The Problem of the Hospital Surgery Department Debottlenecking

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Abstract. We consider the dynamic patient scheduling for the hospital surgery department with electronic health records. Models for increasing the throughput of the surgery are proposed. It is based on classical intellectual optimization problems, such as the assignment problem, the scheduling problem, and the forecasting problem. Various approaches to solving the proposed problem are investigated. The formalization of the surgery planning problem of the large medical hospital surgery department is considered.

Keywords: Dynamic patient scheduling · Health care programs · Electronic information card · Scheduling problem

1 Introduction

High-tech medical care (HTMC) is medical care with the use of high technologies for the treatment of complex diseases. It includes both treatment and diagnostic services that are performed in a specialized hospital. There is a list of HTMC operations that can be done for Russian citizens for free. If the required operation is in the list, the order of further actions is as follows: visit the General Practitioner; consult and get a referral for analysis and diagnostic tests; pass the necessary tests; go to a doctor again with the results of the tests; get a referral from the doctor for a commission; pass the commission; visit a doctor to get a referral for hospitalization; undergo second testing for hospitalization; admission to the hospital registration in the hospital, setting the date of the operation. In total, the entire process of preparing for a free operation can take up to six months. If the operation is needed urgently, patient can agree to a paid operation, and then apply for a compensation. Each organization has its own special aspects of the surgery unit. In the daily activities of a multi-specialty surgical hospital with a large bed capacity, the capacity of the surgery unit can

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often become a limiting factor for the intensification of the whole hospital's functioning. This problem can be particularly acute if individual surgery rooms are specialized and equipped to perform surgical interventions of a dedicated profile (for example, neurosurgery). The Burdenko Neurosurgery Center is a neurosurgical clinic that provides care to patients with diseases of the central and peripheral nervous system. Optimizing the operation of the surgery department of the Burdenko Neurosurgery Center will increase its throughput and improve conditions for patients.

The scheduling practices are being discussed in health care programs of different countries. Patients undergo a series of medical analysis before being eligible for elective surgery. At the same time various aspects of implementation and improvement of medical Electronic Information Card (EIC) are studied and analyzed in many countries, such as technological [1–3], legal [4], managerial [5,6]. In Russia the situation is different [7–9] because of the process of organizing medical care is quite complicated. There are three main areas of research in medical processes automation: electronic medical records in various versions; decision support based on clinical guidelines; clinical process management .

An interesting research is being conducted in the Kaliningrad [10,11] on the use of EIC in solving diagnostic problems and organizing consultations. The most significant analytical information systems (AIS) are the following.

- AIS in the president's polyclinic. The 1st version of it was developed in the 70s and 80s in Institute of Control Sciences of Russian Academy of Sciences.
- The system developed at the Burdenko Neurosurgical Center [12–15].
- Regional information and analytical medical system (an example can be found in [16]).

However, the majority of potential users have insufficient skills to work with modern information technologies [17]. This significantly complicates the implementation and wide distribution of the technologies. Among the restraints to the widespread introduction of EIC, researchers include: unwillingness of many ordinary doctors to spend additional time working on a computer; immetodical approach to automation; bad automation experience obtained earlier; inflated (or low) expectations of the opportunities provided by AIS and EIC; psychological problems; fear of appearing incompetent; unwillingness to provide primary information openly; laziness and illiteracy. All of these interferences inhibit the widespread use of medical AIS and EIC. But this is surmountable. In the last few years, a team of scientists from the Institute of Control Sciences of RAS and the Burdenko Neurosurgical Center creates a more modern EIC focused on solving management problems [18–20].

Features of the treatment process organization in the Burdenko Neurosurgical Center are dependent of the following two main circumstances that creates additional problems during the organization of the treatment process.

1. The system of financing of the treatment is complex and quite confusing.
2. Patients come to Burdenko Center from all over Russia. Forming the input flow of patients is a hard and time-consuming work.

The main source of information and expert opinions for building the concept was expert information received from the specialists of the Burdenko Neurosurgical Center: the chief physician, heads of surgical departments, doctors of the emergency department, etc. Working with experts and analyzing the information received from them requires a special technique. The issue is that different experts have different (sometimes diametrically opposite) opinions on many key aspects of the treatment process organization. It happens because their opinions depend on their position in the organization and the functions they perform. Institute of Control Sciences of RAS has developed a method of collective multivariate expertise for working with experts in a specific language they understand. The method has many modifications for different types of problems, but the principle of cross-discussion is common to all modifications. But the Burdenko Neurosurgical Center has another source of information: a carefully designed and efficient information system that provides electronic storage of medical records and centralized access to the medical information. For each patient, time moments of main treatment events are recorded. This information was not used before this project. In the process of developing the concept, this information have been used to build a clearly arranged picture of the treatment process, to identify the real workload of surgical departments and the surgery units, the available reserves, which allow to check and clarify the opinions of the specialists about the bottlenecks of the system and possible ways to improve it.

The paper is organized as follows. In Sect. 2, we reviewed existing solution methods of health scheduling problems. In Sect. 3 scheme of the hospitalization process in the Burdenko Neurosurgical Center. The initial data of the mathematical model are discussed in Sect. 4. Mathematical model we consider in Sect. 5. Section 6 reviews the experimental results. And some remarks in Conclusion.

2 Health Scheduling

Due to modern technology, medical care is becoming automated. Therefore, the study of optimizing service processes is relevant. There are many publications on health scheduling. Let's consider some articles for the investigated problem of optimizing surgery rooms.

The article [21] is devoted to the study of the schedule of surgical operations and the appointment of surgeons in the operating room focusing on elective patients with different urgency. Long waiting times can increase the urgency of the patient and lead to complications. The goal is to maximize the sum of the urgency values assigned to each operation. The average duration of surgery was obtained from hospital data. Since it takes a long computational time to solve a large-scale model problem, the authors developed a local search algorithm based on a simple heuristic to solve the problem. A simple heuristic (SH) is developed to schedule the surgeries based on their urgency value. An urgency value will determine the assignment of the surgeries to the operating rooms on each days. The SH start by sequencing the waiting list. Authors sequence the patient with high urgency value over patient with lower urgency value. Finally, they will scheduled the patients based on the list. After executing the SH, an initial schedule is obtained. Next you need to improve the schedule in terms of efficiency through LS. This heuristic is developed to assist the hospital by giving priority to the urgent patient based on their condition. LS consider the searching of solutions in the neighborhood and it will move from one neighborhood to another to find a better solution. The iteration will continue until no better solution can be found. If the best solution is found, it will replaced the current solution with the best solution. Based on the results, both heuristics are very good in reducing the large running time of the ILP model. The Local Search is better since it significantly reduce the computational time while giving a good solution which is as close as the optimal solution from the model.

The article [22] presents an integer programming model for scheduling operating rooms. This model tries to minimize the total weighted time to start operations. To calculate the weight, three age groups of patients are taken into account. The setup time for this group of patients depends on the sequence and the duration of the operation is analyzed using fuzzy logic. The proposed model is solved using a hybrid algorithm. When the operation is completed, it takes time to prepare the operating room for the next operation (cleaning the room, changing doctors, replacing equipment). Installation time plays a very important role in choosing the operating room schedule. The main contribution of this study is that the installation time between operations depends on the sequence, and the duration of the surgical operation depends on fuzzy numbers. The scheduling decision for operating room (OR) includes the assignment of surgical operations to ORs, and the operation sequence in each OR. Different types of each operations may need various resources and equipment. Some resources and equipment for each surgical operation can be used among several ORs, some of them are dedicated to particular ORs. Each surgical operation is constrained by the resources and equipment associated with the OR. Solution procedure has two steps: first, need to choose initial scheduled based on Weighted Shortest Processing Time because the objective of proposed model relates to total weighted so this procedure for initial solution is decent option. Second, we tested some local search heuristics, which focus on solution improvement by swapping two different surgeries between OR-days (a two-exchange), or by moving one surgery to another OR (a one exchange). The algorithm is implemented using the software package MATLAB version 8.4. After the launch of the model, acceptable results were achieved. The paper [23] proposes a multi-step approach and a typing priority rule to generate the initial sequence for “bin-packing”. Case studies show that the PTD (Priority-Type-Duration) rule is superior to the LPT (Longest Processing Time) rule based on the cost of operating planning. In the proposed model, patients are divided into 5 groups according to priority. At the planning stage, the interest is in defining a set of planned activities for resource allocation. In this study, N elective cases with different priorities and different types of operations are selected from the waiting list. A set of costs is defined as a measure for evaluating operational cost planning, for example, fixed costs, overtime costs, downtime costs and installation costs. A bin-packing model maximizes utilization and minimizes the idle time, which consequently affects the cost at the planning phase. Since the priority is the most important factor for performing a surgery, authors first sequence surgeries according to their relative priorities. There are 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, authors assign surgeries to surgery room from the head of sequence (the highest priority) to the tail of sequence (the lowest priority), while they avoid combining different surgery types into one surgery room. If there is still some remaining time in the surgery room after assigning all patients, need to search for a compatible patient from lower priority groups with the same surgery type. If there is no compatible cases, they leave the remaining time idle.

Paper [24] focuses on the block operating room planning strategy. In such a strategy, each specialty receives several operating blocks during a certain planning period, in which it can distribute its surgical cases. The planning problem is further complicated by the change in the duration of surgical cases, which reduces the use of operating rooms. The proposed model includes trying to optimize the use of operating rooms without canceling and increasing overtime. The objective function includes patient waiting time, operating downtime and overtime. Patients belong to a waiting list, where they are registered at the moment they are referred. A subset of patients is selected who will be operated on in the planning horizon under consideration and assigned to weeks and operating blocks, while ensuring that the capacity of each block is not exceeded. The objective function is aimed at minimizing the overall penalty due to delays in service of patients. Authors propose an approach combining offline and online decisions. The offline solutions are applied and modified online so as to manage patients who have been cancelled and must be rescheduled and newly patient arrivals. Uncertainty in surgery duration must be considered in the offline step, so as to reduce the number of cancelled patients: Authors apply a cardinality-constrained robust optimization approach to model the off-line scheduling problem. Tests on a set of real-based instances are carried on. They apply the proposed two-step approach on a set of randomly generated scenarios in order to assess its behavior in managing patients to be rescheduled and new arrivals. Beside, we evaluate the benefit of applying a robust solution rather than a non-robust one in the off-line step.

This model can be solved using stochastic programming and various heuristic methods. In [25], a problem of scheduling of the surgical department of a Chinese hospital is considered. Emergency and planned patients can be served in the same operating rooms. There are fixed time slots for planned operations as well as flexible slots for unscheduled operations. Authors propose a simulation-optimization approach consisting of two models. For a two-stage stochastic optimization model, uncertain arrival times of emergency patients are represented by a set of scenarios. The discrete event simulation model is designed to eliminate the uncertainties associated with the duration of the operation and the length of stay in the hospital, as well as to verify the basic schedule of the operation developed using the stochastic model. A simulation model is also used to generate scenarios. The resulting system shows good results both on emergency waiting time and on the stability of the planned operations schedule.

3 Scheme of the Hospitalization Process

The goal is to increase throughput due to two factors: reducing gaps in schedule and increasing the number of resources (bed stock, IDs of surgery rooms). We can use information system of the Burdenko Neurosurgical Center and doctors' expert evaluation to solve the problem. Experts identify subproblems such as hospitalization, surgical department manipulations, and monitoring of surgery rooms.

The problem is divided into three subproblems. The first is the problem of allocating specialists to the appropriate rooms at a certain time. The second problem is to create a schedule for receiving patients for surgery. The third is the problem of predicting downtimes of surgery rooms. Let's consider the facts that determine the features of the problem:

1. Hospitalization. The main focus is on patients who are admitted to the hospital for their planned hospitalization and are registered in the queue. In addition, there are patients who are served on a commercial basis. As soon as a patient leaves the hospital, employees look through the queue list and select the next patient. The choice depends on the department, where a vacant bed is appeared. The person from the queue whose diagnosis corresponds to the service in the department is being selected.
   The constraints of the problem are formed out of the following facts.
   - Patients come from different regions of the Russian Federation as soon as beds are released in 10 specialized surgical departments.
   - All the patient documents are checked.
   - Comorbidities are checked.
   - There is a mandatory list of medical analysis and diagnosing tests.
   - Appearing of unscheduled patients, as well as those who arrived without a call or their representatives.
   - The anesthesiologist consults patients only from 14:00 to 15:00.
   - Necessary time for monitoring the course of the disease.

   The following factors affect the delay in hospitalization.
   A. The difference between the call for hospitalization and the actual arrival of the patient. It is assumed that calling a patient means reserving a bed. We assume that the reserve has a time limit.
   B. Difference between patient arrival and hospitalization. It consists of the time spent on checking documents, the comorbidities, conducting a mandatory list of medical analysis and diagnosing tests, as well as the need to consult an anesthesiologist and other specialists.
2. The surgical department.
   - The patient's stay includes a pre-operation procedures, one or more operations, and restorative treatment.

- Each surgical department has 30 beds.
- When a patient is undergoing surgery or intensive care, a new patient cannot be placed in their bed.
- Necessary time for monitoring the course of the disease.

3. Monitoring of surgeries.
   - The medical center has 14 main surgery rooms, including rooms numbered R1 – R4 (usually less busy) for operations that require x-ray inspection.
   - Each surgery department has priority for using its own surgery room, but if there is free time, it provides the surgery room to other surgery departments.
   - Longer operations are to be started at the beginning of the day.

The rooms. Each department contains a set of rooms. The room can be: registry, consulting, patients, surgery and emergency. Capacity of registry room is determined by the number of available receptionists. In consulting rooms the doctor can consult one patient at a time and doctors can accept patients from different departments. Patients rooms have 30 beds for each department, wards are assigned to certain departments. Only one patient can be in a surgery room at a time. There are 14 surgery rooms, including 4 with x-ray equipment. Each surgery room is assigned to a specific department, but can be provided for the work of another department. In emergency room also can be only one patient at a time. Many rooms of different departments may overlap in certain cases.

The Specialists. The specialist can be: a consulting doctor, a doctor performing a surgery, a GP who is supervising the patient, a receptionist. In cases where several specialists are working with the patient at the same time, the responsible doctor will be designated as a specialist. For example, in the case of an operation, this is the doctor who performs the operation directly. Many specialists from different departments may overlap in certain cases.

The Patients. Each patient is assigned to a specific department upon arrival, from which they can be transferred to other departments during treatment. For each patient, there is a disease (group of diseases) that corresponds to a set of procedures: observation, consultation, operation, resuscitation, delivery of the analysis. We will also include here the procedures necessary for receiving each patient: registration (this also includes checking documents), arriving (time from receiving the call to arriving at the hospital).

Time for each procedure has a fixed upper bound. The set of procedures may change depending on the preceding procedures. For example, an operation may be canceled due to a specialist's consultation, or an unplanned emergency procedures may occur after the operation. After certain procedures are completed, the service may be terminated prematurely if:

- the patient did not collect all the documents (this is checked at the registry just after arrival),
- the patient's analysis and diagnosing tests do not allow the operation to be performed in the near future,
- the consultation states that the operation is contraindicated,

- the patient is being transferred to another hospital,
- the patient died.

The precedence relations between the procedures are set in the form of an acyclic oriented graph. Based on the problem condition, a specific set and sequence of procedures are typical for each department.

4 Data

Burdenko Neurosurgical Center information system includes information about a patient's hospitalization, the principles of his treatment, the work of the department, including occupied beds, the work of the surgical department, etc.

For each patient, information about their operations is generated in the system. This creates a table that consists of the following columns: number of the patient; date; the host department; surgery room ID; complexity category of operation; start of operation; end of operation.

Based on this table, we can conclude that usage periods of surgery rooms usually have gaps, which greatly reduces the efficiency of surgery rooms.

According to examples for each operation we know its duration, complexity category and the department in which it should be performed. The relationship of all entered parameters of the operation is not defined. Thus, the connection between the complexity of the operation and the time of its execution is not known. By using these example we created the frequency dictionary of various parameters and used it in the generation.

In the generated data the Center received a random number of patients n with a 15 min frequency. The value n is distributed normally with parameters μ and σ^2: $n \sim N(\mu, \sigma^2)$. By varying the values of μ and σ^2, it is possible to set the admission density of patients. The department and complexity category for each patient was set randomly based on a weighted selection procedure. That is, the more often the complexity category was encountered in the initial data, the greater will be the probability of its generation. The time of operation was also set on the basis of a weighted selection, but from those values that were usual of the given complexity and for the given department.

A pattern could not be identified for preliminary stay. Thus, the time of preliminary stay of patients awaiting for hospitalization is an random value, evenly distributed at $[T_0, T_1]$ interval.

5 Monitoring of Surgeries

Consider the problem of planning patients $J = \{1, \ldots, n\}$ in the operating room $I = \{1, \ldots, 10\}$. Each patient $j \in J$ has time r_j, after which the patient can start the operation, and processing time of operation p_j. Each patient is tied to a specific operating room $w_j \in I$. We introduce the decision variable X_{ij}^t, which is equal 1 if the patient j starts operation in operating room $i \in I$ in time $t \in l$, and equal 0 otherwise. l - is the upper time limit. A set of times S represents a off-hours. In daytime mode, operations are carried out only from 9:00 to 18:00. As the objective function, we take the total completion time of all operations.

We consider two models: a model of a twenty-for-hour clinic (*Model A*) and a model of a clinic with 'standard' working day from 9:00 to 18:00 (*Model B*).

Model A

Objective function:

$$\sum_{j \in J} C_j \rightarrow \min_{X_{ij}^t} \tag{1}$$

Subject to:

$$\sum_{t=0}^{l} X_{w_j j}^t = 1, \qquad \forall j \in J; \tag{2}$$

$$\sum_{j \in J} \sum_{h=max(0,t-p_j)}^{t-1} X_{ij}^h \leq 1, \qquad \forall i \in I, \quad \forall t \in l; \tag{3}$$

$$C_j = \sum_{i \in I} \sum_{t=0}^{l-1} (t + p_j) X_{ij}^t, \qquad \forall j \in J; \tag{4}$$

$$C_j \geq r_j + p_j, \qquad \forall j \in J. \tag{5}$$

Model B is model A with the following constraints added:

$$C_j - p_j \geq 9:00, \qquad \forall j \in J; \tag{6}$$

$$C_j \leq 18:00, \qquad \forall j \in J. \tag{7}$$

An objective function is to minimize a total completion time of all operations. A set of constraints (2) ensures that each patient will be operated in a pre-assigned operating room. Constraint set (3) allows at most one job to be processed at any time on any machine. Constraint sets (4) and (5) determines the completion time of operations. Constraints (6,7) define the working hours of the surgery rooms.

6 Computational Experiments

We conducted experiments on the real-like data for models A and B.

Experiment 1. The objective and constraints of model A are represented by formulas (1–5). Operating rooms are supposed to work around the clock. The results of the experiments are presented in the Figs. 1 and 2. In the Fig. 1 the department number is plotted on the x-axis, the objective function value is plotted on the y-axis at different densities of patient penetration. The figure shows that with a patient density of 25 patients per hour, a significant increase in the value of the objective function for the 7th department occurs. For the density of patient admission of 5 people per hour, an increase in the objective

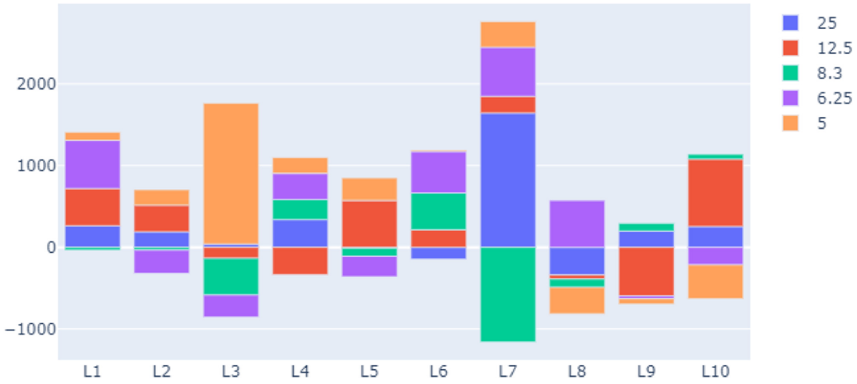

Fig. 1. Histogram of objective function values for different densities, around the clock.

function in the 3rd department is visible. The solution seems to be to compensate for the load on the busiest branch of the department by transferring the load to a less busy department.

The Fig. 2 shows a Gantt chart for a patient density of 25 patients per hour. Departments are on the y-axis. The picture shows that operating rooms loaded with different intensities.

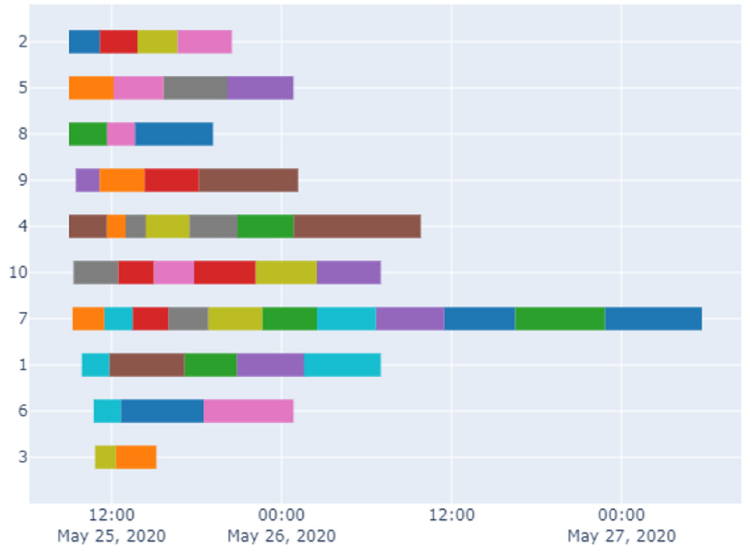

Fig. 2. Gantt chart for round-the-clock operation

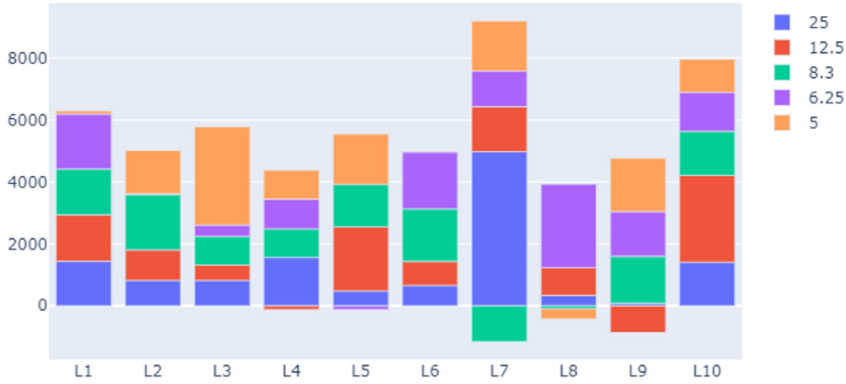

Fig. 3. Histogram of objective function values for different densities, 9:00 to 18:00.

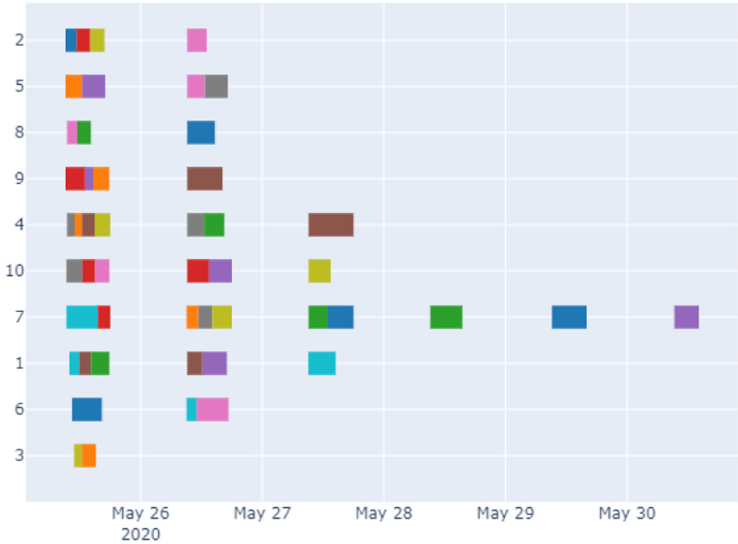

Fig. 4. Gantt chart for working 9:00 to 18:00

Experiment 2. The objective function and constraints of model B are represented by formulas (1–7). Operating rooms are supposed to work from 9:00 to 18:00 and to be closed at night. The results are presented in the Figs. 3 and 4. Figure 3 on the x-axis contains number of the department, on the y-axis contains the value of the objective function for the department, the color of the column indicates the density of patients per hour. We can see a significant increase in the objective function value for 7th department at the patient arrival density of 25 patients per hour, which indicates an overload of the department. For an arrival density of 5 patients per hour, we can see the increase of the objective function in the 3rd department. It is possible to compensate the load of the busiest department by transporting it's patients to the free surgery rooms of less loaded departments.

The Fig. 4 shows a Gantt chart for a patient density of 25 patients per hour for model B. Departments are on the y-axis. The picture shows that with a high load in the 7th department, up to five days delay in patient care can occur. The 7th department should be unloaded at the expense of other departments.

7 Conclusion

This paper presents a formal statement of the problem of predictive planning of surgery units in a large medical hospital and outlines the ways of its optimal solution. Experiments were carried out on the real-like data, which were generated on the basis of data provided by Burdenko Institute. An experiment for operating round-the-clock operating rooms showed that some departments are loaded much more intensively than others.

The Gantt chart in Fig. 2 shows that with a very high load, patients arrived in one day in the 7th department are served in two days. The difference in the load of the departments is even greater. With this intensity of patient admission, it is impossible to establish the work of the department. But at the same time it can be seen on the diagram that there are departments that are complete the service ahead of schedule. If operating rooms in less loaded departments will be used for other departments, the throughput of a large unit can be increased.

Further work will be aimed at creating a schedule for the model, which implies the possibility of transferring the patients to the operating rooms of another departments if it is not busy. Planning the maintenance process with the new condition will allow us to build a long-term schedule with fewer gaps.

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