Adjustment of Fuzzy Cooperative Game for Hospitalization Strategy Selection Based on a Genetic Algorithm

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***Abstract*—The paper proposes an adjustment of the formalization of a fuzzy cooperative game for choosing an action strategy during hospitalization by a genetic algorithm. Adjustment expands the number of possible strategies for the player, additionally introducing the requirement for coordination of actions between the players. Since this increases the number of possible combinations of actions and increases the complexity of the calculation, a genetic algorithm is used in the paper to select an effective strategy for the actions of coalition members in the hospitalization process. As a fitness function, the characteristic function of estimating the gain of the coalition is used. The simulation results on the data obtained during the analysis of the hospitalization process in Russia showed that for small numbers of participants it is more efficient to search for a solution to the game by comparing all possible options, while with an increase in the number of participants, starting from 200 participants, the genetic algorithm starts to win in terms of performance.**

I. Introduction

In solving the challenges posed by the COVID-19 pandemic, a significant role was assigned to systems based on artificial intelligence methods [1]. In addition to developing vaccines and creating predictive models for the spread of disease, crisis management techniques have often been applied to hospitalization, resource allocation, and health system planning. The advantages of using crisis management methods based on artificial intelligence include efficiency, the ability to take into account more factors than are available to a person, and objectivity. However, there are also a number of disadvantages associated with the limited types of situations in which intelligent control can be applied, excessive objectivity, which in a difficult epidemiological situation can bring additional harm to patients.

Studies conducted in the context of the COVID-19 pandemic note that the negative impact on people is caused by insufficient information about the current situation, and the cumulative nature of the stress impact is recorded [2]. Unfavorable factors for all participants in the decision-making process are anxiety, fear of infection, and forced isolation from family members [3], an increase in anxiety and depression [4], which is largely due to the spread of threatening, emotional information about an invisible threat, which leads people to constantly turn to its sources, raises doubts that under these conditions one can count on full-fledged and high-quality medical care. Lack of protective equipment, problems with adequate treatment, as well as a purely human factor - overwork, stress, anxiety and professional burnout of medical personnel [4–6] cause negative emotional states.

Papers [7], [8] propose to take into account the influence of psychological factors on the decision on hospitalization by formalizing the problem of making decisions on hospitalization using fuzzy cooperative games. Psychological factors are taken into account both in the formalization of the dynamics of the state of patients and ambulance personnel, and in the formation of a pool of strategies that can guide each of the types of participants (patients, ambulances, hospitals, laboratory diagnostic centers) when making a decision on hospitalization. The solution to the problem is a set of compositions of coalitions, taking into account their action strategies.

The use of the mathematical apparatus of cooperative games for the selection of the coalition composition in such a way that the actions of the players are aimed at a fair distribution of a predetermined or increase in the total payoff. This approach can be used to make a decision on hospitalization in a difficult epidemiological situation, which requires the coordination of actions of a large number of participants in the hospitalization process. Participants can be divided into four main groups: patients, emergency medical teams, hospitals and laboratory diagnostic centers. When assessing the current situation, it is necessary to take into account a large number of their parameters and limitations related to the physiological and psychological state of patients at the time of their initial examination and the current state of the healthcare system in the region. It makes difficult to solve the problem using linear programming methods.

Considering that the resulting formalization of the problem is NP-complete (since it is necessary to check all combinations of participants with all possible strategies), a complete calculation of a cooperative game in real conditions is not possible with a large number of participants. To meet the requirements of efficiency, this paper proposes the use of a heuristic solution method based on the use of a genetic algorithm. The use of heuristics based on a genetic algorithm is permissible in this type of problem, since they do not require the search for a global maximum - it is enough that the solution be quasi-optimal in the local solution area.

To be able to solve a cooperative game using a genetic algorithm, the paper also proposes an adjustment formalization of a cooperative game to match the fitness function specified in the genetic algorithm to determine the optimization criterion.

The article is structured as follows. Section 2 describes the problem to be solved and introduces the basic concepts related to the types of participants in the hospitalization process, cooperative games, and coalitions. Section 3 describes

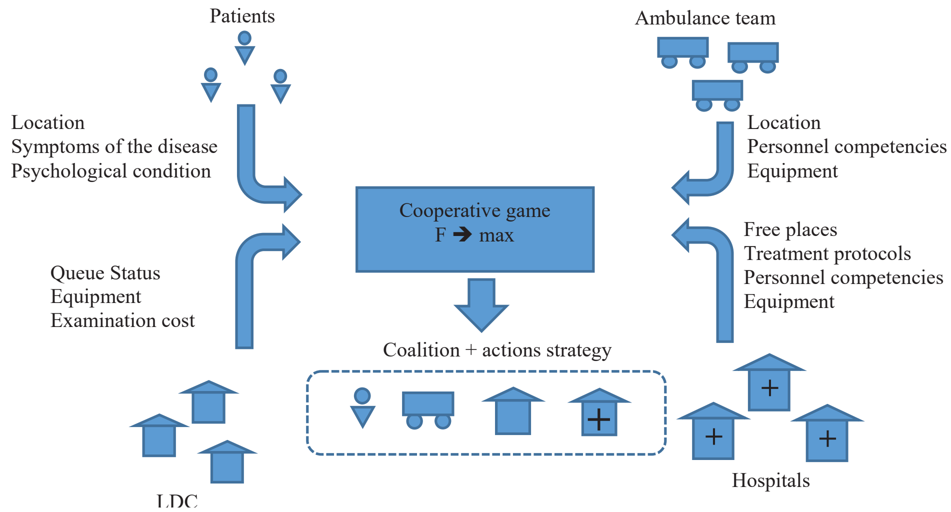

Fig. 1. Scheme of forming a coalition using a cooperative game

approaches related to the use of cooperative games to solve the optimization problem and the use of genetic algorithms for heuristic search for solutions of cooperative games. Section 4 describes the adjustment (adaptation) of the formalization of the cooperative game for the case of multiple and coupled strategies. Section 5 contains a description of a genetic algorithm for finding a solution for the cooperative game. Section 6 presents a description of the implementation and experimental results, as well as their comparison with previously obtained results. In conclusion, discussion of the results is provided and directions for further research are given.

II. Problem Statement

The hospitalization process includes several stages, each of which requires a decision that affects the actions in the next stages. The stages include sending an ambulance to the patient, examining the patient and deciding on the need for additional examination, choosing a place for additional examination and choosing a place for hospitalization. The main active participants in the process are the patient, ambulance, hospital, laboratory diagnostic center (LDC). The ambulance station dispatcher is defined as an independent decision maker based on the requirements of the participants in the process and the current state of the system consisting of all four participants.

The problem considered in the article is aimed at supporting the dispatcher when making decisions at each stage. It is proposed to consider the system "patient" - "ambulance" - "hospital" - "LDC" in the form of a cooperative game with a non-zero sum, where all participants in the game are guided by a common interest and must interact with each other to reduce the risk of deterioration of the patient's condition (Fig. 1). The assessment of the coalition's gain is reduced to an assessment of the overall economic benefit, calculated taking into account the social orientation of the decisions made in the implementation of the chosen strategies [7]. A coalition can only have one member of each type, and all types of members, except patients, can be members of multiple coalitions, subject to additional restrictions such as available time window and spatial distribution of members.

III. Related Work

A. *Using Cooperative Games to Solve an Optimization Problem*

The use of fuzzy logic and cooperative games to describe the interaction of coalition members is a relatively new approach that has shown to be effective in supply chain configuration tasks. [9] and the formation of a coalition of robots [10]. The mathematical apparatus of fuzzy logic and cooperative games can also be used to assess the effectiveness of hospitals. [11], when the effectiveness of their work is evaluated by a large number of parameters, including the number and quality of staff (doctors, nurses, support staff), the number of beds, the number of operations, the cost of treatment and maintenance.

B. *Formation of groups using a genetic algorithm*

The formation of groups of participants based on an assessment of the effectiveness of their interaction in solving a complex problem is an urgent task for many problem areas. The use of evolutionary algorithms for their solution is seen by many researchers as one of the promising options. In particular, approaches based on evolutionary algorithms have been developed to solve the problem of forming groups of students to ensure a greater variety of student profiles in the group. [12]; selection of product suppliers, in the form of a cost-based assignment task [13–16], formation of a group based on geographical distance with maximum packing at a minimum specified distance between group members [17]; coalition formation in a multi-agent system [18]. In the latter case, depending on the specifics of the task, the distribution of members of the coalition and the task can be as follows: one task - one coalition, many tasks - one coalition, many tasks - many coalitions. In any of the cases, approaches using genetic algorithms have been developed to form the composition of coalitions and distribute tasks. [19], [20].

IV. Fuzzy Cooperative Game Adjustment for Multiple Strategies Support and Solving with Genetic Algorithm

This section discusses the formalization of the task in terms of a cooperative game to form a coalition with the selection of an effective strategy for hospitalization in a pandemic. Formalization is based on work [21] and adjusted by the case of having more than two strategies for one of the participants. At the start of the calculation of the game, a set of parameters is formed, which become the initial data for calculating the characteristic function of the coalition. The solution obtained during the calculation will contain coalitions of game participants that provide the maximum benefit in terms of time and cost of hospitalization, as well as the strategies of the coalition participants. It will also determine the hospital to which the patient must be delivered, and the medical center, where, if necessary, it will be possible to undergo an additional examination.

The cooperative game is represented as a set *(N, v)*, where N – set of participants, v – the characteristic function of the game, according to which the payoff of the coalition is estimated. The current situation is described using context C.

The patient is matched with the strategy (η^P), determining consent or refusal to hospitalization. The ultimate payoff in choosing a strategy depends on the combination of the patient's physical and psychological condition. Strategies defined for the hospital (η^H), determining consent or refusal to accept a patient. Three strategies are considered for the ambulance team (η^A):leave the patient at home, transport to the LDC and transport to the hospital. At the same time, the strategy of the ambulance team must necessarily be coordinated with the strategy of the patient, the medical center, and the hospital. LDC is described by two strategies: (η^{CT})admitting or refusing to admit a patient. The general strategy of the coalition, which determines the membership in the coalition and the actions carried out by the participants, is given as a combination of the strategies of its members $\eta_{i,j,k,l} = \{\eta_i, \eta_j, \eta_k, \eta_l\}$, where $i \in P, j \in H, k \in A, l \in CT$.

The function of belonging to a coalition for the variant of two strategies (1) determines the probability of whether a participant will be a member of a particular coalition.

$$\eta(x) = \begin{cases} 0, x < 0.5 \\ 1, x > 0.5 \end{cases}, \quad (1)$$

where x – the probability of a player choosing a strategy.

In the case where the participant belongs to the ambulance type, there are three strategies of action, and the values in formula (1) will be expressed in terms of dependence on the strategies of other participants as follows (2):

$$\eta^A = \begin{cases} 0, (\eta^H + \eta^{CT} + \eta^P)/3 < 2/3 \\ 1, (\eta^H + \eta^{CT} + \eta^P)/3 > 2/3 \end{cases} \quad (2)$$

The payoff of the coalition members is calculated as the sum of the products of the normalized payoffs of individual participants and their strategies, according to formula (3) This adjustment makes it possible to represent the payoff function as a scalar product of the weights of the cost functions for each participant and the chosen strategies. With such an adaptation, the chromosome in the genetic algorithm can be the vector of strategies of the participants, and the input values of the function can be the vector of payoffs.

$$\omega_{i,j,k,l} = \eta_{i,j,k,l} f^P(C^P, t_{i,j,k,l}, C'^P) + \eta_{i,j,k,l} f^H(C^H, t_{i,j,k,l}, C'^H), \\ +\eta_{i,j,k,l} f^A(C^A, t_{i,j,k,l}, C'^A) + \eta_{i,j,k,l} f^{CT}(C^{CT}, t_{i,j,k,l}, C'^{CT}) \quad (3)$$

where $f^P(C^P, t_{i,j,k,l}, C'^P)$ - is a cost function for the patient *i*, $f^H(C^H, t_{i,j,k,l}, C'^H)$ is a cost function for the hospital *j* to treat the patient $f^A(C^A, t_{i,j,k,l}, C'^A)$ is a cost function for the ambulance team *k;* $f^{CT}(C^{CT}, t_{i,j,k,l}, C'^{CT})$ is a cost function for the LDC *l*. The type of equations and the principle of their calculation are described in detail in [7].

V. USING A GENETIC ALGORITHM TO CHOOSE STRATEGIES WITHIN A COOPERATIVE GAME OF HOSPITALIZATION

The use of a genetic algorithm involves the determination of the following main parameters: chromosomes and fitness functions.

For the formalization of the problem characteristic function of the coalition can be used as a fitness function. The condition for stopping the genetic algorithm in this case will be the achievement in several generations of the threshold for the deviation of the payoff value from the maximum for the entire time the algorithm is executed (Fig. 2).

The chromosome for the operation of the genetic algorithm in the problem under consideration can be specified by a vector, the values of which are determined according to the following principle.

To describe the composition and strategies of the coalition, a chromosome is used that describes only one coalition per calculation of the cooperative game. A chromosome is defined by a vector in which each element (chromosome gene) corresponds to the strategy of the participants, while the selection of only one participant from each subset is possible. In this case, it is necessary to carry out several runs of the calculation procedure, sequentially excluding patients for whom a coalition was formed. In this setting, it is easier to take into account the time constraints that arise during the formation of a coalition, but the control over the entry of participants into several coalitions becomes more complicated.

The first set of individuals is formed randomly according to the number of patients. After calculating the fitness function, individuals are selected according to the maximum value of the fitness function. With regard to the described problem, it is proposed to use the steady-state selection method [22], where individuals with the highest fitness function values are selected and their descendants are replaced by individuals with the lowest fitness function values.

Then, a crossover procedure is carried out, during which, from the remaining individuals, a point is determined by random selection at which the chromosome will be broken, and new individuals are formed by mixing. Each new individual is checked against the condition that the coalition must include only one member of each type. All individuals that do not meet this condition are eliminated as unsuitable.

In addition to the crossover, the mutation method can be used to bring the solution out of the local maximum. The application of this method is determined randomly in the case when the composition of the descendants does not change over two iterations. Mutation is carried out by an adaptive method, during which the population is divided into two subsets according to the average value of the fitness function and in the subset with function values less than the median, more mutations are carried out, and in the subset with the function value greater than the median, fewer [23]. If the situation has not changed after the mutation, then it is considered that the solution has been found and the individual from the last population with the highest payoff value is returned as the final solution.

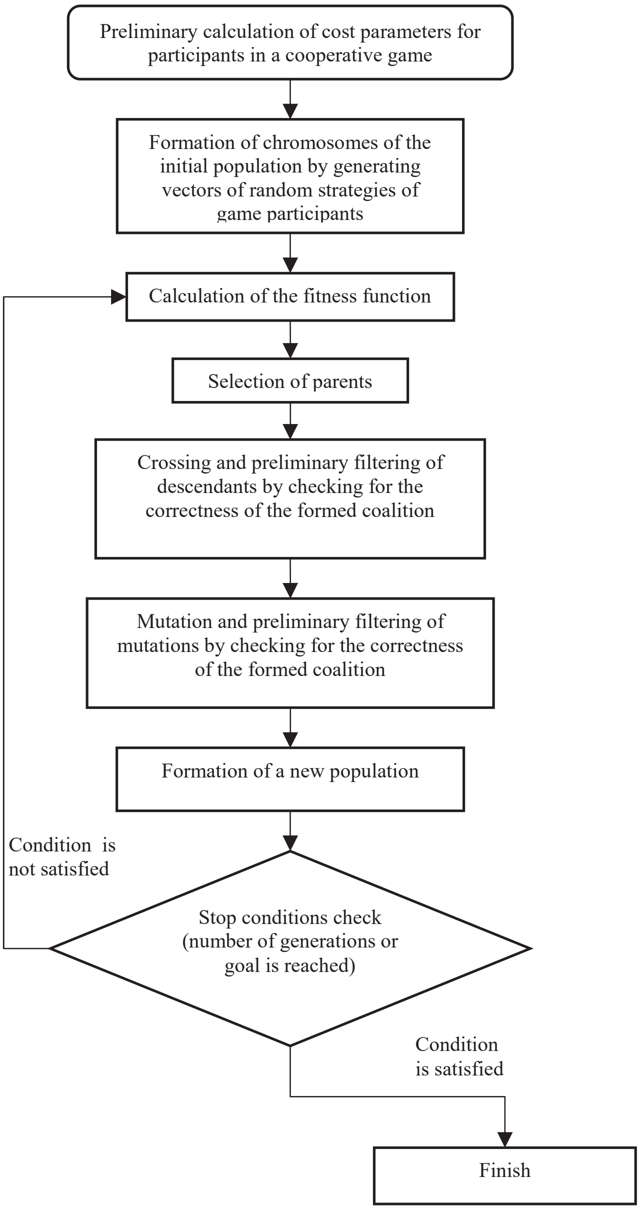

Fig. 2. Diagram of genetic algorithm for strategies choose

VI. ARCHITECTURE OF THE SYSTEM OF OPERATIONAL DECISION-MAKING DURING HOSPITALIZATION

Since there are four types of participants in the hospitalization process, each of them should be able to provide their own context in order to calculate an effective strategy of action. For this, an architecture was developed that provides data collection from all participants in the hospitalization process, the formation of a cooperative game and its calculation with a genetic algorithm. The conceptual scheme is shown in Figure 3. Participants interact by transferring the context of the current situation from the participants' devices, serialized as a JSON file to the dispatcher's automated workplace. Each of the participants sends its context to the dispatcher when one of the parameters is updated. Thus, the dispatcher at any time has a complete picture of current situation.

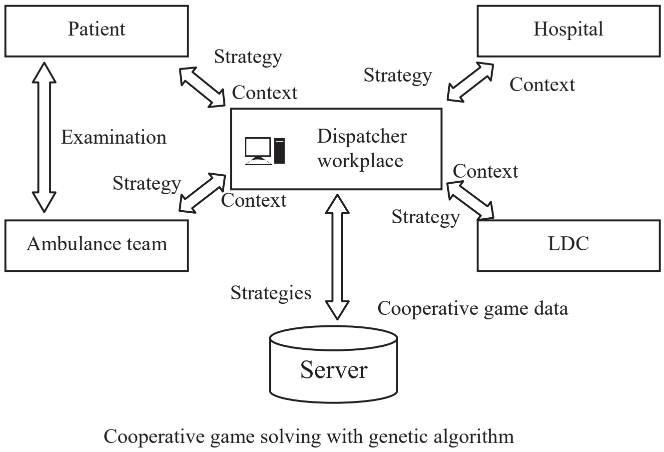

Fig. 3. Decision support system scheme

The patient can interact with the dispatcher both through the application of the healthcare system during a scheduled call, and through phone communications. In the latter case, the dispatcher forms the context of the patient by asking questions that clarify the information required for calculating the game.

Ambulance teams are currently equipped with digital devices for communication with the dispatcher's workstation. Upon arrival at the patient, the team, in addition to its context, supplements the patient's context with the results of the initial examination on the spot.

Hospitals and clinics transmit context when their current situation changes (a patient is admitted or discharged, a change in stocks of medicines, and the state of equipment and personnel).

When it is necessary to make a decision on the selection of a strategy for the actions of participants in the hospitalization process, the dispatcher forms a set of input parameters for a cooperative game by selecting participants and their contexts (Fig. 4). The resulting set is transferred to the computing server, which calculates the cooperative game with the genetic algorithm and forms coalitions of participants. The result of the calculation is returned to the dispatcher's workstation, which performs verification and sends to all coalition participants the action strategies corresponding to the greatest gain for each of the coalitions.

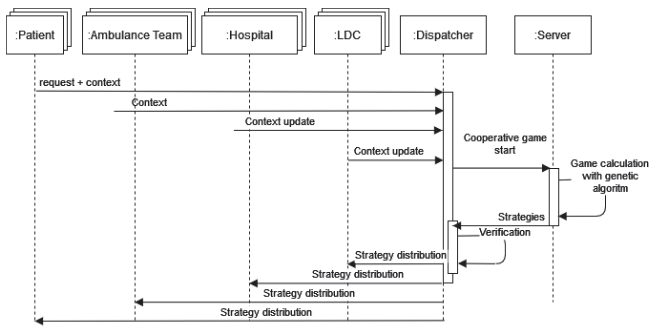

Fig. 4. Sequence diagram of decision support system for hospitalization

VII. Implementation of a genetic algorithm for strategies choose within cooperative game of hospitalization

To implement the genetic algorithm, the Python programming language and the PyGAD library [24] were chosen, which includes a large number of functions that implement existing methods for choosing ancestors, performing crossover, mutation, and forming a new population.

As a test bench, a personal computer was used with the following parameters: Intel Core i9 10900X 3.7 GHz central processor, 64Gb DDR4 RAM, the interpreter was launched in the Docker virtual environment, interaction with which was carried out using the Jupyter software package.

The implementation of the algorithm includes a software description of classes corresponding to the description of each type of participants in a cooperative game. Program classes contain the main parameters of the participant, additional functions for processing parameters, and functions for calculating the cost of a cooperative game.

When calculating the game, two experiments were carried out to evaluate the speed of calculating the genetic algorithm and compare it with exhaustive enumeration in the strategy selection problem. The implementation of exhaustive enumeration is described in [7]. For each type of participant, 10 objects were generated in the first experiment and 100 in the second. By the number of participants in the experiments, the initial population was formed to calculate the cooperative game. The fitness function of the game in both cases was defined separately as the scalar product of the strategy vector and the payoff vector of the coalition members. Additionally, in the fitness function, the correctness of the composition of the coalition is checked. Correctness is checked for the occurrence of only one member of each type in the coalition. Individuals of the population that do not satisfy the correctness condition are assigned a fitness function value equal to zero, which excludes them from consideration as possible parents at the crossing stage and then excludes them from the population at the selection stage.

To run the genetic algorithm, the basic parameters indicated in Table 1 were also determined. The choice of these parameter values is due to the achievement of convergence of the fitness function of the genetic algorithm in less than 3000 generations both in the first experiment (Fig. 5) and in the second one (Fig. 6).

TABLE I. LAUNCH PARAMETERS OF THE GENETIC ALGORITHM

Parameter	Value
Upper bar number of generations	3000
Number of parents to cross	10
Number of offspring in a population	100
Parent selection method	steady-state selection [22]
Number of retained parents	3
Crossover Method	Single point
Mutation method	Adaptive
Number of mutation genes for fitness function values below the median	20
Number of mutation genes for fitness function values above the median	2

Fig. 5 also shows the different convergence rates depending on the initial conditions and the initial population. The top figure shows a high rate of change and the achievement of a local minimum of the fitness function (along the ordinate) for 1500 generations (along the abscissa), which can be interpreted as a start close to the maximum, which is clearly pronounced. On the bottom figure, there is a minimum of changes (the order of changes is 10^{-5}), which means that the original population hit the local maximum and a small adjustment of the value of the fitness function between generations.

For the second experiment, when the number of participants is much larger (400 participants and 10^8 possible compositions of coalitions), there is a lower rate of convergence of the fitness function and a greater number of changes (Fig. 6), however, the parameters defined in Table 1 also provide convergence in less than 3000 generations.

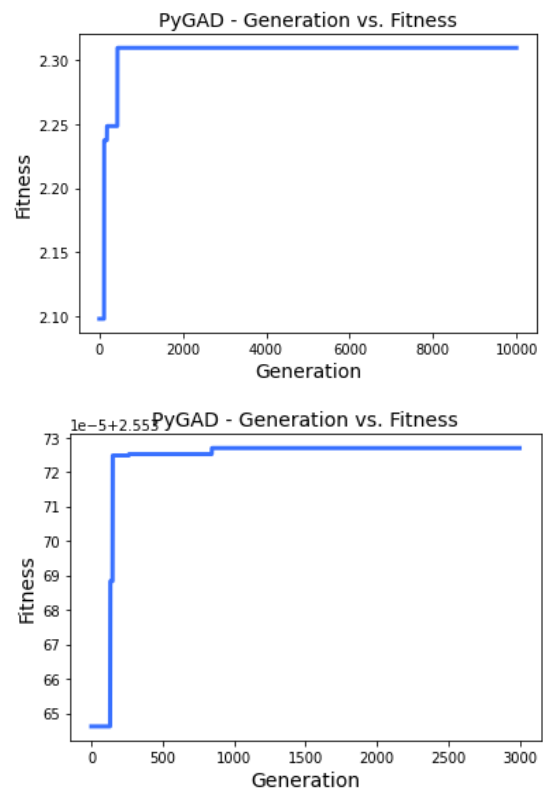

Fig. 5. Examples of changing the value of the fitness function for calculating a cooperative game in the process of selection by a genetic algorithm for 40 participants (10^4 possible compositions of coalitions).

The resulting best solution is a vector of strategies that should be applied by the selected participants in the cooperative game. When following the chosen strategies, the total gain of the coalition is guaranteed equal to the value of the fitness function for the best solution. The full calculation for the case of 40 participants (10^4 possible coalitions) with the selected parameters took 22 seconds, which is slower than in the case of a complete enumeration, and for 400 (10^8 possible coalitions) it took 2328 seconds, which is much faster than a brute force. Comparison of the speed of operation with the variant of brute force from work [7] is shown in Fig. 7.

In this case, the value of the gain to which the fitness function tends converges to the value of function (3) obtained in [7] by brute force over all participants combinations (2.71 on average when running the genetic algorithm and 2.86 with brute force). When translating the value of the fitness function into a monetary equivalent, it is necessary to use the normalization coefficient calculated from the cost of treatment in the hospital (expression (4)) as having the main contribution to the cost function. On average, depending on the chosen strategy and the time of treatment, it is 90,000 rubles. Thus, the average "gain" of the coalition with the chosen strategies using a genetic algorithm can be estimated as 243,900 rubles, against 257,400 with a brute force. This benefit includes both the direct cost of hospital treatment, the cost of hospitalization by the ambulance team and the cost of additional examinations at the LDC, which will be reimbursed to them, as well as an estimate of the funds that the patient will “save” by following the proposed strategy.

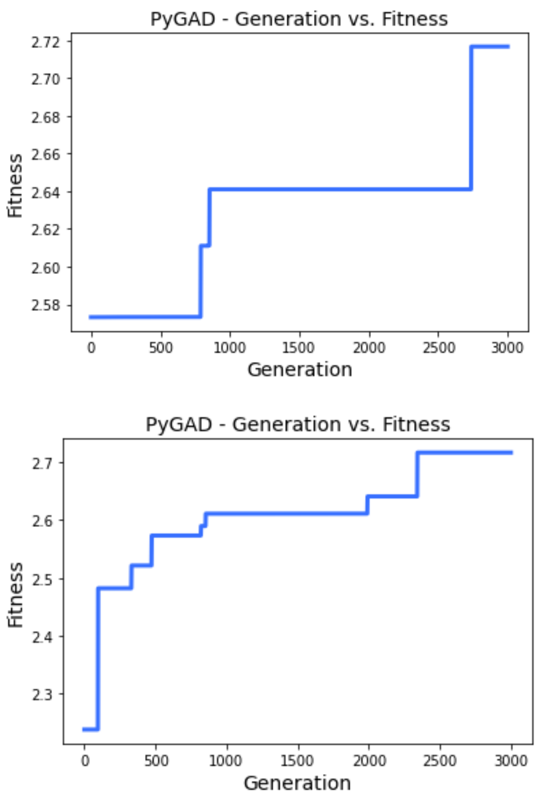

Fig. 6. Examples of changing the value of the fitness function for calculating a cooperative game in the process of selection by a genetic algorithm for 400 participants (10^8 possible compositions of coalitions).

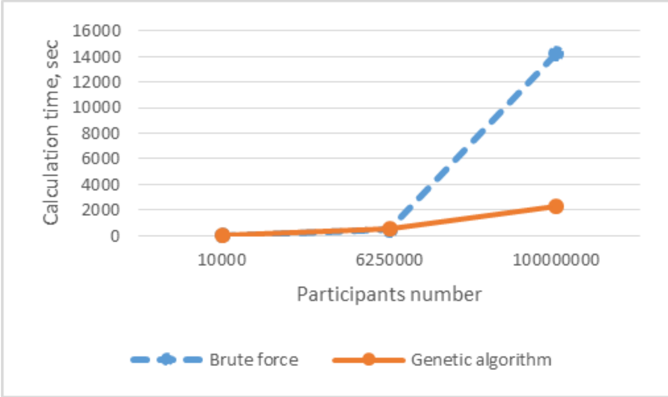

Fig. 7. Comparison of the duration of the brute force algorithm and the genetic algorithm in the problem of choosing an effective strategy of actions during hospitalization.

VIII. CONCLUSION

The paper formalizes the selection of an effective strategies for the actions of participants in the hospitalization process based on fuzzy cooperative games.

Since the selection of strategies for all combinations of participants is an NP-complete problem, a solution using a genetic algorithm was proposed. For this, additional rules for filtering descendants after the crossover and mutation stages were formed in order to check them for compliance with the basic rules for forming a coalition. Also, an adjustment of characteristic function of the cooperative game is proposed to calculate the game with genetic algorithm. The adjustment allows to use strategies vector as a chromosome for the genetic algorithm and gain functions values for each participant as an input parameters of fitness function.

The proposed solution was tested on the data obtained during the analysis of the hospitalization process and the cooperative game model: the convergence of the solution is achieved on average over 3000 generations, the average time to calculate strategies for a game of 40 participants is about 22 seconds, for 400 participants - 2328 seconds. The solution obtained in the process of solving by a genetic algorithm is close to the solution obtained by complete enumeration, which makes it possible to use the proposed method to solve the problem of choosing an effective strategy for the actions of participants in the hospitalization process. At the same time, the duration of the calculation of all possible compositions of the coalition using the genetic algorithm grows almost linearly, while the duration of the calculation using exhaustive search grows polynomial ($O(n^k)$, where $k=4$).

As a direction for further research, the optimization of the mutation and crossover functions is determined to better suit the task. In the implementation given in the article, the standard functions of the PyGAD library were used, which, despite the additional filtering of individuals according to the correctness criterion, do not fully meet the requirements of the task, which significantly slows down the evolution process, since it is necessary to produce a larger number of descendants and filter them. Adjustment of these functions to the task can significantly increase the speed of reaching the maximum fitness function by generating individuals immediately with the correct parameters.

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