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Operating Room Planning under Surgery Type and Priority Constraints

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Abstract
Operating room (OR) planning is critical in healthcare systems to reduce cost and improve the efficiency of OR scheduling. The OR planning problem is complicated, involving many conflicting factors, such as overtime and idle time, both of which affect OR utilization and consequently affect cost to a hospital. Allocating different types of surgeries into OR blocks affects the setup cost, whereas priorities of surgeries affect OR block scheduling. Surgery durations affect both OR utilization and OR block scheduling. Traditionally, one important method for OR block scheduling is the bin packing model, and the longest processing time (LPT) rule is the most commonly used method to generate the initial sequence for bin packing. In this study. We propose a multistep approach and a priority-type-duration (PTD) rule to generate the initial sequence for bin packing. The results of our case studies show that our PTD rule outperforms the LPT rule based on the cost to OR scheduling.

Keywords: Operating room, Planning, Cost, Elective case

1 Introduction

In healthcare systems, the cost of operating rooms (ORs) is high. On average, OR charges are $62 per minute, ranging from $22 to $133 per minute in different hospitals, with OR overtime charges much higher (Macario 2010). The surgical demand of ORs is high too. The total number of surgical cases performed in 2010 in the US was 51.4 million (CDC 2010). Such surgical demand is increasing because of the aging population (Etzioni et al. 2010). To meet the increasing surgical demand, two options are possible. One option is to increase the capacity of the healthcare system, i.e., to build more facilities, train more surgeons, nurses and other staff; and the other is to increase the effectiveness and efficiency of OR management based on the existing capacity. The first option to increase the capacity is under constraints such as budget, space, human resources, and is infeasible for some hospitals in some area, and comparatively the second option to improve the effectiveness and efficiency of OR management is generally more meaningful and feasible for hospitals.

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However, OR management is complicated and manifold, including four factors such as three phases in OR management, three stages in a peri-operative process, different stakeholders, and evolving relationship between system components. First, OR management covers three phases, OR planning, OR scheduling, and adaptive control. OR planning is on a long time horizon, such as a quarter or a year. At planning phase, three of main concerns of OR management are OR block scheduling, resource allocation, and budget allocation. OR block scheduling indicate the allocation of OR block times and the assignment of surgery specialties to daily OR slots. Resource allocation specifies the number of ORs open on a day, human resource (anesthesiologists, surgeons, nurses, staff, etc.) and equipment needed for each OR. Consequently, costs of overtime, idle time, setups, and payment are involved in OR block schedules and resource allocation, and thus under the budget constraints. OR scheduling is on a short time horizon, such as three days or a week. It concerns the assignment of patients to ORs and the sequence of surgeries in each OR. Adaptive control is on a real time horizon, and deals with dynamic disturbances during the real execution of OR schedules, such as variation in surgery times, emergencies, surgery cancellations, etc. Surgery re-sequencing and resource reallocation are involved in the adaptive control phase. Obviously, OR planning is the most important among three phases, because it sets constraints to OR scheduling and adaptive control, such as the number of ORs. At the planning phase OR managers forecast the demand of surgical services based on historical data. They also estimate the duration of each surgery. After determination of these factors they establish a plan to respond to the demand by considering resource and budget constraints.

Second, the peri-operative (peri-op) process generally consists of three stages, pre-operative, intra-operative, and post-operative. OR management for each stage has different concerns. Pre-operative holding unit (PHU) is a place where patients are prepared for anesthesia and surgery. One of the main concerns in this stage is if a patient can arrive at the OR on time. ORs are in the intra-operative stage, and main concerns are OR utilization, overtime, idle time, and the number of setups. Post-anesthesia care unit (PACU) and intensive care unit (ICU) are in the post-operative stage, where patients recover after the surgery. One of the main concerns in this stage is PACU boarding, i.e., a patient stays in PACU too long or overnight, causing all of the beds in PACU are occupied and the next patient is held in OR after the surgery. Three stages in the peri-op process are illustrated in Figure 1.

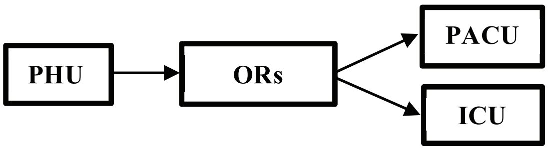

Figure 1: Three stages in the peri-op process.

Third, there are different stakeholders involved in OR management, such as patients, surgeons, nurses, staff, and OR manager. Different stakeholders have different concerns. For example short waiting time and low charges are the main concerns for patients; the number of surgeries performed in the planning phase is one of the main concerns for surgeons; the number of shifts and overtime are the concerns for nurses and staff. High quality of surgical services is one of the main concerns for OR manager, including high patient satisfaction, high patient safety, and low cost (Fei et al. 2010).

Fourth, there are trade-offs between different concerns involved in different phases, stages and stakeholders, and these concerns are changing over time. By the definition of sociotechnical systems (STS), a system consists of many different components, and management has different concerns about the system performance (Briggs et al. 2010, Davis et al. 2013). The performance of an STS system can be evaluated from different perspectives, such as economics, environment, and society (Briggs et al. 2010, Davis et al. 2013, Racherla and Mandviwalla 2013), which are fundamental to evaluate the performance of healthcare systems as well (Braaten 2015, Brennan Ramirez et al. 2008, Zaid et al. 2015). However, these diverse concerns define the relationship among system components differently, and concerns on a system evolve as the system settings change over time (Davis et al. 2013, Beck 2014, Pellegrino 2015). Consequently, as the relationship among system components evolves, inconsistencies of system performance arise over time.

A wide range of research methodologies were used to address, evaluate and optimize the performance of OR planning and scheduling (Cardoen et al. 2010). Marques and Captivo (2012) used integer programming to assign elective surgeries to an operating room, a day and a specific period of time on a weekly planning horizon in order to maximize the use of surgery theater. They used real data to test their approach and to compare their results with actual OR performance. Although their approach increased the overall OR performance, some points are neglected such as stochastic surgery duration or effect of PACU on overall OR performance. Lamiri et al. (2008) established a stochastic model of operating room planning for both elective and emergency cases, in order to minimize the overtime costs of ORs and the costs of elective cases. They used Monte Carlo simulation and mixed integer programming to solve their model. Their model reduced the cost of ORs over the long time horizon, and fulfilled the demand of emergent cases, but their approach considered OR as an isolated component of OR theater, and the correlation among PHU, OR and PACU has not been considered. Hsu et al. (2003) proposed a tabu search approach to sequence elective cases in order to minimize the number of nurses in PACU. Testi et al. (2007) developed a hierarchical three-phase approach for scheduling of operating rooms in order to improve overall operating theatre efficiency. At the first phase, a bin packing problem was solved in order to select the number of surgeries to be weekly scheduled. At the second phase, a blocked booking method was used to determine optimal time tables, which defined the assignment of wards and ORs. At the third phase, the longest processing time (LPT) rule and the shortest processing time (SPT) rule were used to sequence cases. Considering the surgery duration as deterministic can be a shortcoming of this work. Fei et al. (2010) designed a weekly surgery scheduling method for an operating theatre in order to minimize the overtime cost in the operating theatre, maximize the utilization of ORs and to minimize the unexpected idle time between surgical cases. This problem was solved in two phases. First, the planning problem is solved to give the date of surgery for each patient with regard to the availability of operating rooms and surgeons. Second, a daily scheduling problem is devised to determine the sequence of surgeries in each operating room in each day, taking into account the availability of recovery beds.

Many researchers tried to assign the surgery cases to ORs in order to optimize the OR efficiency from different perspectives, but there is a little work on the effect of surgery priority and surgery types on the overall performance of ORs. In most cases the surgery type is omitted at planning phase, and several surgery types are scheduled together in a single OR. This combination not only increases the number of setups for each OR but also the idle time. In most studies at the planning phase, the surgeries are sequenced by the LPT rule according to the surgeries duration.

2 Procedure

According to surgery priorities patients can be divided to five major groups (Valente et al. 2009) as in Table 1.

We divide patients in to five groups by a priority assigned to surgeries. Priority p_i is randomly generated from a uniform distribution of [1, 5] as an integer value, and the larger the p_i the higher priority of a surgery. According to the historical data from a local hospital there are 24 surgery types. Thus the surgery types in this study are randomly generated from uniform distribution of [1, 24] as an integer value. To achieve efficient OR planning the surgery duration must be estimated accurately, many researchers used historical data to estimate surgery duration and some others used log-normal distribution to estimate surgery duration (Zhou and Dexter1998). In this study surgery durations are randomly generated from uniform distribution of [60,180] based on the historical data from the hospital. The unit of time is minute for all time values. OR block time is set to be 10 hours (600 minutes) for all ORs. Each surgery can be assigned to any OR, but a setup cost occurs if different types of surgeries are assigned to the same OR.

Table 1: Urgency Related Groups

URG*	Clinical assessment	MTBT**(days)
A1	Evident fast progression of disease affecting outcome by delay	8
A2	Potential fast progression of disease affecting outcome by delay	30
B	Severe pain and/or dysfunction and/or disability, but no fast progression of disease affecting outcome by delay	60
C	Mild pain and/or dysfunction and/or disability, but no fast progression of disease affecting outcome by delay	180
D	No pain, dysfunction and disability and no fast progression of disease affecting outcome by delay	360

*Urgency-Related Groups (URG)
** Maximum Time Before Treatment (MTBT)

The interest at planning phase is to determine a set of elective surgeries over the planning horizon in order to allocate resources. In this study N elective cases with different priorities and different surgery types are selected from the waiting list. A set of costs are defined as a measure to evaluate the ORs planning, such as the regular cost, overtime cost, idle time cost and setup cost. Equation (1) defines the total cost in the planning phase.

$$\sum_{j=1}^{m}(R_t C_R + O_t C_O + I_t C_I + f_S C_S) \tag{1}$$

Where:

- j: The index of operating rooms (j=1, 2,…m)
- R_t: The amount of regular working time of each OR (min)
- O_t: The amount of overtime working time of each OR (min)
- I_t: The amount of idle time of each OR (min)
- f_s: The number of set-up(s) for each OR

- C_R: Cost per unit of regular working time ($/min)
- C_O: Cost per unit of overtime working time ($/min)
- C_I: Cost per unit of idle working time ($/min)
- C_S: Cost of each set-up ($)

The average cost of OR regular working time varies over a wide range from $22 to $133 per minutes. The actual cost depends on many factors including: which country you are in, as resource costs vary from country to country; which surgical procedure is being performed, whether the OR cost includes fixed overhead costs that are constant regardless of the number of surgeries performed, or if it only accounts for the variable costs, which vary according to the number of cases performed; or whether professional fees of the physician work in the OR are included (Macario 2010). We assume the cost per unit of idle time is equal to the cost per unit of regular time $C_R=C_I$, because monthly payment to staff is fixed regardless of whether they are working or waiting for the beginning of next surgery. According to the Fair Labor Standards Act (FLSA) (USDOL 2011), overtime must be paid at a rate no less than 1.5 times regular rates after 40 hours of work in a week, so we set $C_O=1.5\times C_R$. Setup cost generally depends on the complexity of surgeries, equipment and resources used for surgeries. Thus this cost varies over a wide range. In summary Equation (1) can be expressed as Equation (2).

$$\sum_{j=1}^{m}((R_t + 1.5O_t + I_t)C_R + f_S C_S) \tag{2}$$

A bin-packing model maximizes utilization and minimizes the idle time, which consequently affects the cost at the planning phase. The following model represents the general mathematical model of bin packing for ORs.

Minimize

$$z = \sum_{j=1}^{m} y_j \tag{3}$$

Subject to:

$$\sum_{i=1}^{n} t_i x_{ij} \leq T \tag{4}$$

$$x_{ij} = \begin{cases} 1 & if\ surgery\ i\ is\ assigned\ to\ OR\ j \\ 0 & otherwise \end{cases} \tag{5}$$

$$\sum_{j=1}^{m} x_{ij} = 1 \tag{6}$$

$$y_j = \begin{cases} 1 & if\ \ OR\ j\ is\ used \\ 0 & otherwise \end{cases} \tag{7}$$

T: The total available time of each OR (600min)
i: the index of assigned surgeries to OR j, $i=\{1,2,\ldots n\}$

In the above model the objective function (3) minimizes the number of required ORs. Constraints (4) imposes T as the total available time of each OR. x_{ij} is an integer decision variable that equals to 1 if the surgery i is assigned to the OR j. Constraints (6) guarantees that each surgery is assigned to an OR only once. y_j is an integer decision variable that equals to 1 if the OR j is used over the planning horizon.

We propose a simple multi-step procedure to sequence cases in order to generate initial sequence for bin packing. Since the priority is the most important factor for performing a surgery, we first sequence surgeries according to their relative priorities. Thus we have five groups. The second step is to group surgeries according to surgery types within each priority group. The third step is to sequence surgeries in each subgroup by the LPT rule based on their durations. After obtaining the initial sequence, we assign surgeries to ORs from the head of sequence (the highest priority) to the tail of sequence (the lowest priority), while we avoid combining different surgery types into the same OR. If there is still some remaining time in an OR after assigning all cases, we search for a compatible case from lower priority groups with the same surgery type. If there is no compatible cases, we leave the remaining time idle. The proposed procedure is named as PTD (Priority-Type-Duration) and summarized as follow:

- Step 1. Group surgeries according to their priority.
- Step 2. Group surgeries in priority groups by types.
- Step 3. Within each subgroup sequence surgeries according to their duration by LPT rule. Now we have the initial sequence for bin-packing.
- Step 4. Assign surgeries to ORs according to initial sequence.
- Step 5. Search lower priorities for compatible cases with the same surgery type. This step is to reduce the idle time and number of setup as well.
- Step 6. For the last case of each surgery type overtime is allowable.

3 Evaluation scheme

We use several performance measures such as OR utilization, number of overtime and idle time number of ORs and number of setups to evaluate the performance of ORs. We sequence surgeries in order to minimize the overall cost of planning phase which consists of maximizing the ORs utilization, reducing overtime and under-time, reducing the number of required ORs and reducing the number of set-up. We compare our proposed method with the well-known method LPT. The above-mentioned factors were calculated for both methods. Smoothness Index (SI) is used to compare the evenness of surgery loads distribution between ORs. Equation (8) defines the SI for both methods.

$$SI = \sqrt{\left(\sum_{j=1}^{m}(T - \sum_{i=1}^{n} t_i)^2\right.} \tag{8}$$

Where:
T: Total available time for each OR (600 mines)

Equation 9 defines the utilization of ORs for each method. Utilization is the ratio of regular working time and total available time of all ORs.

$$Utilization = \frac{R_t}{NO \times T} \tag{9}$$

Where:
NO: is the number of ORs required to meet the demand

4 Results and Discussion

500 elective surgeries are randomly generated for one week (H=5 days). The PTD and LPT rules were coded using MATLAB R2015b and the above-mentioned factors for each method were calculated, to prepare more comprehensive data this scenario was replicated 200 times that is equal to four years. Table 2 shows the computational results.

4.1 Number of ORs and number of setups:

From the managerial perspective NO should be minimized to reduce the overhead, staffing and equipment costs. Figure 2 shows the NO for PTD and LPT. As shown in Figure 2 and Table 2, the average number of required ORs for PTD is significantly smaller than those for LPT. A t-test was performed to test the significance of difference between two methods, with p value of $p<0.001$ the difference between two methods is statistically significant. The calculated number of ORs is for a planning horizon of 5 days. So the average daily demand of PTD for ORs roughly equals to 20 that is compatible with the capacity of medium size hospitals.

Number of setup: This factor represents the number of setups different equipment for different surgery types. In our methods we avoid from combining different surgery types in the same OR that reduced the number of setup on average about 4.3 times comparing to LPT. Figure 3 shows the f_s for PTD and LPT. A t-test was performed to test the significance of difference between two methods, with p value of $p<0.001$the difference between two methods is significant.

4.2 Idle time and overtime

Idle time represents the proportion of total available time that elapsed idle either waiting for the start of next surgery or due to lack of compatible surgery duration. As figure 4 shows, on average the PTD reduces the idle time almost 2.5 times comparing with the LPT. A t-test was performed to test the significance of difference between the two methods, with p value of $p<0.001$ the difference between the two methods is statistically significant.

Overtime: For LPT algorithm overtime is not allowed but for PDT we could go overtime just for the last case of each surgery type. This is to reduce the number of setup, because each setup not only causes setup cost but also results in more idle time. Figure 5 shows the overtime for PTD and LPT, average of 286 minutes overtime for 111 ORs means 2.5 minutes for each OR that is negligible.

Table 2: The computational results

		PDT	**LPT**
R_t	Min	58197	58338
	Max	61847	62105
	Average	60024.78	60269.26
	SDV	794.57	800.27
O_t	Min	0	0
	Max	966	0
	Average	286.38	0
	SDV	160.77	0
I_t	Min	3946	14963
	Max	8675	18346
	Average	6801.35	16660.39
	SDV	811.95	661.65
NO	Min	104	123
	Max	116	133
	Average	111.37	128.21
	SDV	1.93	2.03
f_s	Min	104	472
	Max	116	494
	Average	111.37	484.67
	SDV	1.93	4.10
SI	Min	824.01	1431.97
	Max	1490.99	1687.70
	Average	1195.47	1553.20
	SDV	125.58	52.31
Utilization	Min	87.31	76.65
	Max	93.67	79.96
	Average	89.83	78.34
	SDV	1.10	0.61

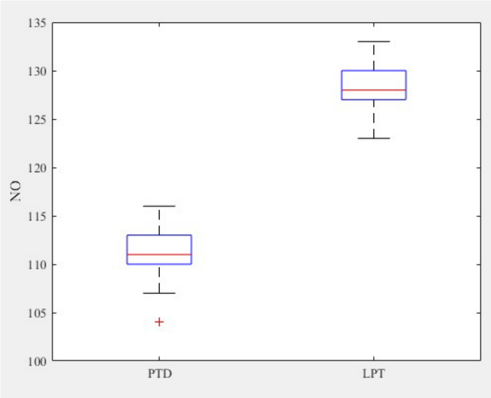

Figure 2: Number of ORs

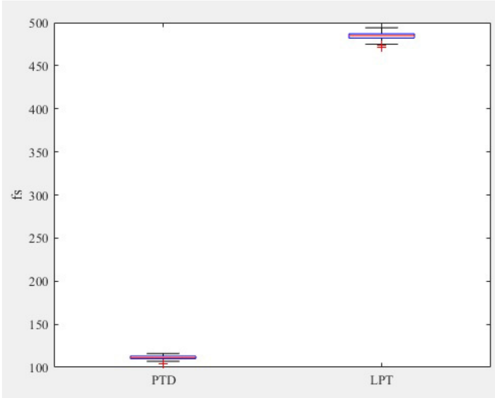

Figure 3: Number of Setup

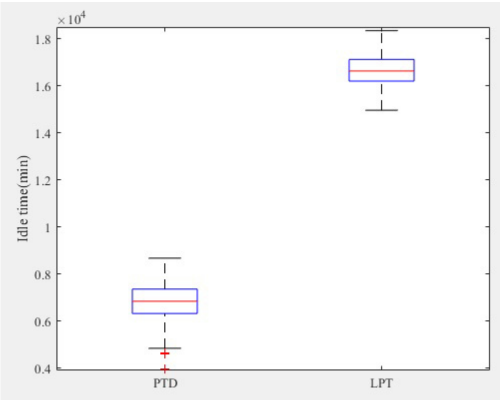

Figure 4: Idle time

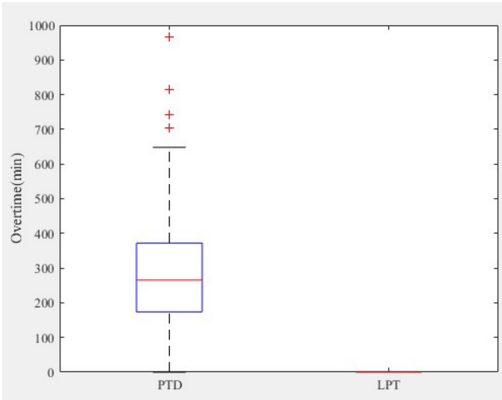

Figure 5: Overtime

4.3 Utilization and smoothness index

Equation (9) defines the utilization of ORs which means the percentage of total available time spent on surgeries. Figure 6 shows the utilization for PTD and LPT. With average utilization of 89.83% PTD performs about 10.4% over LPT. The reason for better performance of PTD is the step 5 that searches for the same surgery types from lower priority groups and also for the last case overtime is allowable for PTD that slightly leads to overtime but decreases the idle time much more significantly. A *t*-test was performed to test the significance of difference between two methods, with *p* value of $p<0.001$ the difference between two methods is totally significant.

Smoothness index represents the load evenness of ORs which means how much the working time of ORs are close together. Figure 7 shows SI for PTD and LPT. A *t*-test was performed to test the significance of difference between two methods, with *p* value of $p<0.001$ PTD performs significantly more even than LPT.

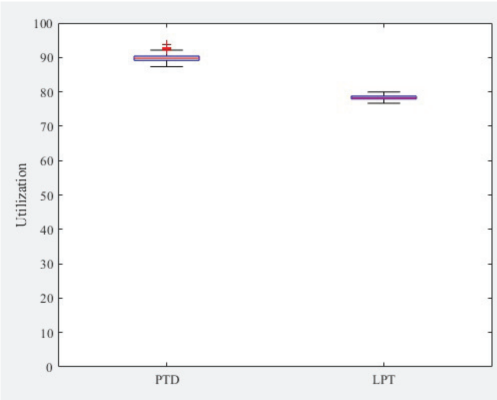

Figure 6: Utilization

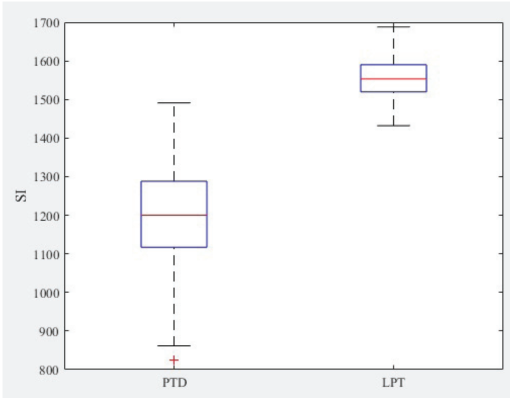

Figure 7: Smoothness Index

4.4 Overall cost

We uses Equation (2) and average value of R_t, O_t, I_t, and f_s to calculate the overall cost of planning horizon for both methods. Equation (10) shows the overall cost for PTD and LPT.

$$C_{PTD} = 67255.7C_R + 111.37C_S$$
$$C_{LPT} = 76929.65C_R + 484.67C_S \quad (10)$$

To compare the overall cost for both methods, we consider the average cost of regular time as C_R=*\$60*. To avoid prejudice in favor of number of setup, we fluctuate the setup cost between 0 and \$2000. As it is shown by Figure 8 the overall cost of PDT is significantly lower than LPT no matter how much the setup cost is. The PDT overall cost has a lower sensitivity to setup cost and ranges over [4.03, 4.26] million dollars with different setup costs but for LPT the overall cost varies more steeply ranging over [4.61, 5.59] million dollars.

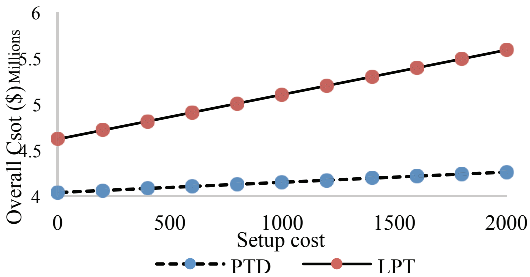

Figure 8: The overall cost with different setup costs

5 Conclusion

Operating room planning is an important phase for OR management; resource allocation is the main objective of this phase. Regular working time, overtime, number of ORs, instrument and equipment are some indicators for capacity dimensioning at the planning phase. An efficient OR planning assesses a tradeoff among these indicators; this assessment could be based on some financial criteria, but cost structure of operating room is often complex. It makes the planning phase more complicated. In this study we propose a multistep procedure to assign surgeries to ORs on a weekly planning horizon. This procedure (PTD) groups surgeries according to their priority, surgery type and duration to form the initial sequence for bin-packing. Using PTD we reduce the idle time, number of required ORs and number of setups that led to higher utilization and more equal load distribution among ORs. By taking surgery types into account PDT reduces the number of OR setups. Since LPT is the most common rule in OR scheduling we compare the PTD with LPT. The LPT does not consider the priority of surgeries and just goes with the surgery duration. Priority is the level of urgency that a surgery has and surgeries with higher priority should be performed earlier and PTD successfully considers the priority. From the cost perspective, PTD in comparison with LPT significantly reduces the idle time and number of setups that leads to a higher utilization and a significant lower overall cost. Although PDT makes more overtime but at the same time it reduces the idle time much more significantly that leads to a much lower overall cost. Although in this study PTD improves several efficiency indicators, there are still some spaces to improve. Considering surgery duration as stochastic value and integration of OR with PHU and PACU can be the next step for us to evaluate the OR performance more realistically.

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