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Operating Room Scheduling considering Patient Priority: Case of Shomal Hospital in Amol

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A B S T R A C T

Nowadays, hospitals are seeking to reduce their costs and to improve their financial circumstances. They are looking to reach the highest level of patient satisfaction as well. Operating rooms are one of the most critical departments and a great source of income in hospitals. In this research, an operating room scheduling problem is studied, which considers patient priorities based on a real case study. The problem comes from a medium-size private hospital in the north of Iran. To tackle this problem, a mixed-integer-program model is presented. The model considers the hospital's resources and constraints as well as patients' priority according to their age and the type of operation they need. In this model, assigning elective patients to operating rooms and the sequence of patients' surgeries have determined to minimize the surgeon waiting time as the objective function. The model is implemented in Cplex 12.9 software, and the efficiency of the model is shown by comparing the obtained results with the current situation. Real data of one week from the hospital is used to prove the efficiency of the model. Analyzing the results show a 35 percent improvement compare to the hospital's current scheduling method.

1. INTRODUCTION & LITERATURE REVIEW

Improving patient satisfaction and reducing the operating costs are two contradictory objectives in today's hospitals. Nevertheless, a successful health center should certainly work to improve both mentioned goals at the same time optimally. Within a hospital, one of the most important and costly departments is the surgery (operating) rooms department. Moreover, it is one of the main sources of income for a hospital at the same time. Hence, hospital performance is significantly affected by how its operating rooms section is managed and performed [20]. Due to abundant research related to operating room scheduling, there is wide-spreading literature on this subject. The first review paper was presented in 1978 [2]. However, because of the growing number of elderly people and consequently increasing the demand for surgeries [13], the importance of operating room scheduling has also significantly increased. Due to the conflicts in priorities and preferences of stakeholders as well as limitations of available resources, planning various and important tasks at the department of operating rooms is a difficult and complex job. All these together, clearly indicate the importance of having an

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optimized schedule for operating rooms in a hospital. Generally, operating room scheduling problems can be categorized based on the following criteria [27].

1.1. Patient characteristics

The research literature on operating room scheduling divides patients into two general categories of elective and non-elective patients, depending on if a surgery must be performed urgently and unexpectedly or if it may be planned well in advance. In this study, we focus only on elective patients. As an example of this type of operating room scheduling, Adan and Vissers [1] consider both inpatients and outpatients in their research. Another example is the work of Wullink et al. [29] in which they try to improve the responsiveness to emergencies by examining whether it is necessary to reserve a separate operating room or to reserve some capacity in all elective operating rooms.

1.2. Performance measures

performance criteria includes operational measures that may directly show the performance of the system such as patient and surgeon waiting time, utilization, makespan, financial value, preferences or throughput, patient deferral, etc. [7]. Patient waiting may happen as staying on the surgery waiting list or as the waiting time between 2 consequent surgeries or because of the lack of operating room capacity. It certainly may decrease the patient satisfaction level. Surgeon waiting time can happen because of man reasons. For instance, the patient is not ready on time. It may also happen because of the shortage in other resources, for example, the operating room is not prepared for a specific surgery, or it is not available due to lack of capacity. On the other hand, operating room overtime means that the total available time of surgeries in an operating room is larger than the scheduled time for that operating room. In fact, it causes an extra cost for the hospital. Denton et al. [9] showed how the surgery case sequencing can reduce both patient and surgeon waiting times as well as operating room overtime. Van Berkel and Blake [28] used a discrete-event simulation approach to examine how a change in throughput causes a decrease in the waiting time. In particular, they studied the impact changing the capacity of beds in the wards as well as the amount of available time at each operating room on the throughput.

1.3. Decision level

it should be determined that for which intervening group of the health system, the decision is being made. For instance, if the decision is related to operating room capacity, patients, or surgeons. For example, Azadeh et al. considered scheduling patients in emergency department regarding the treatments priority of the patients. They formulated the problem as flexible open shop problem and proposed a mixed integer linear programming model to minimize the total waiting time of patients. They also developed a genetic algorithm to solve the problem [3]. Oostrum et al. addressed the problem of operating room scheduling at the tactical level of hospital planning and control. They proposed cyclic operating room schedules, so-called master surgical schedules (MSSs) to tackle the problem. Regarding the uncertain duration of surgeries, constructing the MSSs is modeled as a mathematical model containing probabilistic constraints. They proposed a column generation approach that maximizes OR utilization. They also tested the proposed approach with data given from the Erasmus Medical Center [24]. Li et al. developed a multi-objective integer linear programming (ILP) model to optimally schedule elective surgeries based on the availability of surgeons and ORs. The objectives of this research include: (1) minimizing the number of patients waiting for service; (2) minimizing the underutilization of OR time; (3) minimizing the maximum expected number of patients in the recovery unit; and (4) minimizing the expected range of patients in the recovery unit. They develop two goal programming (GP) approaches, namely lexicographic GP and weighted GP, for this problem [17].

1.4. Uncertainty

Some researchers considered uncertainty related to expected surgery duration, patient's arrival, or access resources. Persson and Persson [24], describe a discrete-event simulation model to study how resource allocation policies at the department of orthopedics affect waiting time and utilization of emergency resources, taking into account both patient arrival uncertainty and surgery duration variability. Hooshmand et al. considered stochastic surgery times for a daily schedule of ORs. They considered scheduling and rescheduling decisions in a single model, simultaneously. For this purpose, they developed a novel mathematical model and applied a genetic algorithm to solve the large-size test problems [14]. Jebali and Diabat developed a two-stage chance-constrained stochastic programming model for ORs planning regarding the random surgery duration, random patient Length of Stay (LOS) in the ICU, and random reserved resources for the emergency cases. The objective function aims to minimize patient-related costs, OR utilization costs, and penalty costs for exceeding ICU capacity. They proposed a sample average approximation algorithm (SAA) to solve the model [15].

1.5. Research Methodology

A variety of techniques or methods are performed to evaluate and solve the operating room scheduling issues. All operational research based techniques can be summarized in two categories of discrete simulation and mathematical programming optimization. Basson and Butler [10], Denton et al. [11], Dexter and Ledolter [12], Ballard and Kuhl [13], Bowers and Mould [14], used the discrete-event simulation to model and solve the operating room planning problems. Mulholland et al. [15], P. Lebowitz [16], Dexter et al. [17], and P´erez et al. [18] used a mathematical programming optimization technique to model these problems.

Generally, surgeries in hospitals can be categorized as elective or non-elective surgery. Bouguerra et al. [19] proposed a mathematical programming model to solve their problem. They optimized two main objectives. The first objective is to maximize the utilization of the operating rooms, and the second objective is to minimize the idle time between the elective surgeries. Zhao and Li [20] studied a model to schedule elective surgeries in operating rooms. They proposed a mixed integer nonlinear programming (MINLP) model as well as a constraint programming (CP) model to solve their problem. They considered three aspects of the daily scheduling decisions, first, the number of operating rooms to open, second, the allocation of surgeries to operating rooms, third, the sequence of operations in each operating room. Nazeriani et al. [21] studied an elective surgery case and proposed an ant colony optimization (ACO)to solve their problem. They considered three steps for an elective surgery: 1- pre-surgery, 2- during surgery, 3- after surgery. Ranjbar and Ghafourian [22]divided each surgery into four steps: 1- From the moment of putting patients on beds of operating rooms until patients anesthesia, 2- surgery, 3- end of surgery and starting nurses' tasks, 4- operating room cleaning. In order to simplify, the duration of steps 1, 3, and 4 were considered fixed for all patients. The objective function of their study includes two parts: 1- minimize surgeons' overtime, 2- minimize surgeons' waiting time between surgeries (operating room idling time). Rostami [23] considered a nonlinear programming model for scheduling and optimal allocation of operating rooms. The objective function of his model is to minimize the maximum delay and utilization time of operating rooms. By this objective function, surgeries and surgical staffs are assigned to operating rooms in such a way that the duration between two surgeries in an operating room, as well as patient and surgeon waiting times, are decreased. Chenani et al. [24] proposed a meta-heuristic method to optimize the allocation of hospital beds. In their study, patients are generally divided into two groups of elective and non-elective patients.

As contributions, in this research, a mathematical model is proposed for the elective surgeries scheduling on operating rooms of a hospital. In this study, patients' priorities are taken into account while minimizing the surgeon's idle time between surgeries. This problem comes out of a real case practice in a medium-size general hospital in Iran. According to this case study, some patients might get priority over the other ones because of their age or type of surgery. Results are discussed by comparing the proposed method with the current practice of the hospital.

2. PROBLEM DEFINITION AND MATHEMATICAL FORMULATION

This study is based on the real case of Shomal Hospital in Amol, Mazandaran, Iran. The current process of operations planning at the operating room departments of this hospital is as follows. In the first stage, patient surgery's time is determined by the surgeon. As a result, patients are elective. In the second step, patients are sequenced and assigned to operating rooms manually. Some of the main practical constraints taken into account in this process include the possibility of surgery of each patient in a particular operating room, avoiding the overlapping of a surgeon assigned to different operating rooms, and priority of patients under the age of 7 years and patients with a hysterectomy surgery to other patients. Depending on the hospital's genericity or specialty, various types of surgeries might be performed in the operating room department. However, some surgeries have to be completed in a special operating room due to the specific facilities that might be needed. In Shomal hospital, eye surgeries should be done in one specific operating room set for this purpose, and the remaining types of surgeries are performed in other operating rooms. Working hours (available time) of all operating rooms are assumed to be the same (From 8 am to 7 pm). Surgeons, as another central resource, have their own patient and their working hours in the surgery department is not the same. Surgeons are usually interested in doing their surgeries at the appointed time to decrease their waiting time. The duration of operations is predictable by surgeons. Therefore, in this study, surgeries' durations are assumed to be known in advance. Anesthetic technicians are considered as an unlimited type of resource in this study. General steps of surgery in this hospital are first, putting the patient on the bed of operating rooms until patient anesthesia (duration of anesthesia assumed the same for all surgeries); Second, the main part of surgery; Third, after operation cares by nurses (length of this step is also considered the same for all patients).; Forth, operating room cleaning and preparedness for the next surgery (this time is also assumed to be the same for all surgeries.).

The sequencing and scheduling of patients and surgeries are planned for each day (24 hours). Therefore, this research seeks to present a timetable for one day of operating room department of the hospital so that the objective is to minimize the total surgeons' waiting time. For this purpose, the explained problem is formulated as a mixed integer linear programming model.

Before presenting the general model, the set of symbols, including parameters and decision variables of the model are introduced in the following section.

2.1. Parameters

$R = \{1, ..., |R|\}$: set of operating rooms.

$S = \{1, ..., |S|\}$: set of surgeries.

$P = \{1, ..., |P|\}$: Set of patients who have surgery in a day.

$[u_s, v_s]$: surgeon s working time interval which is a subset of operating room available time.

M : A large enough positive number.

O_{pq} : 1:if patient p has priority over patient q; 0:otherwise

Y_{pr} : 1:if surgery of patient p can be done in operating room r; 0:otherwise

Q_{sp} : 1: patient p is operated by surgeon s; 0: otherwise

θ^1 : The preparation time of surgical equipment, checking devices, and anesthetizing each patient.

θ_p^2 : Duration of surgery for patient p

θ^3 : Duration of nurses' tasks and patient recovery in operating rooms after operation.

θ^4 : operating room cleaning time and preparedness.

2.2. Decision Variables

t_p : integer variable that shows the moment of putting patient p on an operating room bed.

x_{pr} : 1:if patient p is assigned to operating room r.; 0:otherwise

z_{pq} : 1:if surgery of patient p is performed after surgery of patient q; 0:Otherwise

y_{pqr} : assignening patient q after patient p to operating room r.

fp_s : positive variable that shows starting time of first patient of surgeon s.

lp_s : positive variable that shows ending time of last surgery of surgeon s.

2.3. Mathematical Model

$$Min \sum_{s \in S} (lp_s - fp_s - \sum_{p \in P} \theta_p^2 . Q_{sp}) \quad (1)$$

$$\sum_{r=1}^{4} x_{pr} = 1, \forall p \in P \quad (2)$$

$$x_{pr} \le Y_{pr}, \forall p \in P, \forall r \in R \quad (3)$$

$$y_{pqr} \le x_{pr}, \forall p \ne q \in P, \forall r \in R \quad (4)$$

$$y_{pqr} \le x_{qr}, \forall p \ne q \in P, \forall r \in R \quad (5)$$

$$y_{pqr} + y_{qpr} \le 1 + \mathrm{M}(2 - x_{pr} - x_{qr}), \forall\ \mathrm{p} \ne \mathrm{q} \in \mathrm{P}, \forall\ \mathrm{r} \in \mathrm{R} \quad (6)$$

$$y_{pqr} + y_{qpr} \ge 1 - \mathrm{M}(2 - x_{pr} - x_{qr}), \forall\ \mathrm{p} \ne \mathrm{q} \in \mathrm{P}, \forall\ \mathrm{r} \in \mathrm{R} \quad (7)$$

$$Q_{sp}.u_s \le t_p + \theta^1, \forall p \in P, \forall s \in S \quad (8)$$

$$t_p + \theta^1 + \theta_p^2 \le M(1 - Q_{sp}) + v_s, \forall p \in P, \forall s \in S \quad (9)$$

$$t_q \ \ge \ t_p + \theta^1 + \theta_p^2 + \theta^3 + \theta^4 - M(1 - Y_{pqr}), \forall\ \mathrm{p} \ne \mathrm{q} \in P, r \in R \quad (10)$$

$$M(1 - \mathrm{z}_{pq}) + t_q \ge t_p + \theta_p^2 - M(2 - Q_{s,q} - Q_{s,p}), \forall p \ne q \in P, \forall s \in S \quad (11)$$

$$M(\mathrm{z}_{pq}) + t_p \ge t_q + \theta_q^2 - M(2 - Q_{s,q} - Q_{s,p}), \forall p \ne q \in P, \forall s \in S \quad (12)$$

$$t_p \ \le \ t_q + M\left(1 - O_{pq}\right), \forall\ \mathrm{p} \ne \mathrm{q} \in P \quad (13)$$

$$fp_s \le Q_{sp}.(\mathrm{t_p} + \theta^1) + M(1 - Q_{sp}), \forall p \in P, \forall s \in S \quad (14)$$

$$lp_s \ge Q_{sp}.(\mathrm{t_p} + \theta^1 + \theta_p^2), \forall p \in P, \forall s \in S \quad (15)$$

$$fp_s \ge 0, \forall s \in S \quad (16)$$

$$lp_s \ge 0, \forall s \in S \quad (17)$$

$$x_{pr} \in \{0,1\}, \forall p \in P, \forall r \in R \quad (18)$$

$$y_{pqr} \in \{0,1\}, \forall p, q \in P, \forall r \in R \quad (19)$$

$$t_p \in Z^+, \forall p \in P \quad (20)$$

The objective function (1) minimizes the summation of idle times of all surgeons. Constraints (2) imply the allocation of each patient to only one room. Constraints (3) ensure that the surgery of patient p is assigned to a technically feasible room. Constraints (4) and (5) ensure that if $x_{pr} = 0$ or $x_{qr} = 0$ then y_{pqr} and y_{qpr} are 0. Constraints (6) and (7) ensure that if both x_{pqr} and x_{qpr} are 1, then only one of the two variables y_{pqr} and y_{qpr} may become 1. Constraints (8) ensure that starting time of each patient's surgery will be greater than the starting time of working hours of the corresponding surgeons, and if a patient is not assigned to a surgeon, then the left side of the equation will be 0. Constraints (9) do the same for not violating the ending time of the working hours of the corresponding surgeon. Constraints (10) ensure that if two surgeries are performed sequentially in an operating room, the second patient's start surgery time must happen after finishing the recovery of the previous patient, operating room cleaning, and the current patient preparedness time. Constraints (11, 12) ensure that patients who are assigned to the same surgeon, regardless of the appointed operating room, starting time of the second patient's surgery must be greater than the end time of the first patient's surgery. Constraints (13) determine the patients' priority for an operation. Constraints (14) consider the starting time of each surgeon's first surgery. Constraints (15) determine the end time of the last surgery of each surgeon. The remaining constraints are decision variables' definition in the model.

3. NUMERICAL RESULTS

This study is based on the real case of Shomal Hospital in Amol, Mazandaran, Iran. The hospital is a general private hospital. The current process of operations planning at the operating room department of this hospital includes two main stages. In the first stage, for each patient, the surgery time is determined by the assigned surgeon. As a result, patients are elective. In the second step, patients are sequenced and assigned to operating rooms manually.

Some main practical constraints are taken into account at this stage including the possibility of the surgery of each patient in a particular operating room, avoiding the overlapping of a surgeon assigned to different operating rooms, and priority of patients under the age of 7 years and patients with a hysterectomy surgery over the other types of patients. According to the hospital, various types of surgeries might be performed in the operating room department. However, some surgeries have to be performed in a special operating room due to the specific facilities that might be needed.

In Shomal hospital, there are 4 operating rooms available in the operating room department. Eye surgeries can only be done in one specific operating room, which is equipped with specific facilities for this purpose. All other types of surgeries can be performed in any of the available operating rooms. Working hours (available time) of all operating rooms are assumed to be the same (From 8 am to 7 pm).

Each surgeon has his/her patient(s) and working hours in the surgery department determined for each planning day. The working hours are not the same for different surgeons. Surgeons are usually interested in doing their surgeries at the appointed time to reduce their idle time. The duration of each surgery is assumed to be precisely predictable by the surgeon.

Data related to 7 randomly selected days are collected from the hospital's operating room department and analyzed. Based on the data of these 7 days of surgeries, the number of surgeries and surgeons of each day and starting and end time of each surgery are analyzed. Then, the proposed mathematical model is implemented in Cplex 12.9 software. Using these data, surgeries schedule are planned for each of these 7 days. To have a better view of the case, one sample day plan as an output of the current method is presented in Table (2), and Figure (1). These tables show the assignments and schedule of patients to each operating room manually done by the head nurse of the surgery department of the Hospital. In this sample, 10 patients are scheduled for surgeries. The first column shows the surgery (patient) number. The second column mentions the surgeon assigned to each patient in advance. The duration of each surgery is also presented in column 3(θ^2). Patients 1, 2, and 3 have priority over the rest of patients and need to be scheduled before other patients on the same day. There are 6 surgeons to be planned in this day and some of them have limitations on their start and end of their working time. The beginning and end time limit of each surgeon is presented in Table (1).

Table 1. Surgeons' start time limitation for the Sample Day

Surgeon	1	2	3	4	5	6
Start Time Limit	8:00	8:00	8:15	8:45	9:00	12:00
End Time Limit	12:00	12:00	12:15	13:00	12:00	14:00

The duration of anesthesia for all surgeries is estimated 5 minutes for each surgery ($\theta^1 = 5$); The duration of after operation cares by nurses is expected 30 minutes for each surgery($\theta^3 = 30$); And, operating room cleaning and preparedness for the next surgery is estimated 10 minutes for each surgery ($\theta^4 = 10$). Based on this information, columns 4 to 6 from Table (2) are the plan resulted from head-nurse manual planning. According to this plan, a resource schedule graph for operating rooms is presented in Figure (1). To be able to compare, the results obtained by solving the same data instance using the mathematical model is also presented using the resource schedule graph in Figure (2). As can be seen from both Figures (1) and (2), the objective value which is the total Idle time of all surgeons reduced from 180 in the current practice to 90 in the proposed schedule ((180-90)/180 *100 = 50% reduction).

Table 2. The current schedule of surgeries for the sample day

Surgery Number	Surgeon Number	Surgery duration (minutes)	Surgery Start Time	Surgery End Time	Operating Room Type
1	1	60	8:05	9:05	General 1
2	2	60	8:05	9:05	General 2
3	3	60	8:15	9:15	General 3
4	4	30	8:45	9:15	Eye
5	4	30	10:00	10:30	Eye
6	4	30	11:15	11:45	Eye
7	3	60	9:50	10:50	General 1
8	1	60	10:00	11:00	General 3
9	5	60	9:50	10:50	General 2
10	6	60	12:00	13:00	General 1

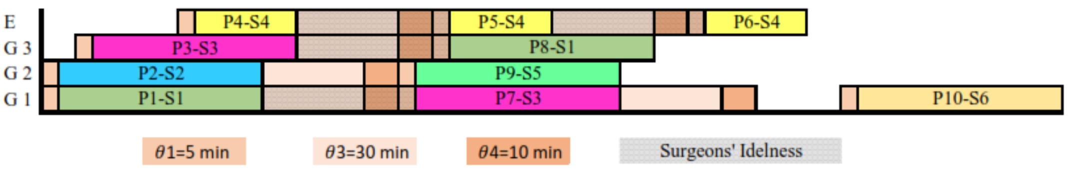

Fig. 1. Resource Graph based on Current Practice schedule for the Sample Day (Total Surgeons' Idle time = 180)

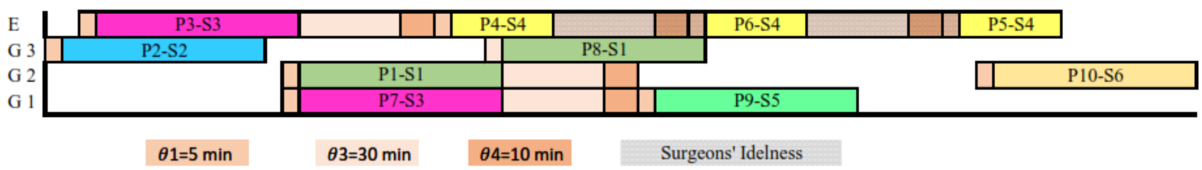

Fig. 2. The resource graph based on the proposed schedule for the sample day (Total Surgeons' Idle time = 90)

Comparing two presented solutions, in the manually planned schedule, surgeons 1, 3, and 4 have some extra idle time in between their surgeries; However, in the proposed schedule by the mathematical model, it is only surgeon 4 who have to wait in between its planned surgeries. This idle time is practically inevitable because of this specific type of surgery (eye) has to be performed in operating room E.

In all 7 sample instances, the number of hospital operating rooms is four in total. Three of them are general operating rooms where all types of surgeries are performed, and one operating room is specialized only for eye surgeries. The number of elective patients for surgeries, based on daily observations was between 6 to 16 patients. Operating rooms are available from 8 am till 7 pm. The number of surgeons with at least one surgery in a day was between 3 to 8 surgeons.

Results obtained by solving these numerical examples using the proposed model are presented in Table (3). To solve the model, all experiments are performed on a personal computer with 4GB RAM and a Core i3 3.60GHz CPU.

Table 3. Comparing the results of the current method with the results of the proposed model

Instance Number	Number of patients	Number of surgeons	Objective value of the current hospital method	Objective value of the proposed model	Improvement (percent)	Computational time (seconds)
1	10	6	180	90	50	40
2	12	5	320	170	46	17
3	10	3	495	320	35	27
4	16	8	675	505	40	47
5	9	6	580	440	24	40
6	11	6	395	305	22	22
7	6	3	720	500	30	55

To compare the results of our model with the current situation at the hospital for scheduling the operating rooms (manual planning), the objective function value (total idle times of all surgeons) is also calculated based on the current situation. These values are presented in the fourth column of Table (3). The next column of Table (3) shows the values of the objective function resulted from solving the presented model. The gap between the two presented values are calculated by subtracting The value of the objective function of the proposed model from the value of the objective function of the current hospital method divided by the value of the objective function of the current state solution. These values are displayed in the sixth column of Table (3). On average, using the presented model indicates around 35 percent improvement in reducing the surgeon waiting times. The computation times to find the optimal solution using the model are presented in the fourth column of Table (3).

4. Conclusion

In this research, an integer programming model is presented to solve the scheduling problem of operating rooms at Shomal hospital in Amol, Iran. The hospital is a private hospital, and its surgical department policy is to decrease the costs of operating rooms, to reduce the time between surgeries and generally, to decrease the total costs of surgeries. Since surgeons are one of the most critical and expensive sources for the hospital, the objective is to minimize the time between surgeries of each surgeon. Moreover, in this study, patients' priority was also considered in the scheduling and sequencing of surgeries. Obviously, this model will also increase the patient satisfaction.

The model is implemented in Cplex 12.9, and real data from the hospital are used to test it. Considering the size of real instances, the proposed method seems practical and useful. The results indicate a significant improvement in reducing the surgeon's waiting time compared to the process currently used in the hospital.

For future studies, we propose solving this model by heuristic and meta-heuristic algorithms. Considering non-elective patients and integrating other related parts of the hospital, such as the ICU, can also be the subject of future extensions of this study.

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