Multicriteria optimization of medical institutions' schedules on the basis of neuro fuzzy models and evolutionary algorithms

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Abstract. Taking into account the expansion of infrastructure and the growth of hospitals, as well as the increase in the influx of patients, the manual preparation of therapies, in particular, regenerative therapy, becomes ineffective and causes frequent dissatisfaction and complaining of patients. Taking into account the large number of factors forming the schedule, the task of multicriteria optimization is presented in accordance with strict restrictions and immediate wishes of patients.

This task can be decomposed into several subtasks that require development of: a reference schedule that would satisfy the strict restrictions imposed by the domain; a method for evaluating the reference schedule and intermediate schedules; the method of optimization of the reference scheduling in order to improve the estimated results.

In the course of solving these problems it is necessary: to carry out the construction of relevant criteria for evaluating the quality of the decomposition and turn their qualitative values into quantitative forms; carry out the transition from multi-criteria optimization to one-criterion by minimizing the set of evaluation criteria in the scalar value that can be used in the process of optimization; to avoid local optimum and reach the global optimal solution.

The article is devised a method of multicriteria assessment and optimization of medical institutions' schedules, based on the use of automatic theory to construct the reference scheduling of the functioning of the clinic, the application of methods and means of fuzzy logic and evolutionary algorithms.

Using an automated system of construction, multicriteria assessment and optimization of schedules of medical institutions can reduce the amount of manual work, as well as increase the level of satisfaction of patients with the quality of regenerative therapy.

Key words: scheduling of medical institutions, optimization of schedules, evolutionary algorithms, multicriteria assessment, neuro fuzzy models.

FORMULATION OF THE PROBLEM

The set of medical procedures at a certain point in time is the schedule of the functioning of the clinic. During its compilation, a number of limitations and factors are taken into account: availability of a qualified doctor; compliance of the sequence of procedures of the patient's plan of therapy; availability of appropriate medical equipment at the time of treatment; the need for specialized premises for procedures, etc.

A schedule can be called optimal if it provides the full implementation of the restrictions of the subject area, the effective use of available resources, taking into account the wishes of the staff of the clinic and patients, compliance with the treatment of established plans [1].

If during its compilation the requirements for rehabilitation plans are not fully taken into account or the restrictions are not satisfied, the quality of treatment decreases, which in turn significantly affects the quality of medicine as such. On the other hand, along with the above restrictions, it is desirable to meet the wishes of patients [2].

Thus, it can be argued that the optimization of the schedules of medical institutions is an important problem, the solution of which increases the efficiency of their functioning and the level of satisfaction of patients.

SETTING OBJECTIVES

Manual execution of the scheduling task is a complex process and requires considerable time expenditures. On the one hand, clinics seek to make the best use of available resources, and on the other hand, to improve the quality of treatment, which largely involves improving patient satisfaction with the services provided. The use of quantitative methods is possible to assess the effective use of resources, such as simple medical equipment or the occupation of medical personnel. However, patients' reviews are mostly expressed in a non-quantitative form, which makes practically impossible the use of classical methods.

Under such conditions it is expedient to make scheduling and its further optimization using the mechanism of multicriteria assessment based on fuzzy logic.

THE MAIN PART

Description of the algorithm. The given task can not be solved without taking into account the specific environment - a medical institution. Each plan must be consistent with the capabilities of the clinic, timetable of staff, hours, etc. [3].

As a result, the task of multicriteria assessment and optimization of plans can be solved by the following steps [4]:

Step 1: Construction of the schedule of the clinic based on patients' plans, taking into account the logic and constraints of the subject area, as well as the specifics of the work of a particular medical institution (the number of medical equipment for each particular type of procedure, the maximum number of patients, workers, etc.);

Step 2: Assessment of the quality of the schedule of the clinic in terms of the categories and their parameters (level of satisfaction of patients, use of clinical capacities, distribution of labor force, etc.);

Step 3: Optimization of the schedule of the clinic and patient recovery plans to improve the evaluation results.

The process of multicriteria assessment and optimization of the clinic's schedule is shown in Fig. 1.

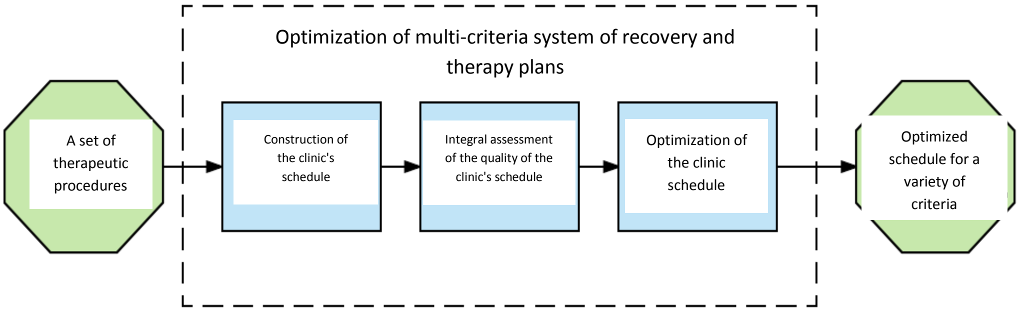

Fig. 1. Algorithm of multicriteria assessment and optimization of clinic schedule

Its analysis suggests that the task of multicriteria assessment and optimization of recovery therapy plans for patients can be decomposed into 3 subtasks. To perform a specific subtask it is expedient to allocate a separate subsystem (building a schedule of the clinic, assessing the quality of schedules, optimizing the schedule). Each subsystem must provide an universal interface, be able to integrate with other systems and encapsulate the logic of its work [5].

The input and output data for each of the systems are shown in the table 1.

Table1. Detailed description of algorithm of multicriteria estimation and optimization of clinic's schedule

System	Input data	Output data
Construction of the reference schedule of the clinic's work	A set of patients with developed regenerative therapy plans Mathematical model of the functioning of the clinic	Formed reference schedule of the clinic
Assessment of the quality of the clinic's work	The reference schedule of the clinic formed at the first stage A set of criteria for assessing the quality of the schedule	Assessment of the schedule of the clinic for the given set of criteria
Optimization of the schedule of the clinic	Results of the evaluation of the quality of the schedule in the previous stage A set of criteria for optimizing the clinic schedule	Optimized schedule of the clinic (and as a result - optimized plans for regenerative therapy of patients)

Using such an approach we can reduce the amount of manual work of medical institutions staff to compile and optimize their work schedules.

Construction of the reference schedule for the functioning of the clinic. The task of compiling and optimizing the schedule belongs to the NP-complete class [6,7]. Approximate methods are used to solve such a category of problems, which allow us to make a suboptimal schedule [8,9], in particular: the method of simulation of annealing of a metal; graph coloring method; method of genetic algorithm.

Most methods in one form or another require a correct first-sample (reference) sample [10,11,12].

Often, the generation of the reference sample is performed randomly, which can not be fulfilled in this situation, given the set of mandatory restrictions imposed by the subject area [13].

On the other hand, the set of constraints is deterministic, the set of necessary operations for creating a schedule and their order are determined.

Accordingly, it becomes possible to develop a mechanism that will satisfy the basic constraints and will enable the construction of a reference sample.

The process of constructing a schedule is advisable to present in the form of an abstract automaton - an abstraction used to describe the way of changing the state of an object, depending on the achieved state and the information received from the outside [14].

An analysis and choice of an abstract automaton. The general scheme of an automaton can be interpreted as a "black box" [15], which makes the transformation of the input vector into the output vector (Fig. 2).

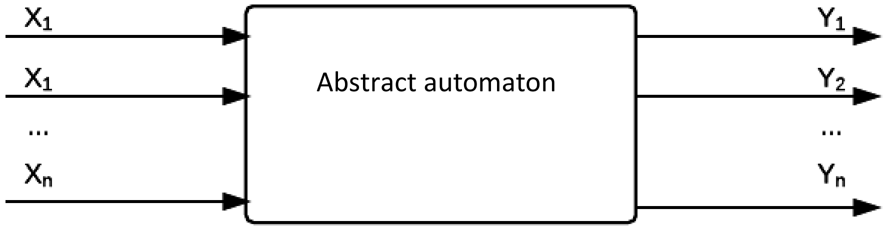

Fig. 2. General scheme of the abstract automaton

The mathematical model of the automaton can be described as follows [16]:

$$A = (X, Y, S, f_y, f_s, S_0) \quad (1)$$

where: X is the set of input data of the automaton;

Y - set of output data of the automaton;

S - set of admissible states of the automaton;

f_y - the output function of the automaton;

f_s - the function of transitions from one state of the automaton to another;

S_o - the initial state of the automaton.

In order to classify automata, a number of features are considered such as the definition of the function of transitions and the function of the outputs, the uniqueness of the given functions, the stability of states, the finiteness of the sets of inputs, output data, and states [17].

By the definition of the characteristic functions, the automaton for constructing the clinic's schedule is defined, since all $(s_i, x_k) \in X \times S$, where $s_i \in S, x_k \in X$, ie the characteristic functions are defined for all pairs of input data and possible states.

By the uniqueness of the transition function, the automaton is deterministic, since under the action of some input signal $x_k \in X$ the automaton can go into only one state $s_j \in S$. The mechanism of transitions is completely determined, a probabilistic transition is impossible.

By the stability of the states the automaton is stable, if under the action of some input signal $x_k \in X$, the transition to the state $s_j \in S$ was made, then the output from it and the transition to another state is possible only when the input of the automaton of another signal $x_z \in X, x_z \neq x_k$.

By finiteness of states, input and output sets, the automaton is finite, since the sets *X*, *Y*, *S* are finite: $|X| \neq \infty$, $|Y| \neq \infty$, $|S| \neq \infty$.

Two models are base for the construction of finite, determined, deterministic, stable automata - the Mealy and Moore's automatic machine [18].

Specifying the base model, the Mealy machine can be supplemented by the following relationships:

$$s(t+1) = f_s\,(x(t), s(t)), \qquad (2)$$
$$y(t) = f_y(x(t), s(t)).$$

The Moore's automaton can be defined as follows:

$$s(t+1) = f_s\,(x(t+1), s(t)),$$
$$y(t) = f_y\,(s(t)), \qquad (3)$$

where: *s (t + 1)* - the next state in which the automatic machine will pass;

f_s - function of transition of the machine to the next state;

x (t) - current value of the input signal;

s (t) - current state of the machine;

y (t) - the value of the output of the machine;

f_y – the exit function of the machine.

From equations (2) it is seen that in the case of the Mealy machine, the arguments of characteristic functions are the current value of the input signal and the current state. From relations (3) it follows that the output signal of an automaton is uniquely determined by its current state and does not depend on the components of the vector of input signals [19].

The specifics of the subject area suggest that the result of the machine will directly depend on the type of procedure that it will receive at the input for inclusion, namely, the inclusion of the procedure in the scheduling will depend on its characteristics and the current state of the schedule. Taking into account these arguments, it is expedient to carry out the construction of the ultimate automaton of the clinic using the Mealy's model.

Construction of an algorithm for the operation of an automaton. Using the Mealy's model, we have proposed a method by which, in the final case, it is possible to develop a clinic schedule.

Verbally, the process of operating an automaton for construction of a clinic schedule can be set as a sequence of the following stages:

Stage 1. Obtaining a set of procedures for constructing a schedule;

Stage 2. Select a procedure for the next inclusion in the schedule. The process of selecting a procedure involves a consistent analysis of the subject of satisfaction of the set of criteria;

Stage 3. Search for available material support, as well as free staff at the clinic for the procedure selected in *stage 2*;

Stage 4. Find the available time intervals for the procedure based on the results obtained in *stage 3*;

Stage 5. Analysis of the possible options for placing the procedure in the schedule based on the data obtained during stages 3-4 and verification of the implementation of limitations of the subject area;

Stage 6. Direct including the procedure in the schedule and proceed to *stage 2*.

For an automaton, the set of input data X consists of a set of therapeutic procedures, of which it is necessary to make a schedule. The set of output data Y is a resulting set of procedures that make up the schedule. Characteristics S, f_y, f_s are determined by the algorithm of the operation of the automaton. The block diagram of the algorithm for constructing the clinic schedule, which involves the implementation of the proposed stages 1 ... 6, is depicted in Fig. 2

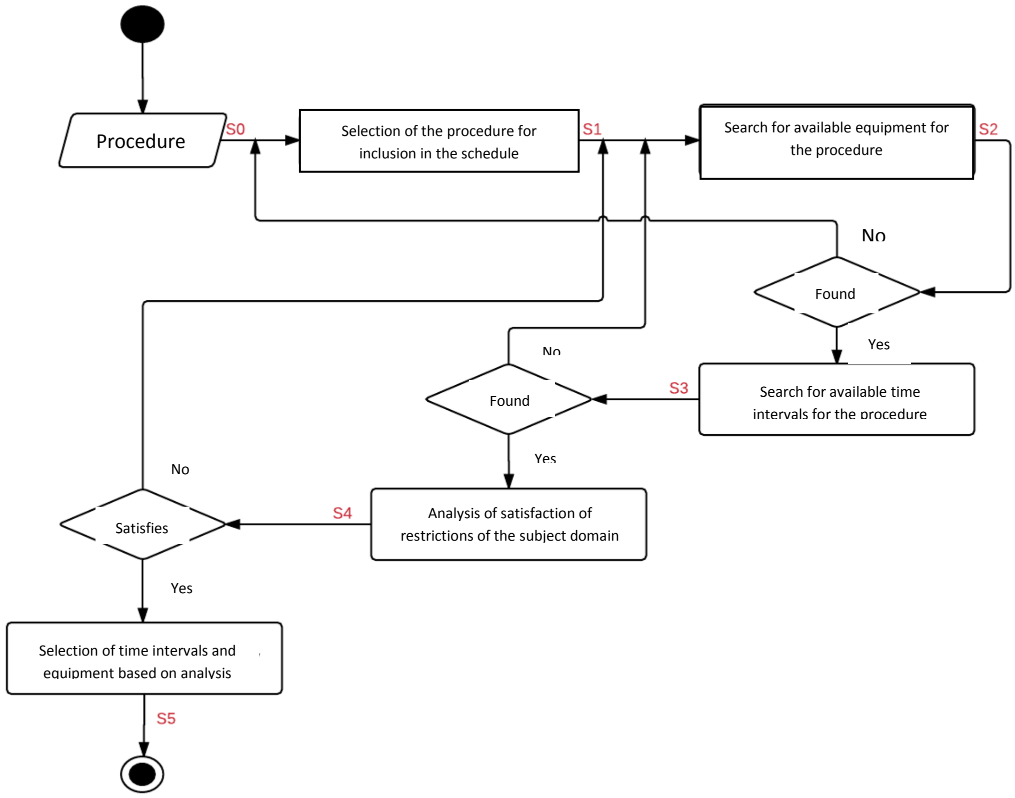

Fig. 3. Block diagram of the algorithm for constructing a clinic schedule

According to the block diagram, the set of states contains six elements and has the form $S = \{S_0, S_1, S_2, S_3, S_4, S_5\}$. At the beginning of its operation, the machine receives input data and passes to its original state (S_0). The next step is to select the procedure from the available and go to S_1. After that, the automatic machine analyzes equipment for the procedure, free staff, etc. In the case of the necessary equipment, the machine enters the state of S_2. With information from the previous step, an analysis of time intervals is performed when all the necessary equipment and medical personnel are available in S_3. For each of the found time frames, an analysis of the satisfaction of domain restrictions is performed. In case of success the machine enters the state S_4. Later, the choice of the time interval and equipment is made on the basis of satisfying the restrictions of the subject area, recording the procedure to the schedule and including it in the initial set of data (transition to the state of S_5).

The transition conditions are Boolean functions (because partial satisfaction of domain constraints is impermissible, etc.), which are determined separately for each state.

Method of multicriteria assessment of the schedule of functioning of the clinic. Before beginning the optimization process, it is necessary to formulate criteria for assessing the quality of the schedule. It must satisfy a multitude of requirements (restrictions) of a medical and organizational nature, of varying degrees of importance. These restrictions often contradict each other, sometimes at all mutually exclusive, which in turn complicates the construction of optimal solutions to the problem. In most cases, there are a number of limitations that are divided into obligatory ("hard"), the failure of which makes it virtually unsuitable for practical use, and desirable ("soft").

The obligatory restrictions imposed on the task of scheduling include:

- planning the procedures requiring the use of specialized technical equipment only in the relevant chambers;
- strict conformity of the sequence of procedures to the patient's plan of treatment;
- availability of the required number of medical staff for each procedure;
- inconsistency of the schedule.

The soft constraints imposed on the scheduling task include:

- limitation of the number of treatment procedures per day (usually not less than two and not more than six);
- uniform distribution of medical procedures during days of the week;

- providing a comfortable sequence of procedures throughout the day for patients;
- providing comfortable recovery periods between procedures.

Each solution obtained is characterized by a certain level of satisfaction of requirements, expressed by the value of the objective function - the mathematical expression of some criterion of the quality of one solution in comparison with others.

Quantitative methods may be used to assess the utilization of resources (staff load, gaps in the work of equipment). But measurement of patients' satisfaction is mainly expressed in a non-quantitative form, which makes practically impossible the use of classical methods.

This problem can be solved by fuzzy logic systems - mathematical systems that have emerged as tools for solving uncertain, inaccurate, or implicit decision-making problems.

Instead of using a classic mathematical model to describe a system, fuzzy logic controllers use integrated expert knowledge that is presented in a structure close to the spoken language and described by linguistic variables and fuzzy sets. Fuzzy system performs the conversion of input data, following a certain method of output.

The structure of the general fuzzy controller contains the following components [20]:

- block of fuzzification;
- base of rules of fuzzy logic;
- a block of decision-making;
- a block of defuzzification.

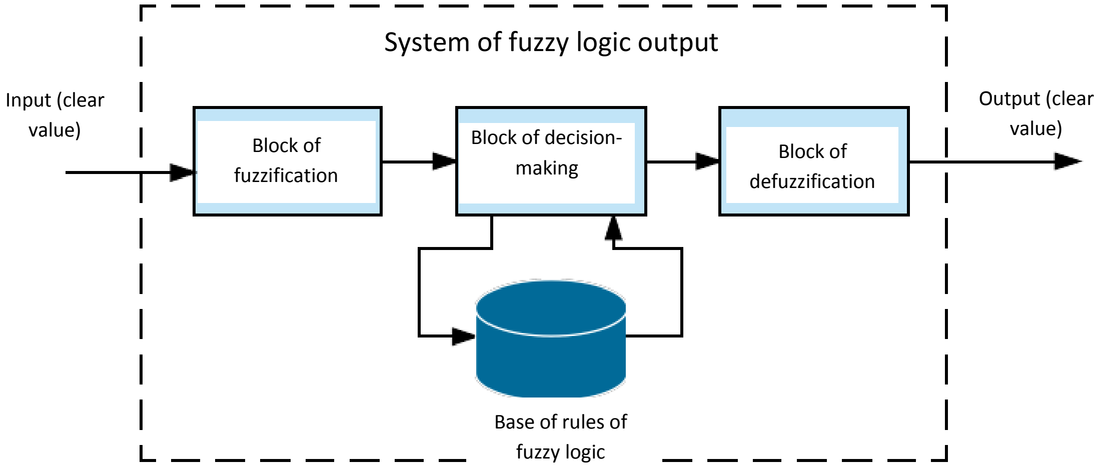

Fig. 4. The general structure of the fuzzy logic controller

The fuzzification block is responsible for displaying any clear value in the correct values in the space of fuzzy logic.

The fuzzy logic rule base contains a set of knowledge of the fuzzy output system in the format (IF-THEN). In the decision making block, fuzzy rules (IF-THEN) are contained in the rule base to transform fuzzy input into necessary control actions that also have fuzzy nature. Once the raw data has been processed by a fuzzy output system, they are converted again to clear values. This task is performed by the defuzzification unit. In other words, the defuzzificaton unit mathematically combines the result of each rule in a single clear value [21].

The development of a fuzzy logic controller for evaluating a clinic schedule consists of several steps:

- definition of input parameters;
- construction of linguistic variables and functions of affiliation;
- construction of the base rules of the controller.

The development of the model is performed with the aid of a neuro fuzzy T-controller to predict the parameters assessment [22]. The T-controller provides a neuro network method of defuzzification, which is implemented with the cascade of two neural networks of the model of geometric transformations (IHP). It is versatile and provides higher precision and speed compared to traditional neural network devices.

To define the input parameters, it is expedient to enter indicators based on the fines set for each parameter for any inconvenient moment in the schedule. Since a large number of different procedures are being conducted in the clinic, it is advisable to cluster them according to the types. For each type of procedure in the schedule, the number of violations is determined. The values of the violations are normalized by the following formula:

$$K_i^S = \frac{K_i^s - K_i^{min}}{K_i^{max} - K_i^{min}} \qquad (4)$$

where: K_i^s is the current value of the i-th criterion of violations;

K_i^{max}- maximum possible value of the i-th criterion of violations;

K_i^{min}- the minimum possible value of the i-th criterion of violations;

$K_i^{min} \le K_i^S \le K_i^{max}$;

$k_i^S \in [0,1]$.

The method of optimizing the schedule of functioning of the clinic. The disadvantage of many methods of constructing and optimizing schedules is that they use iterative techniques to improve the results on their own. During one iteration, a solution is searched, which will be better only in the vicinity of the current one. In the case of a successful finding, it replaces the current one and a new iteration begins. This continues until the delta target function is practically near zero, and the specified number of iterations will not be executed. Obviously, such methods are oriented to finding only local optimums, and the location of the optimum found depends on the starting point [23]. Achieving a global optimum can only happen by accident. To increase the likelihood of achieving optimal results, it is possible to use multiple sets of input data with different starting points, which in turn significantly increases the search time.

In connection with the above it is expedient to develop and use algorithms that would absorb the advantages of the above methods and avoid their drawbacks. These methods include genetic algorithms - stochastic, heuristic, optimization methods, the basic idea of which is taken from the theory of evolutionary development of species [24].

The first step in developing a genetic algorithm is to encode the "chromosome" structure, which will represent the solution. In this case, the chromosome is expedient to present a schedule of the functioning of the clinic. The next step is the generation of the initial sample (population), where it is justified to use a finite automaton to generate chromosomes that satisfy the strict limitations. To work the optimization algorithm, one needs to develop a method for assessing the development of populations. This method may require a minimization of the target function or, in terms of genetic algorithms, fitness function. Here it is expedient to use the integral index of the optimality of the schedule, based on a penalty for the dissatisfaction of the solutions to the requirements. In this situation, the formation and calculation of a fitness function is performed by using a fuzzy logic controller. Mutations, crossover and breeding operations are also subject to severe restrictions, for example, the sequence of follow-up procedures in patient care plans, the availability of medical equipment, etc. Therefore, in this situation it is justified to use the simulation model of the process of constructing a schedule that takes into account the above situations and will in fact reproduce the processes of making changes to the schedule.

Thus, placing the initial population in the created environment and realizing the evolutionary processes, iterative algorithm for finding the optimal solution is obtained. At each of its stages, the following actions are performed: 1) each individual of a population is estimated using the fitness function; 2) the best decisions are copied to the new population unchanged; 3) on the basis of proportional selection from the current population, chromosomes that are subject to recombination are selected; 4) if the new population is formed, the old one is removed, and then we proceed to the point 1. In the opposite case, we proceed to the point 2.

CONCLUSIONS

1. Manual scheduling of the functioning of medical institutions, with the increase in the flow of patients, is ineffective. In this regard, the tasks of their automated construction, evaluation and optimization are being actual.

2. To assess the quality of functioning of hospitals according to criteria that can not be measured quantitatively, the use of neuro-fuzzy models, in particular fuzzy logic controllers, is proposed. It allows assessing the criteria presented in a non-quantitative form and ensuring that the vector criterion is converted into a scalar, which can be used as a fitness function during the optimization process of the developed schedule of the work of the medical institution.

3. Using an automated system of construction, multicriteria assessment and optimization of schedules of medical institutions can reduce the amount of manual work, as well as increase the level of satisfaction of patients with the quality of regenerative therapy.

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