for the recovery of surgery *s* in the PACU ward
$NP(t)$:	The total number of PACU beds available in the time slot *t*
$ES(s)$:	The earliest possible time to start the surgery *s*
$LS(s)$:	The latest possible time to finish the surgery *s*

Decision variables	Descriptions
Y_{sm}:	Id the surgery *s* is started in the operating room *m*, it takes the value of one, otherwise the value of zero
N_{smt}:	If the surgery *s* in the time slot *t* occupies the operating room *m*, it takes the value of one, otherwise the value of zero
ST_s:	The start time of operation *s*
CT_s:	The end time of operation *s*
CT'_s:	The end time of recovery for surgery *s*
Z_{st}:	If the surgery *s* in the time slot *t* occupies the one bed in PACU, it receives the value of one, otherwise the value of zero
$over^m$:	The overutilization of the operating room *m*
$under^m$:	The underutilization time of the operating room *m*

This objective function is related to the minimization of costs, including the costs of underutilization (the first part) and overutilization (the second part) of the operating rooms as follow:

$$Min\ \ \sum_m under^m \times cu^m + \sum_m over^m \times co^m \qquad (1)$$

Constraint (2) states that in each period, each surgery is performed in at most one room.

$$\sum_m N_{smt} \leq 1 \qquad \forall t \in T, \forall s \qquad (2)$$

Constraint (3) ensures in each period, at most one surgery is conducted in each operating room.

$$\sum_s N_{smt} \leq 1 \qquad \forall t \in T, \forall m \qquad (3)$$

Constraint (4) states that each patient must be assigned to one room.

$$\sum_m Y_{sm} = 1 \qquad \forall s \qquad (4)$$

Constraint (5) states if a surgery is assigned to a room, it will occupy d(s) time slots in that rooms.

$$\sum_{t=1}^{T} N_{smt} = Y_{sm} \times d_s \qquad \forall s, \forall m \qquad (5)$$

Constraint (6) ensures if the surgeon c is not available in a time slot, no surgery should be performed by him/her in that time slot.

$$\sum_m \sum_{s|s\in S(c)} N_{smt} \leq A(c,t) \qquad \forall c, \forall t \in T \qquad (6)$$

Constraint (7) shows the start time of a surgery.

$$ST_s \leq t\sum_m N_{smt} + G(1-\sum_m N_{smt}) \qquad \forall s, \forall t \in T \qquad (7)$$

Constraint (8) shows the completion time the surgery.

$$CT_s \geq (t+1)\ \sum_r N_{smt} \qquad \forall s, \forall t \in T \qquad (8)$$

The occupied periods for conducting a surgery in a room are equal to the time difference between the start time and the end time of the operation. Constraint (9) ensures the occupied periods are consecutive.

$$\sum_{t=1}^{T} \sum_m N_{smt} = CT_s - ST_s \qquad \forall s \qquad (9)$$

Constraint (10) states the number of the renewable resources (equipment, nurses and anesthesiologist) required for conducting operations in all rooms in each time slot should be less than the available number of each period.

$$\sum_s \sum_m R_s^e \times N_{smt} \leq A_t^e \qquad \forall t \in T, \forall e \qquad (10)$$

Constraint (11) states the non-renewable materials used in each day should be at most equal to their available amount in that day.

$$\sum_s \sum_m \sum_{t=1}^{T} Y_{sm} \times a_s^v \leq Re^v \qquad \forall v \qquad (11)$$

Constraint (12) states which for the patient needed PACU after performing her/his surgery, he/she should occupy a recovery bed as equal to the required time for recovery.

$$\sum_{t=1}^{T'} Z_{st} = dPACU(s) \qquad \forall s \in PACU \qquad (12)$$

Constraint (13) shows the exit time of the patient from PACU.

$$CT_s' \geq (t+1) \times Z_{st} \qquad \forall t \in T', \forall s \in PACU \qquad (13)$$

Constraint (14) makes the occupied time slots for recovery be consecutive.

$$\sum_{t=1}^{T'} Z_{st} \leq CT_s' - CT_s \qquad \forall s \in PACU \qquad (14)$$

Constraint (15) states the number of occupied recovery beds in each period should not be more than the available number.

$$\sum_s Z_{st} \leq NP(t) \qquad \forall t \in T' \qquad (15)$$

Constraint (16) shows the underutilization time of each operating room.

$$under^m \geq H - \sum_o \sum_{t=1|t\leq H}^{T} N_{smt} \qquad \forall m \qquad (16)$$

Constraint (17) shows the overutilization of each operating room.

$$over^m \geq t\sum_s N_{smt} - H \qquad \forall m, \forall t \in T \qquad (17)$$

Constraints (18) and (19) indicates that in order to comfort and safety of the patient, his/her surgery should be conducted in the interval [$ES(s), LS(s)$].

$$ST_s \geq ES(s) \quad \forall s \tag{18}$$

$$CT_s \leq LS(s) \quad \forall s \tag{19}$$

Constraint (20) shows the domain of variables.

$$N_{smt}, Y_{sm}, Z_{st} = \{0,1\}, ST_s \geq 0, CT_s \geq 0, CT'_s, over^m \geq 0, under^m \geq 0 \tag{20}$$

4. A real example

In order to evaluate the performance of the mathematical model, we employed a real example, according to a normal day in the general surgery theater on Baqiyatallah Hospital in Tehran where we have focused on operating rooms devoted to the General surgery in morning and evening shifts. In the considered day, 20 patients are applicant in conducting surgery and each of them should be operated in one of the three operating rooms devoted to the General surgery and after the operations, they should occupy one of four available recovery beds specialized in general surgery in their recovery duration. The surgery theater is usually available from 8:00 to 18:30. At most, it can be opened for an overtime of an hour and a half. Hence, totally it is available for 24 30-minutes periods. To conduct all general surgeries, a suction device, monitoring and two nurses, including one scrub and one circular, an anesthesia technician, an anesthesiologist and a surgeon are needed. In the considered day, there are 2 suction devices, two monitoring devices, six nurses, three anesthesiologists, three anesthesia technicians, and five surgeons available. The cost of underutilization and overutilization has been set 3200000 Rial(monetary unit) and 4800000 Rial(monetary unit) per hour respectively based on the opinion of the hospital financial manager .The other information considered related to the real example is shown in Tables (3) and (4). The real example is solved by the CPLEX solver in GAMS software and the optimal solution obtained by the software is shown in the Figure (1). In addition, the proposed scheduling obtained by the operating room manager is shown in the Figure (2). It is noteworthy that providing of the scheduling offered by the operating room manager took about 10 minutes; while the scheduling obtained by GAMS software through solving the proposed model only took 16.75 seconds. As Figures (1) and (2) show, the obtained scheduling using the mathematical model benefits from lower costs (4800000 Rials) compared to the proposed schedule by the operating room manager (8800000 Rials). This indicates the appropriate performance of the proposed model in this paper to schedule the surgeries in a short time with the least possible cost. This model can be offered to the operating room manager as a useful tool for targeted management of the surgical theater.

Table 2- The name of the considered surgeries in the real example

Number of surgery	Surgery name
1	Thyroidectomy
2, 3	Moving or transferring the adjacent tissue of any area of the body, more than 10 square centimeters
4	Removal of the catheter of the central venous with subcutaneous tunnel
5	Antrectomy, resection of the small intestine
6, 7, 8	Lymphadenectomy, suprahyoid
9, 10, 11	Inguinal hernia
12, 13	Appendectomy
14, 16	Cholecystectomy
15, 17	Pediatric inguinal hernia repair
19	Incision and drainage of an abscess inside the parietal
18, 20	Hemorrhoidopexy

Table 3- Characteristics of the considered surgeries in the real example

Number of surgery	Surgery duration (30 min)	Recovery duration (30 min)	$[ES(s), LS(s)]$	Responsible surgeon
1	5	3	[8:00,12:00]	1
2	4	2	[8:00,20:00]	1
3	4	2	[8:00,20:00]	1
4	3	3	[9:00,20:00]	2
5	5	4	[8:00,20:00]	2
6	2	3	[8:00,20:00]	2
7	2	3	[8:00,20:00]	2
8	2	3	[8:00,20:00]	3
9	3	4	[8:00,20:00]	3
10	3	4	[8:00,20:00]	3
11	4	3	[8:00,20:00]	3
12	3	4	[8:00,20:00]	4
13	3	4	[8:00,20:00]	4
14	3	3	[11:00,20:00]	4
15	4	3	[8:00,13:00]	4
16	3	3	[8:00,20:00]	5
17	4	3	[8:00,13:00]	5
18	3	2	[8:00,13:00]	5
19	2	2	[8:00,20:00]	5
20	3	2	[8:00,14:00]	5

Table 4- Availability time windows of surgeons.

Number of surgeon	**Availability interval**
1	[8:00,17:30]
2	[8:00,20:00]
3	[10:00,20:00]
4	[8:00,20:00]
5	[8:00,20:00]

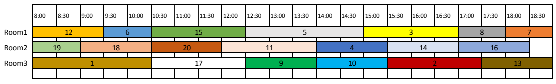

Figure 1- The scheduling resulted from the model

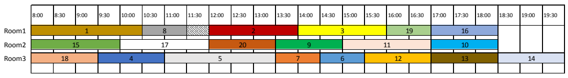

Figure 2- The scheduling proposed by the operating room manager

5. Conclusion

It is significant for the patients and hospital managers Applying proper tools in order to appropriate usage of resources and providing desired services. Meanwhile, hospitals are in one hand intended to reduce their costs and improve their financial conditions, and on the other hand, they try to provide the highest satisfaction level for their patients. The surgical ward is the greatest income and cost center of the hospital that is intensively related to its other wards such as recovery wards and intensive care units and admitting ward; hence, scheduling and planning the surgical ward of the hospitals are paid attention to.

Therefore, in this study, we have presented a comprehensive mathematical model for scheduling the elective surgeries in the surgical theater. The surgical theater consists of two sections of operating rooms and recovery rooms. These two units are in a close relationship with each other and the conditions and limitation of each of them directly influence the performance of the other ward. Therefore, as most researchers have so far dealt with it, individually focusing on the operating room does not consider the conditions and real characteristics of the scheduling problem of the surgical operations. Therefore, besides operating rooms, we take into account the Post-Anesthesia Care Unit (PACU) in this research. Moreover, the other constraint such as timetable of the required human resources for conducting surgery, availability of the equipment and non-renewable materials, have been taken into account in this study. Considering all of these cases along with each other has made the proposed model more real and applicable. It can be a useful tool for the hospital managers towards the efficient management of the operating room. Finally, in order to show the effectiveness of the model, in a usual day in Baqiyatallah Hospital, the model has been solved by GAMS software. The results indicate that the proposed model is able to present a better scheduling in less than one minute in comparison with the scheduling proposed by the operating room manager in terms of cost measure.

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