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Improvement of Operating Room Performance Using a Multi-Objective Mathematical Model and Data Envelopment Analysis: A Case Study

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KEYWORDS
Multi objective model;
OR planning and scheduling;
ε-constraint method;
Data envelopment analysis.

ABSTRACT
Surgical theater is one of the most expensive hospital resources which accounts for a high percentage of hospital receptions. Therefore, efficient planning and scheduling of the operating rooms (ORs) is necessary to improving the efficiency of any healthcare system. In this paper, weekly OR planning and scheduling problem was addressed to minimize waiting time of elective patients, overutilization and underutilization costs of ORs, and the total completion time of surgeries. In our model, the available hours of ORs, recovery beds, the surgeons, legal constraints and job qualification of surgeons, and priority of patients were taken into account. A real-life example was provided to demonstrate the effectiveness and applicability of the model and was solved using ε-constraint method in GAMS software. Then, data envelopment analysis (DEA) was employed to obtain the best solution among the Pareto solutions obtained by ε-constraint method. Finally, the best Pareto solution was compared with the schedule used in the hospitals. The results indicated that the best Pareto solution outperforms the schedule offered by the OR director.

1. Introduction

With a rapid growth of the population, we are witnessing an ever-increasing demand to receive medical service. However, healthcare organizations mostly face limited resources to serve people. These challenges motivated the researches to do this research and help managers of healthcare organization in finding ways to increase service level and decrease costs. One of the main parts of the health care system is hospitals, taking a significant share of clinical risks and the budget [1, 2]. Hence, it is vital to use appropriate tools to efficiently manage these facilities.

Given that the surgical theater is the most important source of income and cost and is the

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most expensive ward of hospitals, decisions made in this unit widely influence the overall performance of hospitals [3]. Managing operation theaters is a difficult and complex task due to the conflicting priorities and preferences of their stakeholders (i.e., surgeons, patients, managers, etc.) [4]. Proper planning and scheduling of surgeries in the operation theater based on the available resources is one of the methods for improving performance of these facilities and decreasing their costs. In planning part of the problem, day and operation room for surgeries are determined considering availability of surgeons and rooms, and in scheduling part, start time of each surgery in the predetermined room is determined.

In the literature of OR, some papers have only focused on either the scheduling aspect or planning aspect of the problem. However, the optimal solution to scheduling problem is influenced by the optimal solution of planning problem [5]. Moreover, solving OR scheduling problem and planning problem separately will result in sub-optimal solutions. Hence, scheduling and planning problems of OR must be considered together to manage a surgical theater. Therefore, these two problems are integrated with each other in our modeling framework on a weekly basis.

When designing a weekly surgery plan and schedule for the surgical theatre, OR manager must take into account several factors such as availability of operating rooms, availability of surgeons, availability of nurses, and medical priority of patients. Furthermore, he/she must consider other aspects related to surgeons, including legal constraints related to their working times, and the job qualification of surgeons to conduct surgeries. Failure to consider any of these constraints results in an infeasible schedule. All these factors are taken into account in our study.

In this paper, an integrated and multi-objective model is presented to plan and schedule elective surgeries and surgeons simultaneously. This paper aims to minimize the cost, the sum of completion times of surgeries, and total waiting time of patients according to their medical priority. Moreover, constraints, such as availability of operating rooms and surgeons, legal constraints, and job qualification of surgeons, are considered in the proposed model. A case study is provided to show the applicability of the model and is solved by ε-constraint method. Finally, the preferred solution is selected by DEA among the Pareto solutions obtained by ε-constraint method. Then, it is compared to the solution proposed by the operating room manager. The structure of this research is presented in Fig. 1.

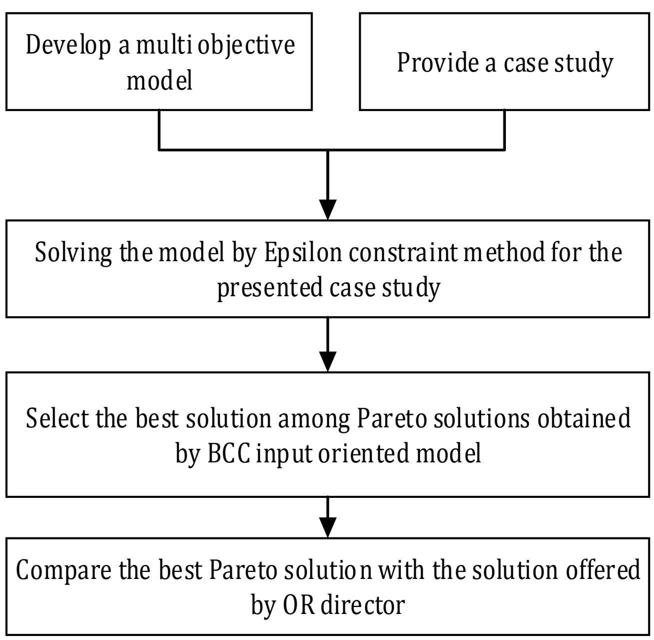

Fig. 1. Structure of this study

The rest of this study is summarized as follows: A review of the previous studies in this field is provided in section 2. The mathematical model is presented in section 3. The solution method is presented in section 4. The case study is provided in section 5. The computational results are provided in section 6; finally, in the last section, the conclusion and future work are presented.

2. Literature Review

OR scheduling problem is widely investigated in the context of health care system management. There are several review papers attending OR scheduling problem from various view angles (e.g., Blake and Carter [6], Smith-Daniels, Schweikhart [7], Yang, Sullivan [8], Cardoen, Demeulemeester [9],Van Riet and Demeulemeester [10],Bai, Fügener [11], Przasnyski [12], Magerlein and Martin [2], and Samudra, Van Riet [13]). For example, in The first review paper, Magerlein and Martin [2] classified the literature of surgical process scheduling into two phases: planning and scheduling. In a conceptual framework proposed by Blake and Carter [6], the process of scheduling surgeries includes advancement, allocation, and external resource; moreover, scheduling problem is addressed in strategic, administrative, and operational decision-making levels. Later, Cardoen, Demeulemeester [9] presented a comprehensive classification in seven areas, including the type of patients, solution methods, performance criteria, uncertainty incorporation, decision delineation, and applicability of research. Recently, Samudra, Van Riet [13] surveyed more than 200 papers from 2000 to 2014 and presented a more comprehensive classification than the review paper of Cardoen, Demeulemeester [9]. In this study, the studies that relate directly to our work are reviewed.

In literature of OR, some researchers just worked on planning problem and scheduling problem separately. For example, Min and Yih [14] proposed a stochastic optimization model to plan elective surgeries considering ICU capacity. Jebali and Diabat [15] presented a stochastic mixed integer model for planning problem to minimize patient-related costs as well as overtime and undertime costs. They extended the model of Min and Yih [14] by taking into account the constraints related to the availability of beds of hospitalization ward. However, similar to the study of Min and Yih [14], they ignored the surgeons' availability and legal constraints pertaining to their working times in their study. Riise and Burke [16] presented a model for OR planning problem to minimize waiting time of patients, waiting time of elective groups of patients such as children and overtime for surgeons. They used the weighted sum method to solve the model. Dios, Molina-Pariente [17] presented a decision support system to plan the times of surgeries. In this system, for planning operations, both approximate and exact optimization methods are used. In another research, Latorre-Núñez, Lüer-Villagra [18] addressed an OR scheduling problem by taking emergency patients into account. However, they neglected some constraints related to surgeons such as available hours and legal constraints. In order to solve the model, they developed a genetic algorithm and a constructive heuristic. Zhao and Li [19] used a model of mixed integer nonlinear programming (MINLP) and constraint programming (CP) to schedule elective surgeries. They investigated performance of the two proposed models using numerical examples. Their results show that the CP model is more efficient than the MINLP model with respect to solution quality. Landa, Aringhieri [20] presented a mathematical model to maximize efficiency of operating rooms and minimize surgery cancellations for elective patients. In order to solve the model, they used a combination of neighborhood search and Monte Carlo simulations. Hamid, Hamidb [21] worked on a comprehensive mathematical model for scheduling problem of elective surgeries. They minimized the undertime and overtime costs by considering the availability of human resources, equipment and recovery beds. They indicated that their proposed schedule has a better performance in comparison with the actual schedule used in the hospital.

Some researchers treated the problem as a two-stage no-wait flow shop. For example, Guinet and Chaabane [22], firstly, planed the times of surgeries using a mathematical model. Then, in the second step, they employed a heuristic method to determine order of the surgeries in the operating room that is assigned in the first step. Similar to the study of Guinet and Chaabane [22], Jebali, Alouane [23] offered a two-stage hybrid flow shop model to plan and schedule surgeries. They optimized the OR underutilization and overutilization costs as well as the hospitalization costs of inpatients. Similar to the two previous studies, Augusto, Xie [24] used a two-step approach. They developed a model for planning and scheduling problems of surgeries considering the availability of operating rooms, recovery beds and porters. However, they assumed that surgeons were always available to perform any surgery. In all the three aforementioned researches, they neglected the legal constraints related to surgeon's working hours. In addition, they did not assume priority for patients.

Fei, Meskens [25] employed a two-stage approach to designing a weekly surgery schedule. They solved the problem in two phases: setting surgery date for patients and determining sequence of operations in each operating room on a daily basis. In order to solve the problem, they used a column-generation-based heuristic procedure and a hybrid genetic algorithm. In another research, Saadouli, Jerbi [26] use a multi-stage approach to planing and scheduling surgeries. Firstly, they selected a list of surgeries using knapsack method. Then, selected surgeries were assigned to operating rooms to minimize makespan and patient's waiting time. Finally, they scheduled surgeries based on SPT rule (i.e., surgeries are ordered in ascending order of their operating time). However, as mentioned in the previous section, solving the planning and scheduling problem separately can lead to suboptimal solutions. Some researchers have employed this perspective and addressed the planning and scheduling problem in an integrated modeling framework. For example, Aringhieri, Landa [27] performed integrated planning and scheduling problem to optimize hospital utilization and minimize waiting time of patients. In order to solve the problem, they developed a meta-heuristics based on the two-step method. Moreover, Roland, Di Martinelly [5] incorporated human and material constraints into a project schedule modeling framework to design a weekly OR schedule. They minimized opening and overtime costs of operating rooms. In order to solve the problem, they developed a genetic algorithm. Vijayakumar, Parikh [28] attempted to maximize the service rate for elective patients according to their medical priorities. They presented a model in which the patients were allocated to the operating rooms, days, time slots, and surgeons. Marques, Captivo [29] presented a mixed integer programming for weekly planning and scheduling problem of elective patients. They aimed to maximize operating room utilization and service level. They developed a genetic algorithm to solve the model. In all six previous studies, the constraints related to the availability of recovery beds were ignored.

In all the articles mentioned above, the surgeon in charge of surgeries was assumed predetermined. While, in many hospitals, especially in teaching hospitals, surgeons are not predetermined. In addition, other aspects such as surgeons' job qualification to perform surgeries, legal constraints on working hours for surgeons, the available hours of operating rooms, recovery beds, and surgeons, and the priority of patients are taken into account in this study. Considering all of these features simultaneously results in a more realistic and practical modeling, which can be a useful tool for hospital administrators to manage operating room efficiently.

3. The Model

The operating room manager at a public hospital in Tehran, Iran, welcomed this research and we tried to model the problem according to their settings. This hospital has a group of surgeons and multiple ORs. Surgeons are available generally at specific times of the day and predetermined days of the week. Moreover, there are several legal constraints about working time of surgeons. For example, a surgeon must not work more than certain limited time determined by the hospital. Surgical cases are given a certain priority (e.g., low, medium, and high) according to the criticality of the case; e.g., a cancer case is considered high priority, while a case requiring hip replacement is considered medium priority. Case priorities must be considered in order to ensure that high priority cases are scheduled as early as possible. After the surgery, the patients may occupy a bed in the recovery room. If there is no available recovery bed after the surgery, it may lead to delay in starting the surgery. The surgery flow is shown in Fig.2.

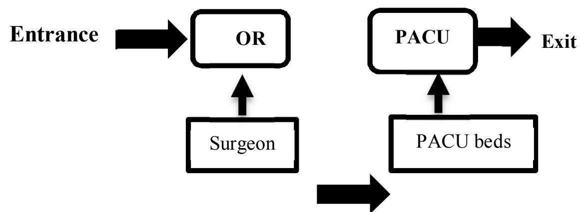

Fig. 2. Surgery flow in a surgical theater

In this section, a three-objective mathematical model is presented for the planning and scheduling surgeries of elective patients as well as surgeons. Based on the model, three decisions are made: 1) determining operating room and day of conducting each surgery, 2) determining start time of each surgery in the operating room, and 3) allocating surgeons to surgeries.

Some assumptions are considered to simplify the problem:

- The number of patients in the waiting list is determined in the beginning of time horizon.
- Non-elective patients undergo surgery in a separate operating room; therefore, they are not considered in the model.
- Overtime hours of operating rooms cannot exceed a specific limit.
- Interruption during a surgery is not allowed.
- Every hour is divided into 15-minute periods.
- Three priority classes are considered for patients (A, B, C), which is based upon medical status of patients. To quantify priority, numbers $\{1, 5, 10\}$ are used, and 10 is given to an A class patient who is a patient with top priority.
- The transportation time between operating room and recovery room is ignored because it is very short.

The indices, parameters, and decision variables are shown in Table (1).

Tab. 1. Index, parameters and decision variables

Index	Descriptions
s	Index of surgical operations
i	Index of surgeons
r	Index of operating rooms
b	Index of PACU beds
d	Index of days in the scheduling horizon
t	Index of time periods in a day
Parameters	**Descriptions**
p_s	Duration of surgery s
dp_s	Length of stay of surgery s in PACU
S_i	The set of surgeries that surgeon i can perform
i_s	The set surgeons that are eligible for performing surgery s
T_{sd}	The set of periods in which surgery s can be started on day d such that it can finish before closing the surgical theater
T_{id}	Set of periods in which surgeon i is available on day d
T_{id}^{max}	The maximum period numbers which surgeon can work at day d
T_{id}^{min}	The minimum period numbers which surgeon should work on day d if he/she is available

	on day d
A_i^{max}	The maximum period numbers which surgeon can work per week
A_i^{min}	The minimum period numbers which surgeon should work on day d
H_{rd}	Regular time of opening operating room r on day d
O_{rd}	Allowed maximum overtime
cu^{rd}	The underutilization cost of room r on day d per periods
co^{rd}	The overtime cost of the room r on day d per period
NB	Number of Periods per hour
$priority_s$	Priority of surgical operation s

Variables	Description
X_{srdt}^i	if surgery s is started by surgeon i in room r on day d at the beginning of t period, take 1, otherwise 0
$pac_{(s,d,b,t)}$	if surgery s is occupied PACU bed b on day d at the beginning of t period, takes 1, otherwise 0
$over_r^d$	Overtime of operating room r on day d
$under_r^d$	The undertime of operating room r on day d

$$MinZ1: \sum_i \sum_{s\in S_i} \sum_r \sum_d \sum_{t\in(T_{id}\cap T_{sd})} ((t-1) + (d-1)\times 24 \times NB) X_{srdt}^i \times priority_s \quad (1)$$

$$MinZ2: \sum_r \sum_d under_r^d \times cu^{rd} + \sum_r \sum_d over_r^d \times co^{rd} \quad (2)$$

$$MinZ3: \sum_s C_s \quad (3)$$

$$\sum_{i\in i_s} \sum_r \sum_d \sum_{t\in(T_{id}\cap T_{sd})} X_{srdt}^i = 1 \qquad \forall s \in S \quad (4)$$

$$\sum_i \sum_{s\in S_i} \sum_{\substack{t'=t-p_s+1 \\ t'\in(T_{id}\cap T_{sd})}}^{t} X_{srdt'}^i \le 1 \qquad \forall r \in R, \forall t \in T, \forall d \in D \quad (5)$$

$$\sum_{s\in S_i} \sum_r \sum_{\substack{t'=t-p_s+1 \\ t'\in(T_{id}\cap T_{sd})}}^{t} X_{srdt'}^i \le 1 \qquad \forall i \in I, \forall t \in T, \forall d \in D \quad (6)$$

$$\sum_i \sum_{s\in S_i} \sum_{t\in(T_{id}\cap T_{sd})} P_s X_{srdt}^i \le \mathrm{H_{rd}} + \mathrm{O_{rd}} \qquad \forall r \in R, \forall d \in D \quad (7)$$

$$T_{id}^{min} \leq \sum_{s\in S_i}\sum_{r}\sum_{t\in(T_{id}\cap T_{sd})} P_s X_{srdt}^i \leq T_{id}^{max} \qquad \forall i \in I, \forall d \in D \qquad (8)$$

$$A_i^{min} \leq \sum_{s\in S_i}\sum_{r}\sum_{t\in(T_{id}\cap T_{sd})}\sum_{d} \mathrm{P_s} X_{srdt}^i \leq A_i^{max} \qquad \forall i \in I \qquad (9)$$

$$under_r^d \geq (\mathrm{H_{rd}} - \sum_{\substack{t\in(T_{id}\cap T_{sd})\\ ,|t\leq \mathrm{H_{rd}}}}\sum_{i}\sum_{s\in S_i}\sum_{t'=t}^{\min(t+p(s)-1,\mathrm{H_{rd}})} X_{srdt}^i) \qquad \forall r \in R, \forall d \in D \qquad (10)$$

$$over_r^d \geq \sum_{i}\sum_{s\in S_i}\sum_{\substack{t\in(T_{id}\cap T_{sd})\\ ,(t+P_s-1)>\mathrm{H_{rd}}}} (t+P_s-1)X_{srdt}^i) - \mathrm{H_{rd}} \qquad \forall r \in R, \forall d \in D \qquad (11)$$

$$C_s \geq \sum_{i\in i_s}\sum_r\sum_d\sum_t X_{srdt}^i(t+p_s) \qquad \forall s \in S \qquad (12)$$

$$\sum_{r}\sum_{i\in i_s} X_{srdt}^i = \sum_{b} pac_{(s,d,b,t+dp_s)} \qquad \forall s \in S, \forall d \in D, \forall t \in T' \qquad (13)$$

$$\sum_{s}\sum_{\substack{t'=t-dp_s+1\\ t'\in T'}}^{t} pac_{(s,d,b,t')} \leq 1 \qquad \forall b \in B, \forall t \in T', \forall d \in D \qquad (14)$$

$$pac_{sdbt} \in \{0,1\}, X_{srdt}^i \in \{0,1\}, \\ under_r^d \geq 0, over_r^d \geq 0, C_s \geq 0 \qquad (15)$$

Three objective functions are considered in this study. The first objective function (Equation1) minimizes the sum of the waiting time of patients according to patients' priority. The second objective function (Equation2) minimizes costs, including costs of underutilization (the first part) and overutilization (the second part). The third objective function (Equation 3) minimizes sum of completion times of the surgeries.

Constraint (4) ensures that every surgery is started in only one room, one day, and one period by an eligible surgeon. Constraint (5) states that at most one surgery is performed each day and each room in a time period by a qualified surgeon. Constraint (6) disallows surgeons to be available in several surgeries at the same time and day. Constraints (7) checks the availability of operating rooms. Constraint (8) imposes a limit on the total working time of a surgeon in one day. Constraint (9) imposes a limit on the total working time of each surgeon over a week. Constraints (10) and (11), respectively, show the underutilization and overutilization time of every operating room per day, and Constraint (12) shows the completion time of surgeries. Constraint (13) states that a PACU bed must be immediately reserved after finishing each surgery for post anesthesia care. Constraint (14) disallows PACU beds to be available in several surgeries at the same time and day. The domain of variables is defined in constraint (15).

3-1. Model validation

In order to validate the proposed model, a small example (| S | * | I | * | R | * | T | * | D | = 8 * 3 * 2 * 40 * 1) is designed, where | S |, | I |, | R |, | T |, and | D | indicate the number of surgeries, the number of surgeons, number of rooms, number of time periods in a day and number of days in horizon time, respectively. Then, we solved the model as three single-objective problems considering each objective separately. Each single-objective problem is solved by the CPLEX solver in GAMS software. Their optimal solutions are shown in Figs. 1 to 3 (A to C represent surgeons, and 1 to 8, indicate surgeries). It can be seen that the optimal solutions obtained by each problem are different, and this shows a conflict between the objective functions.

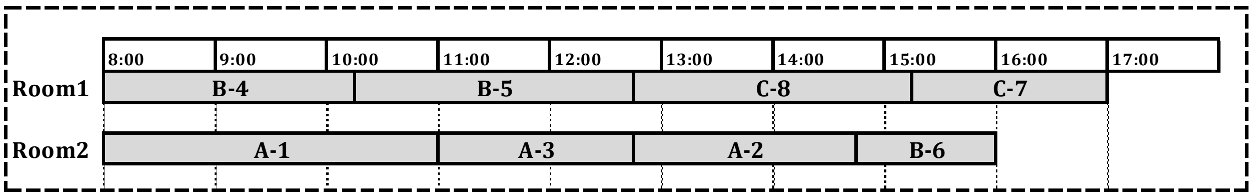

Fig. 3. The optimal solution obtained by solving the model considering only the first-objective function

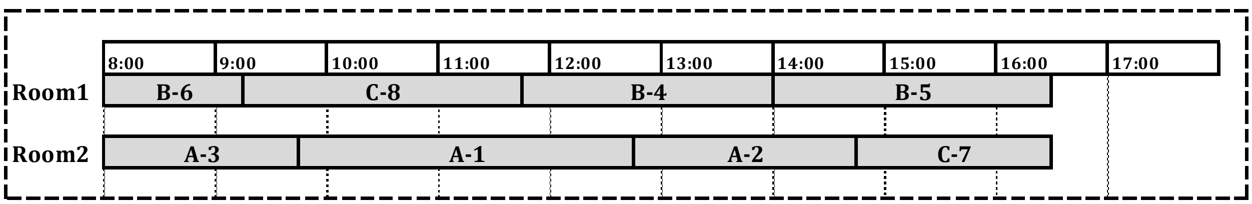

Fig. 4. The optimal solution obtained by solving the model considering only the second-objective function

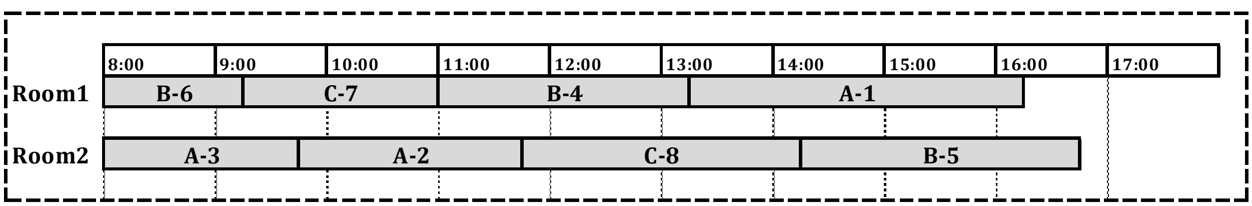

Fig. 5. The optimal solution obtained by solving the model considering only the third-objective function

4. Solution Method

4-1. ε-constraint method

The basic idea of this method is based on selecting one of the multiple objectives as the main objective function in the optimization problem and the rest of objective functions are converted to constraints. Assume the following model with *k* objective functions.

$$\text{Min } (f_1(x), f_2(x), \ldots, f_k(x)) \quad (14)$$
$$s.t.$$
$$x \epsilon S,$$

Where x is the vector of decision variables and S is the feasible region. Applying ε-constraint method, the model (14) is converted to the following model. To reach the efficient solution for the model (15), we must change the RHSs values of the constrained objective functions, parametrically [30, 31].

$$Max\, f_1(x) \quad (15)$$
$$s.t.$$
$$f_2(x) \geq \varepsilon_2$$
$$f_3(x) \geq \varepsilon_3$$

…
$f_k(x) \geq \varepsilon_k$

This method produces a Pareto optimal solution set, including non-dominated solutions. Then, to determine the most efficient solution among the Pareto solutions' set, obtained from ε-constraint method, data envelopment analysis is used that is explained in the next section.

4-2. Data envelopment analysis

DEA is a mathematical technique based on linear programming, introduced by Charnes, Cooper [32] for the first time. This method has been used in various contexts such as Health Care Services (e.g., [33, 34]), optimization Manufacturing Methods (e.g., [35, 36]), project selection (e.g., [37]), safety improvement (e.g., [38, 39]), and supply chain (e.g., [40, 41]).

By this method, the performance of a group of decision-making units (DMU) with multiple inputs and outputs can be determined [32], [42]. This performance will be used as an indicator for evaluating the performance of DMU and comparing between them.

To determine the weight of each input and output, DEA allows each DMU to specify a set of weights, which show that unit in the most favorable situation. The problem for DMU_o is defined as in model (A).

$$Max \quad \theta_o = \frac{\sum_{r=1}^{s} u_r\, y_{r0}}{\sum_{i=0}^{m} v_i\, x_{i0}}$$
$$s.t. \qquad \text{(A)}$$
$$\frac{\sum_{r=1}^{s} u_r\, y_{r0}}{\sum_{i=0}^{m} v_i\, x_{i0}} \leq 1 \qquad j = 1, \dots, n$$
$$u_r, v_i \geq 0 \qquad i = 1, \dots, m, \quad r = 1, \dots, s$$

where r and i are index of outputs and inputs, respectively. The variables of model (A) are u_r and v_i weights which indicate weight of input i and output r, and θ_o is the efficiency of DMU_o. This model (A) is not linear; however, it can be easily converted to a linear programming problem as follows:

$$Min \quad \theta = \sum_{i=1}^{m} v_i x_{i0}$$
$$s.t. \qquad \text{(B)}$$
$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \qquad j = 1, \dots, n$$
$$\sum_{r=1}^{s} u_r y_{r0} = 1$$
$$u_r, v_i \geq 0 \qquad i = 1, \dots, m, \quad r = 1, \dots, s$$

There are the four conventional and more frequently used DEA models, namely BCC input oriented, BCC output oriented, CCR input oriented, and CCR output oriented. According to the minimizing nature of objective functions, BCC input oriented DEA model with a VRS frontier type was employed because the percentage's changes in output values are not a function of direct change in input values [43], [44]. Model (C) shows BCC input-oriented DEA model.

$$Min \quad \theta$$
$$s.t. \qquad \text{(C)}$$
$$\theta x_{i0} \geq \sum_{j=1}^{n} \lambda_j x_{ij} \qquad i = 1, \dots, m$$
$$y_{r0} \leq \sum_{j=1}^{n} \lambda_j y_{rj} \qquad r = 1, \dots, s$$
$$\sum_{j=1}^{n} \lambda_j = 1$$
$$\lambda_j \geq 0 \qquad j = 1, \dots, n$$

Given that the proposed model (model C) considers the efficiency of efficient units equal to one, they are, hence, not able to complete ranking of efficient units. In order to have full ranking units. Model (C) is converted into a super efficiency model by eliminating DMU_o from the model [45].

5. Case Study

This study focuses on the operating rooms devoted to the orthopedic surgeries of Baqiyatallah Alazam hospital in Tehran. The hospital was founded in 1984 with an area of over 52,000 square meters and is one of the largest and the most advanced hospitals in Middle East with an annual average of 42000 surgeries. In this hospital, nine types of surgeries, including orthopedic, urology, general, ophthalmology, ENT, brain and nerves, kidney transplant, maternity, and cardiac and vascular surgeries are performed. This study, as mentioned, is formulized for a normal week in the orthopedic surgery ward which has two operating rooms, and one recovery room accommodated three PACU beds. Normally, operating rooms work 8 hours and a half from Saturday to Wednesday and 7 hours on Thursday and Friday. In addition, the maximum overtime hours in a day is 1.5 hours from Saturday to Wednesday and 1 hour on Thursday and Friday. It should be noted that the recovery room opens simultaneously with the operating rooms and does not close until the last patient has left the surgical theater. According to the data collected in the mentioned week, there are 54 elective patients ready to undergo surgery and, during this week, 8 surgeons are available. According to a timetable determined by the hospital regulations, surgeons must not perform surgery more than 8.5 hours per day and 40 hours per week. Moreover, if a surgeon is available in a surgical theater, the surgical theater manager must reserve at least two vacant hours for conducting surgeries which he/she can perform in that day.

6. Computational Results

The case study was solved using ε-constraint method and CPLEX solver in GAMS software. The non-dominated solutions obtained by ε-constraint method are depicted in Fig 6. Table 2 shows the value of these solutions as well as the schedules offered by the surgical theater manager. These solutions are considered as DMUs and are ranked by BCC input-oriented model. Due to the minimizing nature of the objective functions (i.e., Z1, Z2, and Z3), they have been considered as input in DEA model and labeled as input1, input2, and input 3, respectively, which are shown in Table (2). The ranks achieved by the DEA model are indicated in Table 3.

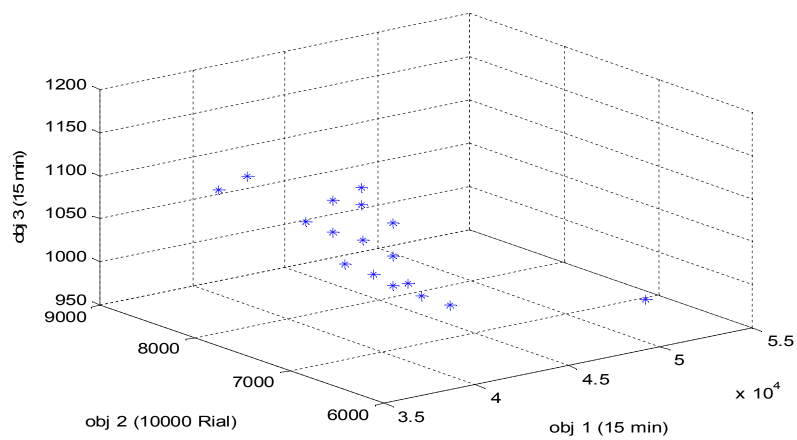

Fig. 6. The non-dominated solutions

As shown in Table 3, DMU 14 is selected by the DEA model as the preferred solution while the schedule offered by operating room manager (i.e., DMU 17) takes the rank of 14. The preferred schedule obtained by DEA model (PSOD) and the schedule offered by operating room manager (SOORM) are shown in Figs. 7 and 8, respectively (A to H represent surgeons, and numbers 1 to 54 indicate surgeries).

Tab. 2. The non-dominated solutions obtained by ε-constraint method and the actual schedule used in hospital

DMU	Z1 (15min)	Z2 ($\times 10^4$ $Rials$)	Z3 (15 min)
1	50691	6300	990
2	40136	6300	1030
3	40120	6900	1030

4	40128	6600	1030
5	37852	6300	1066
6	37472	6600	1067
7	37468	6900	1067
8	37045	6300	1101
9	36941	6600	1109
10	36879	6900	1107
11	36875	7200	1107
12	36786	8100	1110
13	37000	6300	1140
14	36865	6600	1150
15	36847	6900	1143
16	36762	7800	1138
17	36839	6600	1170

Tab. 3. The efficiency and rank of the solutions model

DMU	The rank	Efficiency
1	15	0.99998
2	7	1.01002
3	8	1.01000
4	6	1.01120
5	17	0.98999
6	5	1.01210
7	9	1.00121
8	2	1.03110
9	4	1.01310
10	12	1.000006
11	16	0.99984
12	13	1.00000
13	3	1.02875
14	1	1.10037
15	10	1.00021
16	11	1.00003
17	14	0.99999

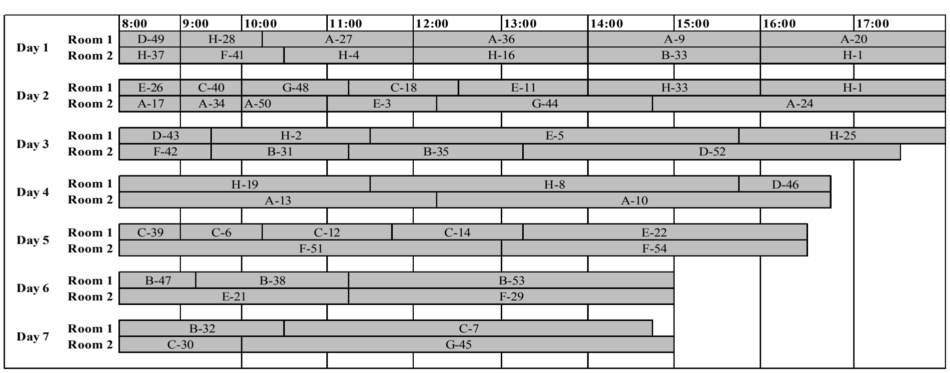

Fig. 7. The preferred schedule obtained by DEA model

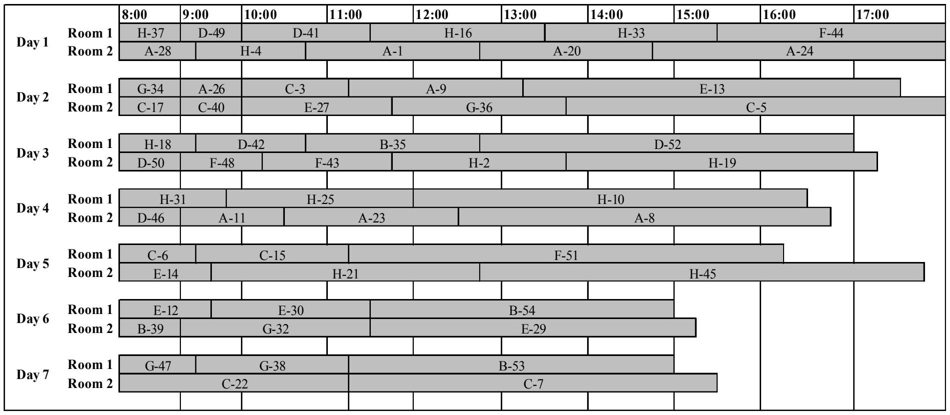

Fig. 8. The actual schedule used in hospital

For further evaluation of POSD in comparison with SOORM, two criteria are also employed: 1) the utilization average of surgeons (UAS) and 2) the coefficient of variation of working times of surgeons (CVWTS). The utilization of the surgeon is the sum of her/his working times divided by the sum of her/his available times in horizon times. The greater values of UAS are more desirable. The coefficient of variation of working times of surgeon (CVWTS) is calculated as the ratio of the standard deviation to the mean and is applied to assess the balance of the working times of surgeons. A lower CVWTS value means a more balanced situation in working times of surgeons.

The two mentioned criteria are calculated for PSOD and SOORM (see Fig. 9). As seen in Fig 9, PSOD has a better performance in terms of CVWTS. However, as long as UAS is concerned, SOORM outperforms POSD because it has a higher value (0.607 vs. 0.596).

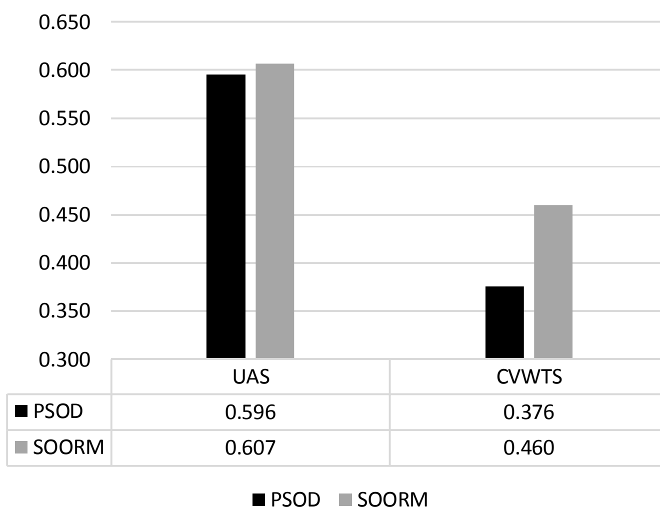

Fig. 9. Comparison between the PSOD and SOORM.

6-1. Sensitivity analyses

In this section, a sensitivity analysis is performed to evaluate the effect of variations of maximum value of overtime (MVO) in the number of surgeries selected among the candidate surgical cases. For this purpose, the various values for MVO in day are considered. The results depicted in Figs. 10 and 11 show that more surgical cases can be selected by increasing in MVO. However, the overtime cost is uptrend. Therefore, the operating room manager can select the favorable value of

MVO based on his/her preferences. Moreover, as can be seen in Fig. 11, it can be stated that the favorable value for MVO is three time-slots, such that all 54 surgical cases can be selected to conduct. This sensitivity analysis can help an operating room manager make better decisions.

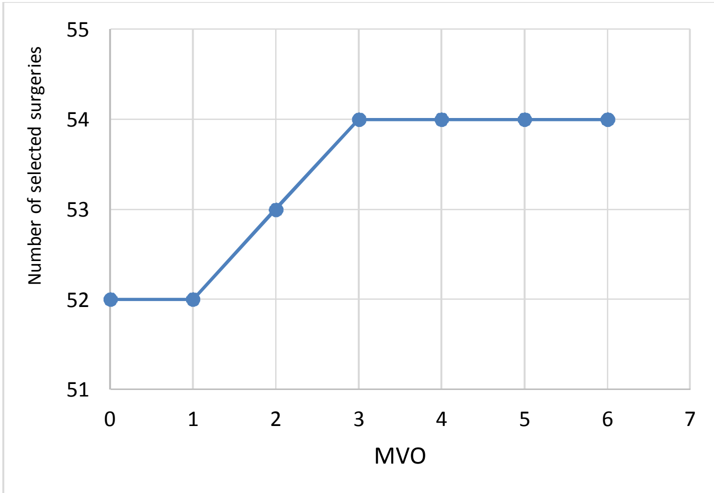

Fig. 10.Number of selected surgeries versus alteration of MVO

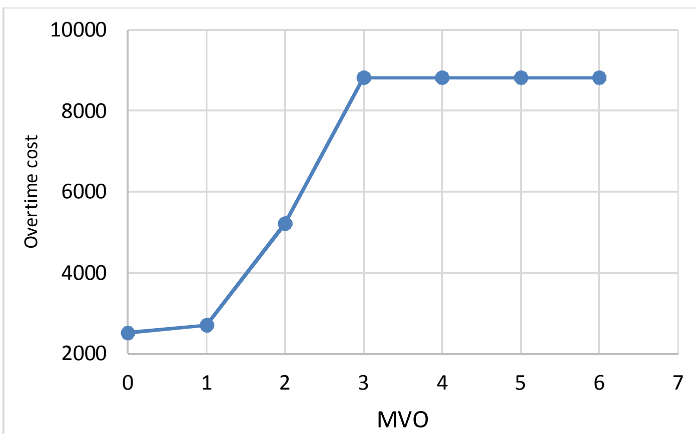

Fig. 11. Overtime cost versus alteration of MVO

7. Conclusion and Future Work

In this research, a multi-objective model was presented for weekly planning and scheduling problem of surgeries of elective patients in operating rooms. The objectives were to minimize waiting time of the patients according to their medical priority, the undertime and overtime costs of operating rooms, and the sum of completion times of surgeries. In the first step, to solve the proposed model for a case study, ε-constraint method was used. Then, DEA model of the BCC input oriented was used for ranking non-dominated solutions obtained by the ε-constraint method as well as the schedule resulted from the operating room manager. The results showed the superiority of the schedule obtained by the model in comparison with the actual schedule used in the operating room. Furthermore, several sensitivity analyses were carried out to investigate the influence of overtime value variations on the number of selected surgeries. For future researches, the following suggestions are recommended:

- Considering the uncertainty related to the arrival of emergency patients and the surgery duration
- Using simulation in the planning and scheduling problem of surgical theater

- Considering the surgeons' errors during surgery
- Considering other departments influenced in the operating room performance, such as a post anesthesia care unit (PACU), hospitalization ward, the intensive care unit (ICU), etc.

References

[1] Zadfallah, F., M. Bastan, and A. Ahmadvand. *A Qualitative System Dynamics Approach to Clinical Risk Management*. in *The 13th International Conference on Industrial Engineering*. (2017).

[2] Magerlein, J.M. and J.B. Martin, *Surgical demand scheduling: a review.* Health services research,. Vol. 13, No. 4, (1978), p. 418.

[3] Macario, A., et al., *Where are the costs in perioperative care?: Analysis of hospital costs and charges for inpatient surgical care.* The Journal of the American Society of Anesthesiologists, Vol. 83, No. 6, (1995), pp. 1138-1144.

[4] Glouberman, S. and H. Mintzberg, *Managing the care of health and the cure of disease—Part I: Differentiation.* Health care management review, Vol. 26, No. 1, (2001), pp. 56-69.

[5] Roland, B., et al., *Scheduling an operating theatre under human resource constraints.* Computers & Industrial Engineering, Vol. 58, No. 2, (2010), pp. 212-220.

[6] Blake, J.T. and M.W. Carter, *Surgical process scheduling: a structured review.* Journal of the society for health systems, Vol. 5, No. 3, (1997), pp. 17-30.

[7] Smith-Daniels, V.L., S.B. Schweikhart, and D.E. Smith-Daniels, *Capacity management in health care services: Review and future research directions.* Decision Sciences, Vol. 19, No. 4, (1988), pp. 889-919.

[8] Yang, Y., et al. *Applications of computer simulation in medical scheduling*. in *Proceedings of the joint conference on information sciences*. (2000).

[9] Cardoen, B., E. Demeulemeester, and J. Beliën, *Operating room planning and scheduling: A literature review.* European journal of operational research, Vol. 201, No. 3, (2010), pp. 921-932.

[10] Van Riet, C. and E. Demeulemeester, *Trade-offs in operating room planning for electives and emergencies: a review.* Operations Research for Health Care, Vol. 7, (2015), pp. 52-69.

[11] Bai, J., et al., *Operations management in intensive care unit scheduling: A literature review.* (2016).

[12] Przasnyski, Z.H., *Operating room scheduling: A literature review.* AORN journal, Vol. 44, No. 1, (1986), pp. 6770747882-68727679.

[13] Samudra, M., et al., *Scheduling operating rooms: achievements, challenges and pitfalls.* Journal of Scheduling, Vol. 19, No. 5, (2016), pp. 493-525.

[14] Min, D. and Y. Yih, *Scheduling elective surgery under uncertainty and downstream capacity constraints.* European Journal of Operational Research, Vol. 206, No. 3, (2010), pp. 642-652.

[15] Jebali, A. and A. Diabat, *A stochastic model for operating room planning under capacity constraints.* International Journal of Production Research, Vol. 53, No. 24, (2015), pp. 7252-7270.

[16] Riise, A. and E.K. Burke, *Local search for the surgery admission planning problem.* Journal of Heuristics, Vol. 17, No. 4, (2011), pp. 389-414.

[17] Dios, M., et al., *A decision support system for operating room scheduling.* Computers & Industrial Engineering, Vol. 88, (2015), pp. 430-443.

[18] Latorre-Núñez, G., et al., *Scheduling operating rooms with consideration of all resources, post anesthesia beds and emergency surgeries.* Computers & Industrial Engineering, Vol. 97, (2016), pp. 248-257.

[19] Zhao, Z. and X. Li, *Scheduling elective surgeries with sequence-dependent setup times to multiple operating rooms using constraint programming.* Operations Research for Health Care, Vol. 3, No. 3, (2014), pp. 160-167.

[20] Landa, P., et al., *A hybrid optimization algorithm for surgeries scheduling.* Operations Research for Health Care, Vol. 8, (2016),pp. 103-114.

[21] Hamid, M., et al., *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.* (2017).

[22] Guinet, A. and S. Chaabane, *Operating theatre planning.* International Journal of Production Economics, Vol. 85, No. 1, (2003), pp. 69-81.

[23] Jebali, A., A.B.H. Alouane, and P. Ladet, *Operating rooms scheduling.* International Journal of Production Economics, 2006. Vol. 99, No. 1, pp. 52-62.

[24] Augusto, V., X. Xie, and V. Perdomo, *Operating theatre scheduling with patient recovery in both operating rooms and recovery beds.* Computers & Industrial Engineering, Vol. 58, No. 2, (2010) pp. 231-238.

[25] Fei, H., N. Meskens, and C. Chu, *A planning and scheduling problem for an operating theatre using an open scheduling strategy.* Computers & Industrial Engineering, Vol. 58, No. 2, (2010), pp. 221-230.

[26] Saadouli, H., et al., *A stochastic optimization and simulation approach for scheduling operating rooms and recovery beds in an orthopedic surgery department.* Computers & Industrial Engineering, Vol. 80, (2015),pp. 72-79.

[27] Aringhieri, R., et al., *A two level metaheuristic for the operating room scheduling and assignment problem.* Computers & Operations Research, Vol. 54, (2015), pp. 21-34.

[28] Vijayakumar, B., et al., *A dual bin-packing approach to scheduling surgical cases at a publicly-funded hospital.* European Journal of Operational Research, Vol. 224, No. 3, (2013), pp. 583-591.

[29] Marques, I., M.E. Captivo, and M.V. Pato, *Scheduling elective surgeries in a Portuguese hospital using a genetic heuristic.* Operations Research for Health Care, Vol. 3, No. 2, (2014), pp. 59-72.

[30] Mavrotas, G., *Effective implementation of the ε-constraint method in multi-objective mathematical programming problems.* Applied mathematics and computation, Vol. 213, No. 2, (2009), pp. 455-465.

[31] Zhalechian, M., S.A. Torabi, and M. Mohammadi, *Hub-and-spoke network design under operational and disruption risks.* Transportation Research Part E: Logistics and Transportation Review, Vol. 109, (2018), pp. 20-43.

[32] Charnes, A., W.W. Cooper, and E. Rhodes, *Measuring the efficiency of decision making units.* European journal of operational research, Vol. 2, No. 6, (1978), pp. 429-444.

[33] Yazdanparast, R., et al., *An Intelligent Algorithm for Optimization of Resource Allocation Problem by Considering Human Error in an Emergency Department.* Journal of Industrial and Systems Engineering, Vol. 11, No. 1, (2018),pp. 0-0.

[34] Rabbani, M., A. Farshbaf-Geranmayeh, and R. Yazdanparast, *A simulation*

optimization approach for integrated resource allocation in an emergency department, pharmacy, and lab. Intelligent Decision Technologies, (Preprint): pp. 1-26.

[35] Ziaei, M., M. Farahmand, and M. Karbasian, *Proposing a Model for Evaluating Gate Valve Cover Manufacturing Methods by Value Engineering and Data Envelopment Analysis Approaches with a Case Study in Petro Tajhiz-e-Sepahan Company.* International Journal of Industrial Engineering & Production Research, Vol. 6, No. 2, (2015).

[36] Nasiri, M.M., R. Yazdanparast, and F. Jolai, *A simulation optimisation approach for real-time scheduling in an open shop environment using a composite dispatching rule.* International Journal of Computer Integrated Manufacturing, Vol. 30, No. 12, (2017), pp. 1239–1252.

[37] Mahmoudi, J., S. Nalchigar, and S.B. Ebrahimi, *Two DEA Models Employment in IS Project Selection for Iran Ministry of Commerce.* International Journal of Industrial Engineering & Production Research, Vol. 20, Nos, 1-2, (2009), pp. 71-88.

[38] Azadeh, A., M. Zarrin, and M. Hamid, *A novel framework for improvement of road accidents considering decision-making styles of drivers in a large metropolitan area.* Accident Analysis & Prevention, Vol. 87, (2016), pp. 17-33.

[39] Azadeh, A., N. Salmanzadeh-Meydani, and S. Motevali-Haghighi, *Performance optimization of an aluminum factory in economic crisis by integrated resilience engineering and mathematical programming.* Safety science, Vol. 91, (2017), pp. 335-350.

[40] Olfat, L., M. Amiri, and M. Ebrahimpour Azbari, *A Network data envelopment analysis model for supply chain performance evaluation: real case of Iranian pharmaceutical industry.* International Journal of Industrial Engineering & Production Research, Vol. 25, No. 2, (2014), pp. 125-138.

[41] HEIDARI, R., et al., *A FUZZY DATA ENVELOPMENT ANALYSIS FOR THE SUPPLY CHAIN RESILIENCE ASSESSMENT: AN IRANIAN CAR MANUFACTURER.* Recent Applications of Data Envelopment Analysis, Vol. 978, No. 1, (2017), p. 122.

[42] Banker, R.D., H. Chang, and W.W. Cooper, *Equivalence and implementation of alternative methods for determining returns to scale in data envelopment analysis.* European Journal of Operational Research, Vol. 89, No. 3, (1996), pp. 473-481.

[43] Azadeh, A., Z. Gaeini, and B. Moradi, *Optimization of HSE in maintenance activities by integration of continuous improvement cycle and fuzzy multivariate approach: A gas refinery.* Journal of Loss Prevention in the Process Industries, Vol. 32, (2014), pp. 415-427.

[44] Banker, R.D., A. Charnes, and W.W. Cooper, *Some models for estimating technical and scale inefficiencies in data envelopment analysis.* Management science, Vol. 30, No. 9, (1984), pp. 1078-1092.

[45] Andersen, P. and N.C. Petersen, *A procedure for ranking efficient units in data envelopment analysis.* Management science, Vol. 39, No. 10, (1993), pp. 1261-1264.

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