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Multi-period and multi-resource operating room scheduling and rescheduling using a rolling horizon approach: a case study

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Abstract

In this paper a multi-period and multi-resource operating room (OR) scheduling and rescheduling problem with elective and semi-elective (semi-urgent) patients is addressed. A scheduling-rescheduling framework based on the so-called rolling horizon approach is proposed to solve the problem. The core of the proposed framework is a novel proposed mixed-integer linear programming (MILP) model with the objectives of minimizing tardiness, idle time and overtime. Pre-operative holding unit beds and recovery beds as important resources in surgery departments are taken into account. At first, a schedule is set for all of the days of the planning period.Then, at each iteration, the scheduled patients are fixed (frozen) for the first day of the planning period and a rescheduling is done due to arrival of the semi-urgent patients.Then the planning period is shifted. This process continues until all days of the planning horizon are covered. Numerical analysis and comparisons are done between the proposed approach and two scenarios which are applied in many hospitals. In the first scenario, the semi-urgent patients would be operated in the first available OR after operating elective patients and in another scenario; a specified amount of capacity is allocated for semi-elective patients. The outcomes conclude that the proposed method has much better performance and alsostatistical test supports this superiority. Finally, a case study is implemented in a hospital in Iran. Numerical analysis shows that our proposed approach surpasses the actual schedule of hospital significantly.

Keywords: Operating room scheduling, healthcare, rolling horizonframework, rescheduling approach, elective and semi-urgentpatients, resource constraints.

1- Introduction

Healthcare industry is a large, fast-growing and important industry in many countries. Hospitals are one of the fundamental elements of the healthcare industry and surgery departments are one of the most crucial sectors in hospitals. Conflicting desires of different stakeholders, scarcity of the surgical recourses and the increasing of surgical demands and aging population has been added to challenges and difficulties of operating theatre management (Cardoen et al, 2010). Operating rooms are one of the most expensive resources in a hospital and they are usually bottleneck resources (Landa et al., 2016). On the one hand, around 40% of hospital resource costs arerelated to surgical expenses (Denton et al., 2007; Guerriero and Guido, 2011) and on the other hand, around 67% of hospital revenues are generated by surgeries. Also, almost 60% of patients who refer to a hospital need surgery and should visit an operating room (Van Essen et al., 2012). Long waiting times, delays and cancellations, overtime and resources overload are frequent problems in healthcare systems like

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hospitals. Hiring more personnel, providing more equipment and beds and similar solutions are not economic and applicable ways (Meskens et al., 2013). In order to avoid the mentioned problems in surgery departments, efficient planning and scheduling seem to be crucial needs. The benefits of efficient scheduling have been revealed in many industries (Pham and Klinkert, 2008). Effective scheduling of operating rooms has become a serious issue for surgery departments because it has a great effect on reducing costs and increasing the quality of care (Jebali et al., 2006).

Based on previous research papers, there are three managerial procedures for planning and scheduling of ORs (Operating Rooms). Guerriero and Guido (2011) described these three management procedures including open, block and modified-block scheduling strategy. Under block scheduling strategy different set of time blocks are assigned to different surgical specialties for some weeks or months. In open strategy, time blocks are not allocated to specific surgical groups and surgical cases are scheduled based on convenience and opinions of surgeons (Ghazalbashet al., 2012). Finally, modified-block strategy is same to block strategy but the difference is that for creating more flexibility some time blocks are left open. In this paper, open scheduling strategy is chosento plan surgery of patients in operating rooms. Another classification that has been considered in many research papers is related to patient characteristics. There are two main classes in the literature including elective and non-elective patients. Also, for non-elective patients sometimes researchers differentiate between emergency and urgent patient and sometimes semi-urgent patients (or semi-elective) (Cardoen et al, 2010). The emergency patients have to be operated as soon as possible, but the surgery of urgent patients can be postponed for a short period of time. Semi-urgent patients should be operated soon but not necessarily on the arrival day (Zonderland et al. 2010).

Planning and scheduling of operating rooms include assigning the surgical cases to ORs and days and determining the sequence and detailed schedule of patients. Implementing different surgeries involves multiple resources including personnel, equipment, ORs, required beds (like PHU beds, recovery beds) and etc. The availability, limitations and coordination of different resources are so important (Pham and Klinkert, 2008; Xiang et al, 2015).

In this paper, we study multi-period operating room planning and scheduling for elective and semi-urgent patients considering pre-operative holding unit and recovery beds. A rolling horizon approach is applied to cope with arrival semi-urgent patients and make the schedule more flexible. The open scheduling strategy is adopted. A MILP model with considering resources constraintsis developed with objective of minimizing idle time, overtime and tardiness.

The main contributions of our paper are as follows:

- Proposinga novel mixed-integer linear programming model for scheduling elective and semi-urgent patients,
- Developing a scheduling-rescheduling rolling horizon framework using the MILP model in order to add a good flexibility forplanning and handling elective and semi-urgent patients,
- Covering all three stages for implementing a surgery Including pre-operative, intra-operative and post-operative stages and considering the limitations of PHU and recovery beds,
- Implementing a case study for showing the applicability and superiority of the proposed model and framework.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 illustrates the problem in details. Section 4 describes the mathematical model and proposed rolling horizon scheduling approach. Experimental results are described in section 5. Section 6 explains the case study. Finally, Section 7 concludes the paperand presents some offers for future research.

2- Literature review

In the past 60 years, many research papers have been conducted about operating room planning and scheduling (Cardoen et al, 2010). Due to the extensive literature, only the relevant papers are reviewed in this section. Detailed reviews can be found in Cardoen et al. (2010), Guerriero and Guido (2011) and May et al. (2011).

Jebali et al. (2006) presented a two-step approach for OR scheduling and proposed a mixed integer programming model and took into account resources including surgeons and ICU beds in their model. They noted under time, overtime and the costs incurred by keeping the patients in thehospital as performance criteria. Perdomo et al. (2006) studied the assigning of patients to operating rooms and recovery beds. They solved the problem via Lagrangian relaxation and dynamic programming with the aim of minimizing total completion time.Cardoen et al. (2009*a*) focused on daily OR scheduling problem under consideration of post-anesthesia care unit (PACU) beds, surgeons and nurses with regarding various criteria such as the priority of patients and leveling the recovery beds occupancy. The authors presented a MILP model and a heuristic to cope with complexity. A similar study can be found in Cardoen et al. (2009*b*).OR scheduling under consideration of surgeons' constraints and recovery beds have been studied in the works of Persson and Persson (2009), Fei et al. (2010) and Van Huele and Vanhoucke (2014). Augusto et al. (2010) considered three resources including transporters, ORs and recovery beds for operating theatrescheduling. They assumed that patients' recovery can be done in ORs when there is no available recovery bed. Lagrangian relaxation-based method was utilized to solve the problem. They considered some performance criteria based on patients' completion times. Min and Yih (2010) proposed a stochastic optimization model for elective patients scheduling with considering uncertainty in surgery durations and availability of ICU beds. They applied sampling average approximation to solve the problem. Li et al.(2015) studied the trade-off among capacity of recovery unit,waiting patients and operating room utilization applying goal programming models. Aringhieri et al. (2015) focused on elective patients scheduling with the aim of leveling ward beds occupancies using variable neighborhood search. Recovery beds were also considered in Saadouli et al. (2015). The authors used stochastic optimization and simulation approaches to schedule. Lee and Yih (2014) formulated the problem of scheduling elective patients as a flexible job shop (with fuzzy durations) with considering thelimitation of PACU beds. They proposed a scheduling strategy in order to determine thestarting time of surgeries. A two-stage decision process is applied for solving the problem using a genetic algorithm and a decision-heuristic. Xiang et al. (2015) proposed an ant colony optimization approach to solve surgery scheduling problem in order to minimize makespan. They presented a model based on multi-resource constraint flexible job shop scheduling problem to consider patient flow in pre-operative intra-operative and post-operative stages. Recently, Latorre-Núñez et al. (2016) studied operating rooms scheduling with considering PACU and required recourses in ORs. They presented an MILP model based on flexible flow shop scheduling problem and a constraint programming model. Genetic algorithm and a constructive heuristic were applied to solve large instances. Heydari and Soudi (2016) studied predictive/reactive scheduling of operating rooms with consideration of PACU and used a two-stage stochastic programming due to arrival of emergent patients.

Some researchers have considered operating room rescheduling problem. Pham and Klinkert (2008) considered the rescheduling of elective patients upon the arrival of emergency patients and proposed a mathematical model as an extension of the job shop scheduling problem. Stuart and Kozan (2012) considered the rescheduling problem of the day-to-day running of a surgery unit for elective and non-elective patients. Theystudied the disruption management and modeled the problem as asingle machine scheduling problem. Erdem et al. (2012) developed a MILP model to reschedule elective patients due to the arrival of emergency patients in order to minimize overtime cost, rejection cost (emergency patients), postponement of elective surgeries cost and costs of applying more beds and personnel in PACU. They considered thelimited capacity of PACU during the planning horizon. In addition to solving by GAMS software, they developed a genetic algorithm to obtain near optimal solutions. Van Essen et al. (2012) focused on a single day operating room rescheduling problem due to emergency arrivals and duration variability. They proposed an ILP with theobjective of minimizing the preferences of stakeholders.In the context of applying rolling horizon approach in operating room schedulingand rescheduling problem, Addis et al. (2016) studied the problem of assigning patients to OR blocks (OR, week, day) with uncertainty in surgeries durations. They applied a rolling horizon approach to take into account new arrivals in different days and reschedule the patients. Recently, Luo et al. (2016) considered one-day surgery scheduling problem. They presented two mixed integer programming model including a non-rolling horizon scheduling model and a rolling horizon scheduling model in order to consider the variation in day-to-day demand. In these two papers, authors did not consider pre-operative and post-operative recovery beds.

In this paper, we discuss of scheduling elective and semi-elective patients. Zonderland et al. (2010) used queuing theory in order to schedule elective and semi-urgent patients and investigated the trade-off between operating semi-urgent surgeries and cancellation of elective surgeries. A detailed review about thetrade-off between scheduling elective and emergency patients (including emergency, urgent, semi-urgent patients and etc.) can be found in Van Riet and Demeulemeester (2015).

In this paper, a rolling horizon scheduling-rescheduling framework containing a MILP model is proposed to consider all three units for implementing a surgery including pre-operative and post-operative (recovery) units for scheduling elective and semi-elective patients. Resource constraints including limitations in pre-operative and recovery unit beds and also the availability and specialty of surgeons are taken into account.

3- Problem description

The process for implementing a surgery usually consists of three main stages. At first, the patient is transported to the pre-operative holding unit (PHU) from ward and occupies a bed. A nurse checks the patient's condition and documents and prepares him/her for surgery. Then, the patient will be moved to an operating room. Generally, hospitals have different operating rooms with different sizes and applications. Depending on the surgery type, a suitable operating room should be selected. In the OR, at first the patient is anesthetized by an anesthetist specialist and then will be operated by the surgical team and when finished the patientwill be transported to recovery unit (or PACU) for recovery under the care. After that, the patient may go to ICU or ward based on surgeon's opinion. Figure 1 illustrates these three stages for implementing a surgery. The part shown with dashed lineshave been considered in our problem.

The assumptions and conditions of our problem are described as follows:

1. Time is discretized into 20-minute intervals.
2. Surgeons are available in pre-determined times.
3. A surgical case can be performed one time in the planning horizon by only one surgeon who has the relatedspecialty for that kind of surgery. Besides, it can be done in the OR which meets the conditions.
4. Pre-operative and post-operative beds are limited.
5. The duration of surgeries and also durations of staying a patient in pre-operative and recovery known in advance.
6. No uncertainties are considered in durations and availability constraints.
7. We have focused on elective patients (including inpatients and outpatients) and semi-urgent patients.
8. Open scheduling strategy is adopted.
9. The transfer time between two consecutive stages for a surgery is neglected.

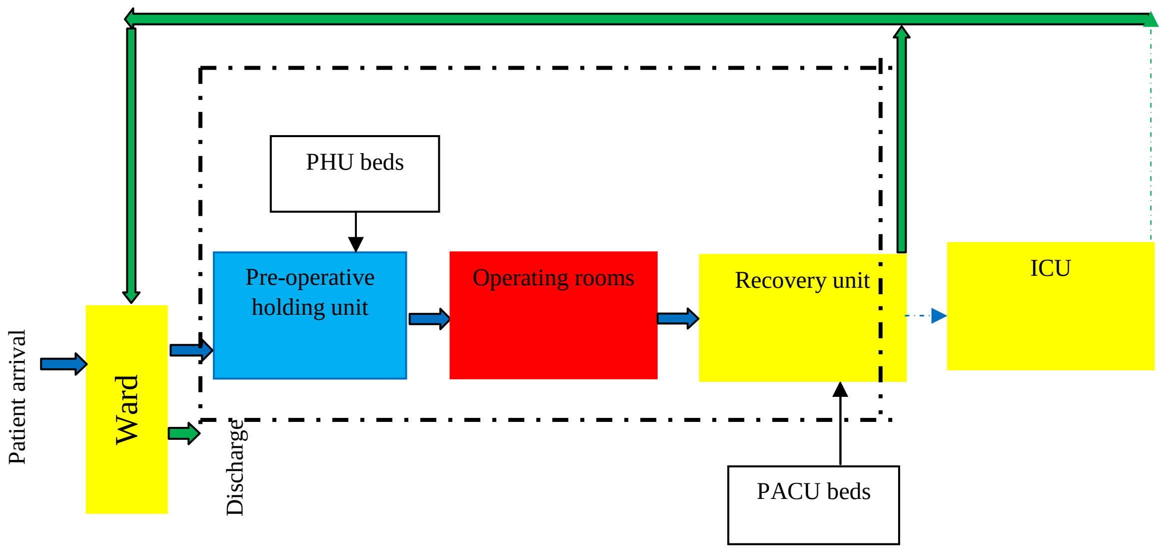

Fig. 1 Main stages for implementing a surgery

4- Rolling horizon scheduling-rescheduling framework

Rolling horizon method is suitable for environments that meet new demands all the time, like hospitals.With applying the rolling horizon approach, the schedule updates due to changes in waiting list or demands. The benefit of using this approach is that the schedule has more flexibility and adaptability (Luo et al., 2016). In this section, at first the proposed mathematical model is explained as the core of the rolling horizon scheduling-rescheduling framework and then the rolling horizon approach is described.

4-1- Mathematical model

The indexes, parameters and decision variables of the mathematical model are defined as follows:

Indexes

p	Index for patients requiring a surgery	$p = 1,2,...,P$
s	Index for surgeons	$s = 1,2,...,S$
o	Index for operating rooms	$o = 1,2,...,O$
d	Index for days in the periods	$d = 1,...,D$
t	Index for time slots during day	$t = 1,2,...,T$

Parameters

RO	Last time slot in regular opening hours
MO	Last time slot which an operating room can be active
du_p	Total surgery time for patient p
S_{std}	1, if surgeon s is available at time t on day d ; 0 otherwise
B_{pos}	1, if surgery p can be done in OR o by surgeon s; 0 otherwise
u_p	1, if surgery p is a semi-urgent patient; 0 otherwise
ph_p	Duration of staying patient p before surgery in PHU (in time slots)
B_{PHU}	Total number of PHU beds
re_p	Duration of staying patient p after surgery in PACU (in time slots)
B_{PACU}	Total number of PACU beds
w_T	Weighted factor for The minimization of tardiness
w_O	Weighted factor for The minimization of overtime
w_{id}	Weighted factor for The minimization of idle time

Decision variables

x_{postd}	1, surgery of patient p starts in OR o with surgeon s at time slot t on day d ; 0, otherwise.
$\bar{x}_{postd}$	1, if surgery of patient p occupies time slot t in OR o with surgeon s on day d ; 0, otherwise.
bs_{ptd}	1, if patient p occupies a bed at PHU at time slot t on day d ; 0, otherwise.
ps_{ptd}	1, if patient p occupies a bed at PACU at time slot t on day d ; 0, otherwise.
idt_{od}	The idle time of OR o on day d .
ovt_{od}	The idle time of OR o on day d .

The mixed-integer linear programming model for non-rolling horizon scheduling is as follows:

$$Min \quad \frac{w_T}{D*P}\left(\sum_{\substack{p \\ dt_p \le D}} \sum_o \sum_s \sum_t \sum_{\substack{d \\ d>dt_p}} (d-dt_p)x_{postd} + \sum_{\substack{p \\ dt_p<D}} (D-dt_p+1)\left(1-\sum_o \sum_s \sum_t \sum_d x_{postd}\right)\right)$$

$$+\frac{w_O}{O*D*(MO-RO)}\left(\sum_o \sum_d ovt_{od}\right)+\frac{w_{id}}{O*D*RO}\left(\sum_o \sum_d idt_{od}\right) \quad (1)$$

Subject to:

$$\sum_o \sum_s \sum_{t=ph_p} \sum_{d=wab_p} \sum_w x_{postd} \le 1 \qquad \forall p: u_p = 0 \quad (2)$$

$$\sum_o \sum_s \sum_{t=ph_p} \sum_{d=wab_p} \sum_w x_{postd} = 1 \qquad \forall p: u_p = 1 \quad (3)$$

$$\sum_s \sum_o \sum_t d * x_{postd} \le dt_p \qquad \forall p, d: u_p = 1 \quad (4)$$

$$\bar{x}_{postd} = \sum_{t'=\max(t-du(p)+1,1)}^{t} x_{post'd} \qquad \forall p, s, o, t, d \quad (5)$$

$$\sum_p \sum_s \bar{x}_{postd} \le 1 \qquad \forall o, t, d \quad (6)$$

$$\sum_p \sum_o \bar{x}_{postd} \le 1 \qquad \forall s, t, d \quad (7)$$

$$\sum_p \sum_o \sum_s \sum_{\substack{t \\ t>MO}} \sum_d \bar{x}_{postd} = 0 \quad (8)$$

$$\sum_o \bar{x}_{postd} \le S_{std} \qquad \forall p, s, t, d \quad (9)$$

$$\sum_d \sum_t x_{postd} \le B_{pos} \qquad \forall o, p, s \quad (10)$$

$$\sum_{t'=t-ph_p}^{t} bs_{pt'd} \ge ph_p * \sum_o \sum_s x_{postd} \qquad \forall p, d, t \quad (11)$$

$$\sum_p bs_{ptd} \le B_{PHU} \qquad \forall d, t \quad (12)$$

$$\sum_{t'=t+du_p}^{t+du_p+re_p-1} ps_{pt'd} \ge re_p * \sum_o \sum_s x_{postd} \qquad \forall p, d, t \quad (13)$$

$$\sum_p ps_{ptdw} \le B_{PACU} \qquad \forall t, d \quad (14)$$

$$idt_{od} = RO - \sum_{p}\sum_{s}\sum_{\substack{t \\ t \le ro}} \bar{x}_{postd} \qquad \forall o,d \qquad (15)$$

$$ovt_{od} = \sum_{p}\sum_{s}\sum_{\substack{t \\ t > RO}} \bar{x}_{postd} \qquad \forall o,d \qquad (16)$$

$$x_{postd}, \bar{x}_{postd} \in \{0,1\} \qquad \forall p,o,s,t,d : d > dt_p$$

$$idt_{od}, ovt_{od} \in \{0, I^+\} \qquad \forall o,d \qquad (17)$$

$$bs_{ptd}, ps_{ptd} \in \{0,1\} \qquad \forall p,t,d$$

The objective function is presented in equation (1). It seeks to minimize three criteria. The first term is related to minimization of tardiness for thescheduled patient and unscheduled ones, respectively (tardiness is the difference between the due date of the patient and his/her schedule date). The second and third terms are related to minimization of total overtimes and idle times. Since the objectives have different units, they are normalized. Constraint (2) states that each elective patient (surgery) is operated at most once. Constraint (3) states that each semi-urgent patient should be operated exactly once. Constraint (4) ensures that semi-urgent patients are operated before their due dates. Constraint (5) determines the time slots which a surgery occupies them. Constraint (6) ensures that at most one surgery can be done on a given day and time in an operating room. Also, each surgeon can operate at most one surgery on a given day and time which is stated in constraint (7). Constraint (8) guarantees that surgeries are not permitted to be done after the last time slot that ORs are permitted to be active. Constraint (9) states that a surgery can be done in a given time slot and day if the relevant surgeon is available.Based on constraint (10), a surgeon should have the required specialty and skills to perform a surgery and also the related OR should be suitable for that kind of surgery. Before a surgery starts, thepatient will be moved and stays in one of the available beds of PHU for a while, represented in Equations (11) and (12). Constraints (13) and (14) are similar constraints which are related to occupying PACU beds and the limitation of the number of these beds, respectively. Constraint (15) and (16) calculate the idle time and overtime of each OR on each day, respectively. Finally, constraint (17) is a bounding constraint and defines the variables to be integer or binary.

4-2- Rolling horizon approach

For implementing rolling horizon scheduling an iterative process is proposed. The steps of this iterative process are as follows:

Step 0- Schedule the patients (demand) for a determined planning period (days 1:*P*) using MILP model;Set *k*=1and go to step 2.

Step 1- Implement the schedule for the day=*k*it means that do the surgeries based on the schedule.

Step 2-Update the waiting list considering operated patients and patients who have canceled their surgeries.

Step 3-Set a schedule for days *k*: *P* using MILP model. If all of the days in the planning horizon are covered terminate the iterative process, otherwise Set *k*=*k*+1 and *p*=*p*+1 and go to step 1.

Figure 2 depicts the scheme of rolling horizon approach. Also, the above iterative process that is the rolling horizon scheduling-rescheduling framework is depicted in Figure 3.

The elective patients who register within the current planning horizon along with current patients who have not been operated in the planning horizon (remained in the waiting list) will constitute the demand pool for the next planning horizon.

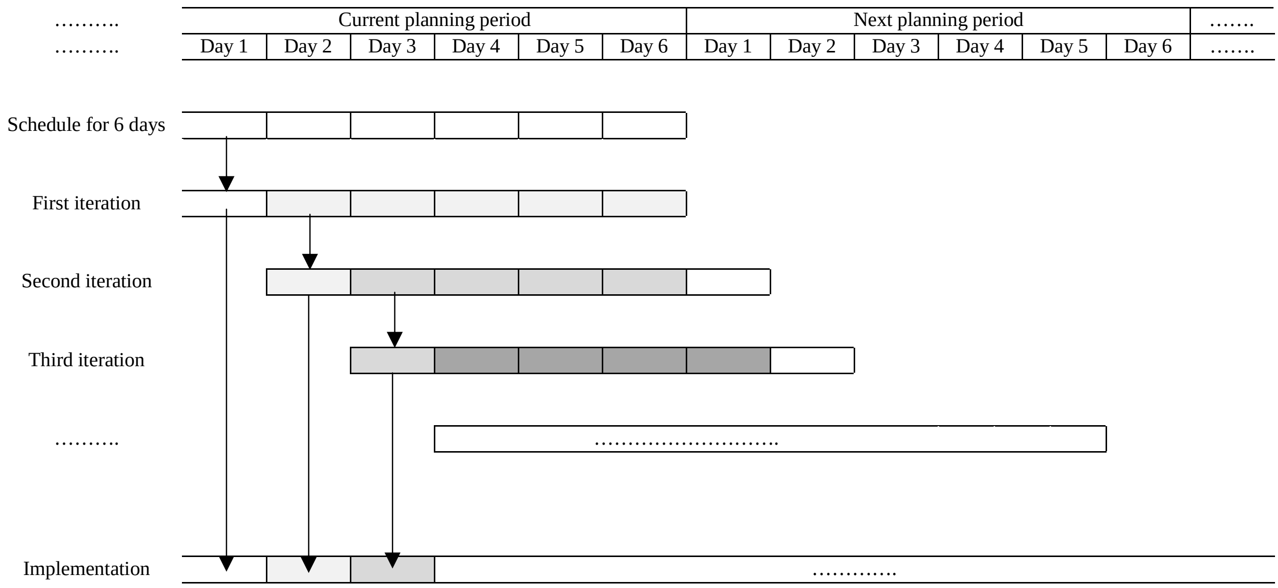

Fig. 2 Rolling horizon scheme

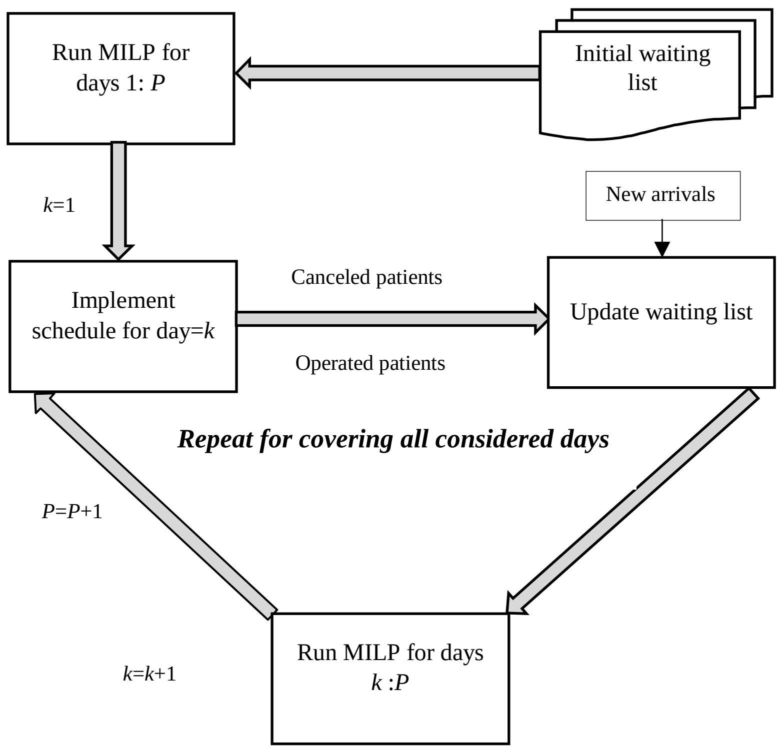

Fig. 3 Structureof the proposed rolling horizon scheduling-rescheduling framework

5- Experimental results

This section presents the computational results and analysis of the proposed model and rolling horizon approach. Two scenarios are developed in this section in order to compare with our proposed approach (many hospitals use these two methods to handle semi-urgent arrivals). These scenarios are as follows:

- ***First scenario (Sc 1)***

In this scenario, the schedule is built for a period (e.g. 6 days) and if a semi-urgent patients arrive in a day, he/she will be operated by special surgeon in an operating room that its surgeries have finished with twoconditions: first, the special surgeons, OR and recovery bed should be available and second there should be sufficient allowable time slots (allowable time slots include regular time and overtime) in that day, otherwise his/her surgery will be postponed to the next day. Note that, the surgery department would choose an OR that its assigned surgeries have been finished sooner than other ORs (i.e., the first available OR). This process will be done for all days of the period. For the next period, the remaining patients and new arrivals will be scheduled for all days and the described scenario will be implemented.

- ***Second scenario (Sc 2)***

In this scenario, a determined percent of each day's total capacity (e.g. 15%) is assigned for semi-urgent arrivals, i.e. elective patient would not be scheduled in some time slots. In this scenario, the patients are scheduled for a period (e.g. 6 days) and when implementing the schedule for each day, semi-urgent patients (if any exists) will be operated in the pre-allocated free time slots. Also, semi-urgent patients can be operated in other free time slots if it is possible.

The comparisons are done based on three data sets. Table 1 shows the conditions of these three data sets. Each data set consists of three different instances, so totally there are nine problem instances. Table 2 represents the details of each instance, including the number of initial elective patients, thenumber of new elective arrivals, thenumber of new semi-urgent arrivals and number of canceled patients.

ORs are open from Saturday to Thursday. The surgeries can be done from 7 amto 4 pm. The range from 2 pm to 4 pm is overtime and is used if needed. The duration of the surgical cases is generated using log-normal distribution and using the data existing in the paper of Marcon et al. (2003). Four types of surgeries are considered including general, otorhinolaryngology, orthopedics and ophthalmology. The recovery duration is generated utilizing a log-normal distribution where the mean is equal to the duration of the surgical case minus 1 time slot and the standard deviation is 1 time slot (similar to Jebali et al., 2003). The duration of the pre-operative stage is identical for all patients (similarto Xiang et al., 2015) and is equal to 1 time slot. All of the durations are round to the smallest integer number greater than or equal to the randomly generated number. The proportion of the number of surgeries related to each specialty is generated randomly.

Authors have used statistical distributions for generating the due dates. For example, uniform distribution (Fei et al, 2009) and log-normal distribution (Guinet and Chaabane, 2003). In this paper, uniform distribution is used. The due dates of patients are generated randomly using a uniform distribution that is $[3,2*D]$. Based on the definition of semi-urgent patients, their due dates are 1 or 2 (randomly selected).

The number of operating rooms for each data set is generated using sum of surgery duration divided by multiplying the regular opening time slots and number of days in the planning period that is: $O_k = \left\lceil \min_k \left\lceil \sum_p du_{pk} / (OT * D_k) \right\rceil \right\rceil$ where k is the number of instances in the data set. The number of PHU and recovery beds for each data set is randomly generated using the range $O_k - 1 \leq N_{PHU,PACU} \leq 2O_k$ (similarto Latorre-Núñez et al., 2016). The number of surgeons is selected double of the number of ORs. All of the operating rooms are considered multi-functional in a way that all of the surgeries can be done in any OR. Each surgical case needs its specialist surgeon. The surgeons are available at all time slots on all days, but there is only one surgeon for each specialty on the weekends.

Table 1. Data sets used for computational analysis

Data sets	Total slots	Over t. slots	ORs	PHU beds	Recovery beds	Surgeons	Days
1	27	6	2	1	1	4	3
2	27	6	3	2	2	6	3
3	27	6	3	2	2	6	6

The number of new arrivals in a period is an integer randomly selected in the range of $10\%P_k \leq N_{semi-urgent} \leq 20\%P_k$ .Also, the number of patients that cancel their surgeries is generated randomly varying in the range $0 \leq N_{cancel} \leq 5\%P_k$. The day of the arrival for semi-urgent patients and patients who cancel their surgery is selected randomly between the days of the planning period.

Table 2. Conditions of instances used for computational analysis

Data set	Instances	Number of initial elective patients	Number of semi-urgent arrivals	Number of leaving patients
DS 1	**1**	10	1	0
	2	15	2	0
	3	20	3	0
DS 2	**4**	25	3	1
	5	30	4	1
	6	35	5	1
DS 3	**7**	40	7	0
	8	45	7	0
	9	50	8	2

The MILP model has been coded and solved with an optimization's software on a computer with corei5 and 4GB RAM. Also, for implementing the rolling-horizon-scheduling-rescheduling framework we utilized the link between two softwares. The comparisons and analysis are done based on patient's point of view and hospital point of view.

Tables 3 and 4 represents thecomparison of the proposed scheduling-rescheduling framework and two introduced scenarios based on hospital and patients point of view respectively. The weights of all objectives (tardiness, overtime, idle time) are equal i.e. all of them are $1/3$ in the computations.

On the hospital's point of view (Table 3), for each method, the first column is related to operating rooms utilization rate. The second and third columns are related to idle time and overtime respectively and the last column reports utilization rate of recovery beds. Note that, the utilization of PHU beds is not considered because theduration of staying in PHU is short (in this paper 1 time slots or 20 minutes), so this unit is not reckoned a bottleneck resource. The allocated capacity in Sc 2 is considered 15% in this paper.

On the patients' point of view (Table 4), for each method, the first column shows the total number of operated patients. The second column is related to the number of patients operated before their due dates (or precisely on their due dates). The third column represents patients who are still in the waiting list. Finally, the last column reports the number of patients who have not been scheduled and their dates have been exceeded.

As can be seen in Table 4, the number of operated patients in scenario 1 is a little more than RH and scenario 2 in most of the instances. While the average number of operated patients is almost equal in scenario 1 and RH approach. In compensatory, the overtime used in Sc 1 is much more than RH which can cause related costs and dissatisfaction in personnel. In addition, in Sc 1 and Sc 2, there are one or two patients which their due dates have been exceeded in 6 instances, while there is not any patient whose due date is exceeded in the proposed framework. About theidle time of operating rooms, the proposed rolling horizon framework has performed better than Sc 1 and Sc 2 obviously. Subsequently,the utilization rate related to operating rooms in RH is more than two other methods. Also, the overtime consumed in the proposed RH approach is so little and is zero in most of the instances while the overtime in Sc 1 and Sc 2 are more. As can be observed, the average overtime in RH is 1.67 while it is 16 and 8.44 in Sc 1 and Sc 2 respectively. These points show the advantages of proposed scheduling-rescheduling framework in comparison whit two scenarios.

The comparisons of methods based on overtime and OR utilization rate are also depicted in Figures 4 and 5 which better shows the superiority of proposed method. As expected, with increasing the number of patient the utilization rate increases in each data set.

Table 3. Results of comparison of proposed method and two scenarios based on hospital points of view

Instance	Proposed rolling horizon approach				Scenario 1				Scenario 2			
	U.R	**Id.T**	**Ov.T**	**R.U.R**	**U.R**	**Id.T**	**Ov.T**	**R.U.R**	**U.R**	**Id.T**	**Ov.T**	**R.U.R**
1	0.48	65	0	0.40	0.44	71	6	0.40	0.48	65	0	0.41
2	0.75	32	0	0.50	0.75	32	5	0.50	0.77	29	6	0.51
3	0.93	9	0	0.54	0.93	9	14	0.58	0.80	25	3	0.48
4	0.81	36	0	0.42	0.77	43	8	0.45	0.76	45	9	0.43
5	0.91	17	0	0.49	0.83	33	18	0.50	0.74	50	7	0.47
6	0.95	10	3	0.55	0.90	19	21	0.57	0.81	35	5	0.53
7	0.77	86	5	0.57	0.69	118	18	0.55	0.72	106	18	0.56
8	0.80	75	3	0.68	0.72	106	25	0.68	0.75	92	12	0.67
9	0.84	62	4	0.76	0.75	94	29	0.76	0.78	82	16	0.74
Ave.	**0.80**	**43.56**	**1.67**	**0.55**	**0.75**	**58.33**	**16**	**0.55**	**0.73**	**58.78**	**8.44**	**0.53**
%RPD	**0%**	**0%**	**0%**	**0%**	**6%**	**34%**	**858%**	**0%**	**9%**	**35%**	**405%**	**4%**

Table 4. Results of comparison of RH method and two scenarios based on patients and hospital point of view

Instance	Proposed rolling horizon approach					Scenario 1					Scenario 2				
	Op.	<dt	waiting		>dt	Op.	<dt	Waiting		>dt	Op.	<dt	Waiting		>dt
			Elec.	s-u.				Elec.	S.U				Elec.	s-u.	
1	11	11	0	0	0	11	11	0	0	0	11	11	0	0	0
2	16	16	1	0	0	16	16	1	0	0	16	16	1	0	0
3	20	20	3	0	0	21	21	2	0	0	18	18	5	0	1
4	26	26	1	0	0	26	26	1	0	1	25	25	2	0	0
5	29	29	4	0	0	30	30	2	0	1	26	25	5	0	2
6	32	32	5	0	0	33	31	2	0	2	29	26	4	0	4
7	47	47	0	0	0	46	46	1	0	1	47	47	0	0	0
8	50	50	2	0	0	51	51	1	0	1	50	50	2	0	0
9	55	55	1	0	0	55	55	1	0	1	53	53	3	0	2
Ave.	31.78	31.78	1.88	0	0	32.11	31.89	1.22	0	0.67	30.56	30.11	2.44	0	1
[Ave.]	**32**	**32**	**2**	**0**	**0**	**32**	**32**	**1**	**0**	**1**	**31**	**30**	**2**	**0**	**1**

Table 5. Results of comparison of RH method and two scenarios based on value of objective function

Instances	Proposed RH			Scenario 1		Scenario 2	
	Obj.	**CPU (s)**	**%RPD**	**Obj.**	**%*RPD***	**Obj.**	**%*RPD***
1	0.15	1.35	0%	0.15	41%	0.17	0%
2	0.08	4.23	0%	0.12	50%	0.13	63%
3	0.02	39.18	0%	0.15	650%	0.10	400%
4	0.09	71.96	0%	0.19	111%	0.20	550%
5	0.04	1205.35	0%	0.26	550%	0.23	475%
6	0.05	1821.43	0%	0.21	320%	0.18	260%
7	0.27	235.92	0%	0.48	0.78%	0.44	63%
8	0.22	457.51	0%	0.52	136%	0.35	59%
9	0.20	831.56	0%	0.52	160%	0.38	90%
Average	**0.13**	**518.72**	**0%**	**0.30**	**224%**	**0.24**	**218%**

Table 5 reports the value of the objective function for all instances with applying the rolling horizon method and two scenarios. Also, the CPU time of proposed framework is given. According to the obtained results represented in Table 4, the value of the objectivefunction obtained by proposed rolling horizon approach is significantly better than two introduced scenarios in all instancesand on the average, the value of the objective function of proposed scheduling-rescheduling framework is 224% and 218% better than Sc 1 and Sc 2, respectively. Figure 6 represents this comparison and excellence of proposed scheduling-rescheduling method.

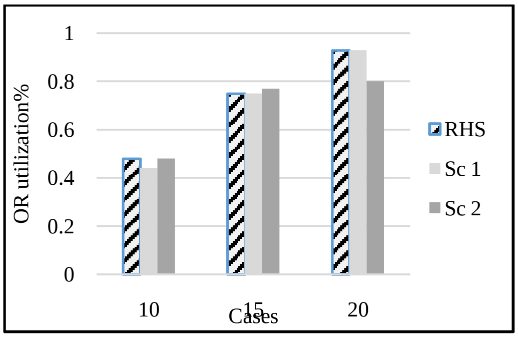

Fig. 4.a. OR utilization for data set 1

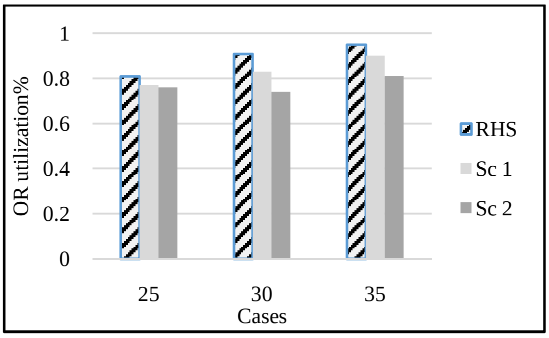

Fig. 4.b. OR utilization for data set 2

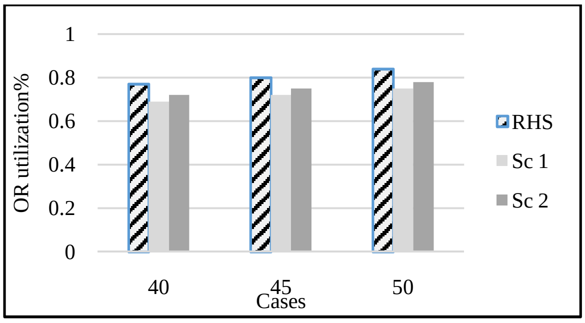

Fig. 4.c. OR utilization for data set 3

Fig. 4 OR utilization rate for data sets

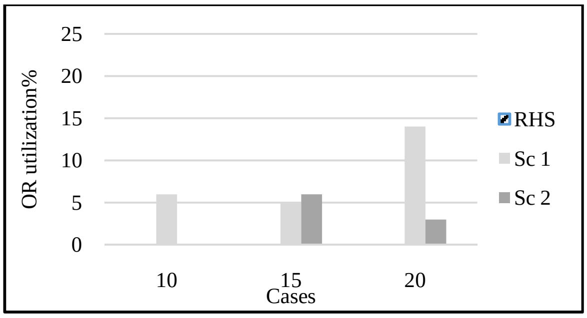

Fig. 5.a. OR overtime for data set 1

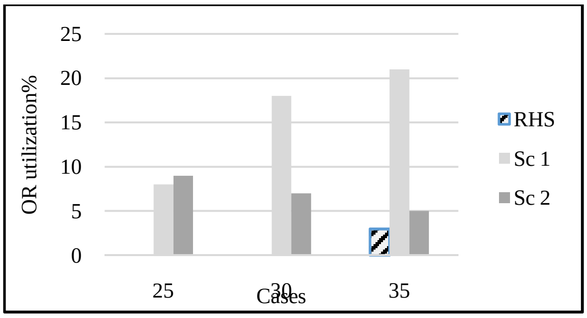

Fig. 5.b. OR overtime for data set 2

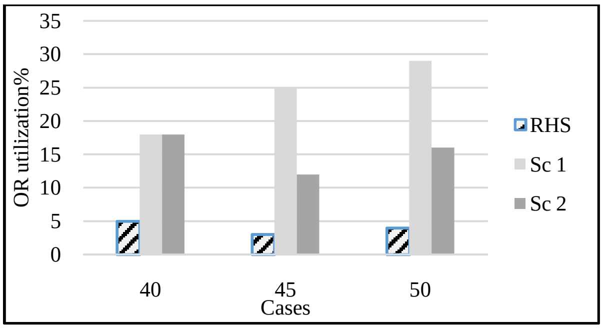

Fig. 5.c. OR overtime for data set 3

Fig. 5 OR overtime for data sets

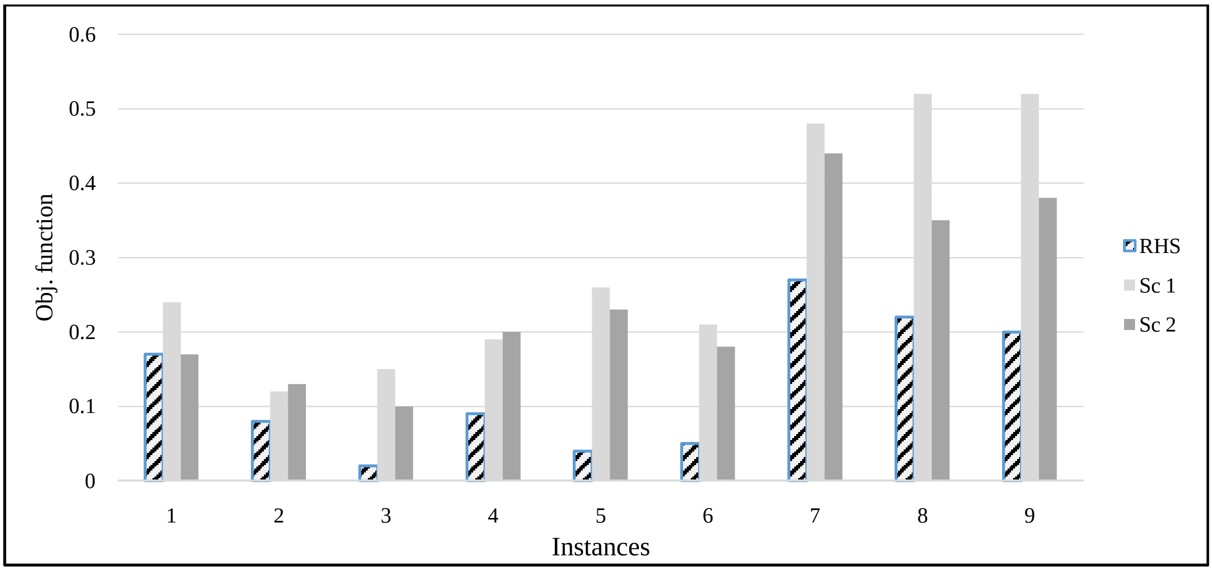

Fig. 6 The value of objective function obtained by three methods for test problems

- **Statistical comparison of methods**

In order to make the results statistically convincing, non-parametric paired Wilcoxon test is used based on number of operated patients (*op.*), number of patients remained in the waiting list (*wait.*), number of patients whose due dates have been exceeded (including who have been operated after their due dates and patients who have not been operated and their due dates is exceeded.(>*dt*)), utilization of operating rooms (*%Util*), number of idle time slotsand overtime slots recovery beds utilization (*%Re. util*.) and finally the values of objective function (*obj.*). Note that, because the obtained results were not normally distributed, Wilcoxon test is applied. In Table 6, the values of asymptotic significance and the Z statistic are reported. The tests are implemented using SPSS 22 statistical software. The significance level is selected 0.05 in the study. The results indicate that totally, proposed method outperforms two other methods. About thenumber of operated patients, the number of patients who are still in the waiting list and recovery beds utilization; there is no significant difference between RHS and Sc 1. Besides, there is no significance difference between RHS and Sc 2 under the number of patients who are still in the waiting list and recovery beds utilization. But in other items, especially, about objective function RHS outperforms Sc 1 and Sc 2. With comparing Sc 1 and Sc 2, it can be concluded that totally Sc 2 performs better than Sc 1.

Table 6. Wilcoxon signed rank test for RH, Sc 1 and Sc 2 based on performance measures

Performance metric		RHS-Sc 1	RHS-Sc 2	Sc 2 – Sc 1
OP.	Z	-1.34	-2.04	-2.04
	Assymp.sig.	0.180	0.04	0.04
Wait.	Z	-1.73	-1.30	-2.05
	Assymp.sig.	0.08	0.19	0.04
>dt	Z	-2.33	-1.83	-0.88
	Assymp.sig.	0.02	0.07	0.38
%Util.	Z	-2.39	-2.39	-0.30
	Assymp.sig.	0.02	0.02	0.77
Idle time.	Z	-2.37	-2.38	-0.29
	Assymp.sig.	0.02	0.02	0.77
Over time	Z	-2.67	-2.52	-2.11
	Assymp.sig.	0.01	0.01	0.04
%Re. Util.	Z	-1.36	-1.63	-1.79
	Assymp.sig.	0.18	0.10	0.07
Obj.	Z	-2.67	-2.52	-2.31
	Assymp.sig.	0.01	0.01	0.02

6- Case study

In order to evaluate the performance of scheduling-rescheduling framework better, a case study is implemented. This case is done in Sevome-Shaban hospital, Damavand city, Tehran province, Iran. In this hospital, the head nurse is responsible for planning and scheduling of operating rooms. Data for a week in October 2016 was available to us (it has been tried to choose a relatively busier week).The collected data related to patients include the date, start time and finish time of patients' surgeries and the start time and finish time of their staying in PHU and recoveryunit. Table7 represents the summary of data taken from surgery department of the hospital. There are four specialties including general surgeries, orthopedics, obstetrics, gynecology and ophthalmology.There are three operating rooms which are not multifunctional, such thatobstetrics and gynecology surgeries are done OR 1, general surgeries in OR 2 and orthopedics and ophthalmologyin OR 3. In this hospital, the first scenario is implemented which was explained in thelast section.The operating rooms are open from 8 am to 2 pm from Saturday to Thursday. If any surgery is done after 2 pm it is included in overtime.

Table 7. Summary of data related to the case study

Number of operating rooms	3
Number of surgical specialties	4
Number of surgeons	9
Availability of surgeons	2-6 days per week (ophthalmology surgeon only 1 day per week)
Number of PHU beds	1
Number of recovery beds	2
Number of surgical cases	62 (51 elective + 11 semi-electives)
Expected duration of surgeries	40-240 minutes per case
Expected duration of recovery (staying in PACU)	20-80 minutes per case
Expected duration of staying in PHU	20 minutes

The comparison of proposed rolling horizon scheduling-rescheduling framework and the actual schedule is done based on two criteria also used in thelast section including overtime and utilization rate or (Equivalently under time). The results reported in Table 8 indicate that the proposed framework outperforms the hospital schedule significantly. Also, figures7 and 8 depict overtime and OR utilization in the actual hospital schedule and the rolling horizon schedule. They clearly show that our proposed method surpasses the hospital existing schedule.

Table 8. Results of comparing between proposed RH approach and actual schedule of the hospital

Proposed rolling horizon scheduling							Hospital scheduling					
Op.	**<dt**	**Id.T**	**CPU (s)**	**Ov.T**	**% Ut**	**Obj.**	**Op.**	**<dt**	**Id.T**	**Ov.T**	**% Ut**	**Obj.**
62	62	126	95.63	4	61%	0.14	62	62	187	43	0.42	0.28

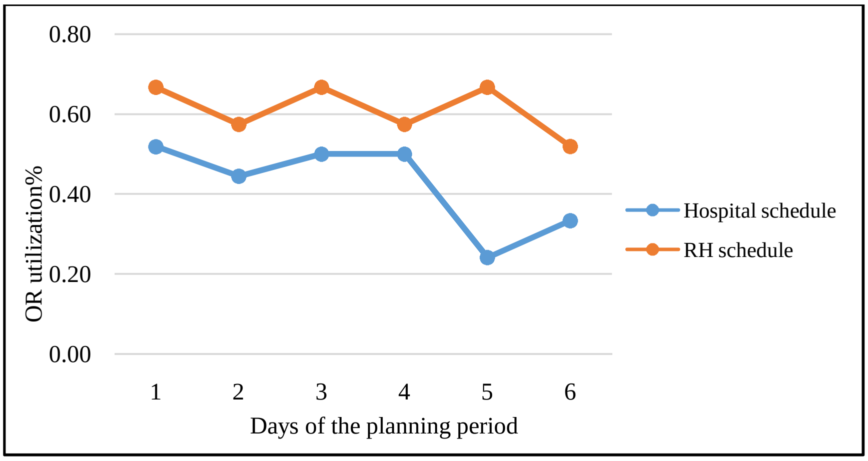

Fig. 7 Comparing of OR utilization between RH approach and the hospital schedule

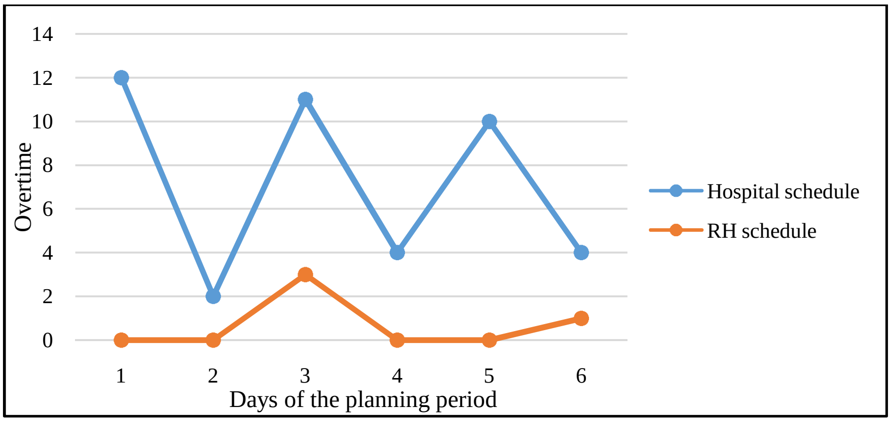

Fig. 8 Comparing of OR overtime between RH approach and the hospital schedule

Overtime is high and OR utilization is relatively low in the actual schedule (hospital). It seems that the schedule of the hospital has some weaknesses. The responsible of planning and scheduling of the hospital (head nurse) can use the proposed scheduling-rescheduling framework to enhance the efficiency of the planning and scheduling of the surgery department which leads to decrease overtime, increase OR utilization and finally enhance the satisfaction of patients and medical personnel.

7- Conclusions and future research

Efficient planning and scheduling is an important issue in surgery departments of hospitals and it has its own special difficulties particularly when two or more types of patients (base on urgency) should be scheduled. In this paper, we proposed a scheduling-rescheduling framework based on rolling horizon approach to handle elective and semi-elective patients. A novel MILP model as the core of the proposed approach was proposed and the process of the scheduling and rescheduling was explained. In summary, at first a schedule is set for all of the days of a planning period and on each day the scheduled patients are fixed and a rescheduling is done because of semi-urgent arrivals. the period moves forward to cover one more day. This process continues until all days of the planning horizon are covered. Various test problems were generated and the proposed approach was compared with two scenarios which are usually used by many hospitals. The numerical analysis and comparisons based on patients and hospital point of view indicated that the proposed rolling horizon approach outperforms two scenarios. In the first scenario,the semi-urgent patients would be operated in the first available OR (after operating elective patients) and in another scenario, a specified amount of capacity is determined for semi-elective patients.Besides, in order to make the results statistically convincing, statistical tests were conducted and the results were confirmed. In addition, a case study was implemented to bring up the applicability and evaluate the performance of the proposed rolling horizon scheduling-rescheduling framework in real-world problems. The proposed approach was compared with a hospital schedule and the outcomes indicated the superiority of the proposed method. Surgery departments can utilize the presented scheduling-rescheduling method in order to decrease overtime and idle time, increase the utilization of operating rooms and generally enhance the quality and efficiency of scheduling which leads to increase thesatisfaction of patients and personnel and quality of care.

As mentioned, in Operating room scheduling various resources should be considered such as surgeons and nurses, recovery beds, ICU beds, ward beds andetc., because they affect planning and scheduling of surgeries.Future research papers may deal with considering other resources not considered in this paperand studying the trade-off between them. Also, Uncertainty is an inherent characteristic of operating room scheduling problem, because of variability in the surgery duration, thelength of stay after surgery and also unexpected arrivals. Considering uncertainty in the studied problem of this paperincludinguncertainsurgery and recovery duration and handling other types of patients based on the urgency of surgeries such as emergency patients would be interesting.

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