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Применение генетических алгоритмов для управления организационными системами при возникновении нештатных ситуаций

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Оптимальное управление системой топливоснабжения заключается в выборе варианта развития энергетики, при котором достигается наиболее эффективное и надежное топливо- и энергоснабжение потребителей. В рамках реализации программы перевода распределенной системы теплоснабжения Удмуртской Республики на возобновляемые источники энергии была разработана информационно-аналитическая система управления топливоснабжением региона альтернативными видами топлива. В работе представлена математическая модель оптимального управления логистической системой топливоснабжения, состоящая из трех взаимосвязанных уровней: пункты накопления сырья, пункты производства топлива и пункты потребления. С целью повышения эффективности функционирования системы топливоснабжения региона информационно-аналитическая система расширена функционалом оперативного реагирования при возникновении нештатных ситуаций. Возникновение нештатных ситуаций на любом из уровней требует перестроения управления всей системой. Разработаны модели и алгоритмы оптимального управления в случае возникновения нештатных ситуаций, связанных с выходом из строя производственных звеньев логистической системы: пунктов накопления сырья и пунктов производства топлива. В математических моделях оптимального управления в качестве целевого критерия учитываются расходы, связанные с функционированием логистической системы при возникновении нештатной ситуации. Реализация разработанных алгоритмов основана на применении генетических алгоритмов оптимизации, что позволяет достичь наилучших результатов по времени работы алгоритма и точности полученного решения. Разработанные модели и алгоритмы интегрированы в информационно-аналитическую систему и позволяют оперативно реагировать на возникновение чрезвычайных ситуаций в системе топливоснабжения Удмуртской Республики путем применения альтернативных видов топлива.

Ключевые слова: генетический алгоритм, оптимальное управление, топливоснабжение, математическое моделирование, альтернативная энергетика, нештатная ситуация

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MODELS OF ECONOMIC AND SOCIAL SYSTEMS

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The application of genetic algorithms for organizational systems' management in case of emergency

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Optimal management of fuel supply system boils down to choosing an energy development strategy which provides consumers with the most efficient and reliable fuel and energy supply. As a part of the program on switching the heat supply distributed management system of the Udmurt Republic to renewable energy sources, an "Information-analytical system of regional alternative fuel supply management" was developed. The paper presents the mathematical model of optimal management of fuel supply logistic system consisting of three interconnected levels: raw material accumulation points, fuel preparation points and fuel consumption points, which are heat sources. In order to increase effective the performance of regional fuel supply system a modification of information-analytical system and extension of its set of functions using the methods of quick responding when emergency occurs are required. Emergencies which occur on any one of these levels demand the management of the whole system to reconfigure. The paper demonstrates models and algorithms of optimal management in case of emergency involving break down of such production links of logistic system as raw material accumulation points and fuel preparation points. In mathematical models, the target criterion is minimization of costs associated with the functioning of logistic system in case of emergency. The implementation of the developed algorithms is based on the usage of genetic optimization algorithms, which made it possible to obtain a more accurate solution in less time. The developed models and algorithms are integrated into the information-analytical system that enables to provide effective management of alternative fuel supply of the Udmurt Republic in case of emergency.

Keywords: genetic algorithm, optimal management, fuel supply, mathematical modeling, alternative energy, emergency

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1. Introduction

The development of fuel and energy complex (FEC) and its inner industry systems is a complex multistage process that covers decision-making issues along all production stages: from the extraction of raw materials to their processing, transportation and final consumption. Optimal management of fuel supply system boils down to choosing an energy development strategy which provides consumers with the most efficient and reliable fuel and energy supply.

Overall energy situation in our country impacts the choice of energy-saving technologies and priorities among energy-efficient methods which are to be introduced.

In the context of housing and utilities reform efficiency and reliability of heat sources as well as heat supply of local utility consumers are particularly relevant. The upward trend of the amount of deteriorated equipment and pipelines in the main components of heat supply systems demands to use modern management approaches along with information technologies and mathematical and simulation modeling.

The aims, objectives and main directions of the country's energy policy are determined in accordance with Energy Strategy of Russia for the period up to 2020 by Federal Law on energy efficiency and the President of the Udmurt Republic's decree.

Because of FEC being one of the major infrastructural industries in the country its possible development strategies will also determine the possibilities of further economic growth in every region. Thus, the priorities of energy development strategy can be distinguished as follows:

- complete and sound energy supply of the population and national economy, energy supply risk and emergency management;
- energy supply of the population with moderate pricing that stimulates energy efficiency;
- the reduction of unit production costs and energy resources utilization by means of rationalization of their consumption, employment of energy-saving technologies and equipment, loss reduction within the course of extracting, processing, transporting and delivering of FEC products.

Theory and methodology of modern energy research and strategic planning are established and developed in the works by L. S. Belyaev, N. I. Voropai, A. A. Makarov et al. [Belyaev, Podkovalnikov, 2004; Voropai, 2004; Makarov, Melentyev, 1973]. Systematic approach to solving strategic issues of heat supply development is based on the research by A. G. Granberg, V. I. Ishaev, V. V. Kuleshov [Granberg, 2004; Ishaev, 1998; Kuleshov et al., 1986].

Modern research in the field of mathematical modeling of emergency situations is given in the works of G. Wu, X. Li, V. Orlov and others. For instance, the paper [Wu et al., 2013] proposes a novel coordinate scheme of emergency control, which is based on technology of Multi-agent, and an algorithm to identify the minimum control area, which is based on the principle of Run the Horse Stable Place. The paper [Li et al., 2011] describes covering models and optimization techniques for emergency response facility location and planning, from the perspective of mathematical models and operations research. The paper discusses various optimization techniques used to solve the above proposed models, including exact methods, simulation and heuristics, among which the most popular are Genetic Algorithms and Tabu Search. Mathematical modeling of emergency situations is considered on the example of power system [Wu et al., 2013], objects of production and gas transportation [Orlov et al., 2018], emergency transportation [Tlili et al., 2018], wind power [Huang et al., 2011].

In 2010 the program on switching the heat supply distributed management system to renewable energy sources has launched in the Udmurt Republic [Rusyak et al., 2010]. This paper observes a developed program "Information-analytical system of regional alternative fuel supply management" [Rusyak et al., 2013].

Information-analytical system is designed to dealing with problems of optimal management of regional distributed fuel supply system of the Udmurt Republic. The structure of information-analytical fuel supply management system comprises three main blocks:

- information subsystem,
- analytical subsystem,
- geoinformation subsystem.

Functioning of the regional distributed fuel supply system involves operational risks which may depend primarily on the malfunctioning of logistic system components. The disruption of technological fuel preparation operations poses a threat for the security of the given region's energy resources and may cause not only significant financial losses, but also serious social implications. High-quality risk analysis and management enables prompt responding to failures in fuel supply system operation and, hence, raising the level of energy security, while optimal management of emergencies minimizes negative effects of disruption. In order to increase effective the performance of regional fuel supply system a modification of information-analytical system and extension of its set of functions using the methods of quick responding when emergency occurs are required.

2. Mathematical model of optimal management of fuel supply system

Logistic scheme of supply of heat sources with fuel consists of three levels [Rusyak et al., 2017]. In logging and woodworking enterprises as well as timber harvesting zones wood raw materials are produced and then are transported to the raw material accumulation points (RMAP) — it is the first level. At RMAP primary processing of wood raw materials is executed. The collection of raw materials at RMAP begins at the time t^{+}_{RMst} and uniformly runs until the time t^{+}_{RMend}. The outflow of raw materials to fuel preparation points starts at the time t^{-}_{RMst} and runs until the time t^{-}_{RMend}. Basic technological operations related to fuel preparation emerge at the second level. The second level comprises fuel preparation points (FPP) where primary processed wood raw materials are sorted, cut into small pieces, heat-treated and packed. After that finished fuel is delivered to heat sources in the region — it is the third level of logistic system. The time required to supply fuel to heat sources is determined by the interval $\left[t^{+}_{\text{Fst}}, t^{+}_{\text{Fend}}\right]$. Fuel consumption at heat sources occurs during the heating season $\left[t^{-}_{\text{Fst}}, t^{-}_{\text{Fend}}\right]$. Fuel consumption at heat sources is determined by their loading and change of temperature during the heating season. Every level of logistic system includes warehouses for raw material storage.

The diagram of raw material movement on different levels of logistic system is demonstrated in Figure 1 [Ketova, Trushkova, 2012a].

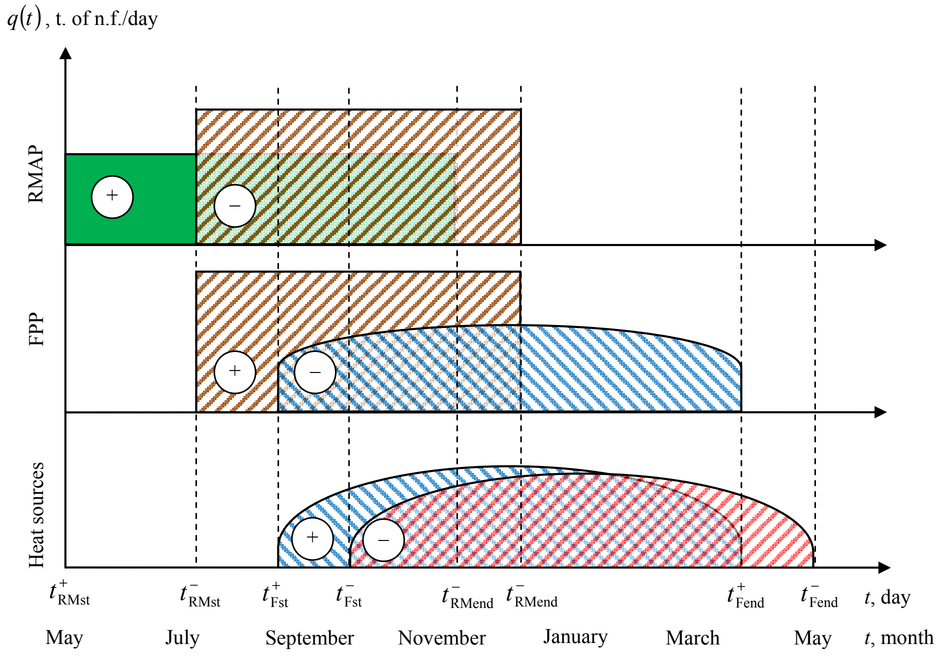

Fig. 1. The scheme of changes in stocks of raw materials and fuel during the year at different levels of logistics system: raw material accumulation points, fuel preparation points and heat sources

The solving of fuel supply logistic system design problem consists of four stages each of which boils down to dealing with certain tasks: routing [Revelle et al., 1991; Bramel, Simchi-Levi, 1995; Ketova, Trushkova, 2012], clustering [Ketova et al., 2010], optimal distribution of resources [Daskin, 2008] and stock control [Trushkova, 2011, 2013; Shen et al., 2003]. As a result of consistent execution of all design stages a fuel supply logistic system with defined locations for all objects, their links as well as volumes and performances of raw material and fuel preparation and consumption at every object of the system is developed [Rusyak et al., 2011].

The given logistic system contains M raw accumulation points, N fuel preparation points and L heat sources.

Let $\tilde{Q}_{\mathrm{RM}i}^{\mathrm{RMAP}}, \tilde{Q}_{\mathrm{RM}k}^{\mathrm{FPP}}, \tilde{Q}_{\mathrm{F}k}^{\mathrm{FPP}}, \tilde{Q}_{\mathrm{F}j}^{\mathrm{H}}$ denote current volumes of wood raw materials at i^{th} RMAP $(i=\overline{1,M})$, current volumes of wood raw materials and fuel at k^{th} FPP $(k=\overline{1,N})$ and current volumes of fuel at j^{th} heat source $(j=\overline{1,L})$ respectively, t. of n. f.; $q_{\mathrm{RM}i}^{+RMAP}, q_{\mathrm{F}j}^{+H}$ are speeds of wood raw material replenishing at i^{th} RMAP and refueling at j^{th} heat source, t. of n. f./day; $q_{\mathrm{RM}i}^{-RMAP}, q_{\mathrm{F}j}^{-H}$ are speeds of wood raw material consuming at i^{th} RMAP and fuel consuming at j^{th} heat source, t. of n. f./day; $q_{\mathrm{RM}k}^{-FPP}, q_{\mathrm{F}k}^{+FPP}$ are speeds of wood raw material consuming and refueling at k FPP, t. of n. f./day. The speed of raw material replenishing at k^{th} FPP is defined as a sum of speeds of wood raw material consuming q_{RM}^{-RMAP} at RMAP that supplies that given FPP.

Fuel preparation line launches at the time t_{RMst}^{-FPP} when wood raw material is delivered to FPP warehouse. Therefore, speeds of wood raw material consuming and refueling at k^{th} FPP are equal and are defined by the performance of equipment $p_k(t)$, t. of n. f./day:

$$q_{\mathrm{RM}k}^{-FPP}(t) = q_{\mathrm{F}k}^{+FPP}(t) = p_k(t), \quad k=\overline{1,N}.$$

Fuel preparation line works under normal conditions. The performance of equipment at FPP can be increased, if needed, by γ, %. Raw material and fuel warehouses have capacity reserve:

$$p_k^{\max}(t) = (1+\gamma)\, p_k(t), \quad k=\overline{1,N}.$$

The lack of capacity in case of emergency can be mitigated by increasing the capacity of working equipment.

Speeds of wood raw material replenishing at RMAP depend upon the amount of deforestation approved by the forest plan.

The amount of fuel consumed by heat sources during the heating season is not constant. The dynamics of fuel consumption are defined depending on the seasonality function $s(t)$:

$$q_{\mathrm{F}j}^{-H}(t) = q_{\mathrm{Fo}j}^{-H}\, s(t), \quad j=\overline{1,L};$$

where $q_{\mathrm{Fo}j}^{-H}$ is specific fuel consumption at j^{th} heat source with uniform consumption during the heating season, t. of n. f./day.

Seasonality function is based on the results of temperature measurements during the heating season according to the formula:

$$s(t) = s_0 \frac{\theta_{\mathrm{in}} - \theta_{\mathrm{out}}(t)}{\theta_{\mathrm{in}} - \theta_{\mathrm{c}}};$$

where θ_{in} is an indoor air temperature of heated buildings, $°C$; θ_{c} is a calculated temperature of outdoor air (the average temperature of five coldest consecutive days), $°C$; $\theta_{\mathrm{out}}(t)$ is a outdoor air temperature at the time t, °C; s_0 is a that can be found from the following equation:

$$s_0 \int_{t_{\text{Тн}}^{-}}^{t_{\text{Тк}}^{-}} \frac{\theta_{\text{in}} - \theta_{\text{out}}(\tau)}{\theta_{\text{in}} - \theta_{\text{c}}} d\tau = \frac{Q_j^{-H}}{q_{\text{Fo}j}^{-H}},$$

where $Q_j^{-\text{H}}$ is the volume of fuel consumed at j^{th} heat source during the heating season (t. of n. f).

The system of equations describing stock change on different levels of fuel supply logistic system is as follows:

$$\frac{d\tilde{Q}_{\text{RM}i}^{\text{RMAP}}}{dt} = q_{\text{RM}i}^{+RMAP}(t) - q_{\text{RM}i}^{-RMAP}(t), \quad i = \overline{1, M}, \tag{1}$$

$$\sum_{j=1}^{N} \frac{d\tilde{Q}_{\text{RM}j}^{\text{FPP}}}{dt} = \sum_{i=1}^{M} q_{\text{RM}i}^{-RMAP}(t) - \sum_{j=1}^{N} q_{\text{RM}j}^{-FPP}, \tag{2}$$

$$\sum_{j=1}^{N} \frac{d\tilde{Q}_{\text{F}j}^{\text{FPP}}}{dt} = \sum_{j=1}^{N} q_{\text{F}j}^{+FPP} - \sum_{k=1}^{L} q_{\text{F}k}^{+FPP}(t), \tag{3}$$

$$\frac{d\tilde{Q}_{\text{F}j}^{\text{H}}}{dt} = q_{\text{F}j}^{+FPP}(t) - q_{\text{F}j}^{-FPP}(t), \quad j = \overline{1, L}. \tag{4}$$

Suppose that in the end of each period all fuel resources at FPP warehouses and heat sources as well as wood raw material supplies at RMAP are consumed without remainder. This implies following balance equations:

$$\int_{t_{\text{RMst}}^{+}}^{t_{\text{RMend}}^{+}} q_{\text{RM}i}^{+RMAP}(t)\, dt = \int_{t_{\text{RMst}}^{-}}^{t_{\text{RMend}}^{-}} q_{\text{RM}i}^{-RMAP}(t)\, dt, \quad i = \overline{1, M}, \tag{5}$$

$$\sum_{i=1}^{M} \int_{t_{\text{RMst}}^{-}}^{t_{\text{RMend}}^{-}} q_{\text{RM}i}^{-RMAP}(t)\, dt = \sum_{k=1}^{L} \int_{t_{\text{Fst}}^{+}}^{t_{\text{Fend}}^{+}} q_{\text{F}k}^{+H}(t)\, dt, \tag{6}$$

$$\int_{t_{\text{Fst}}^{+}}^{t_{\text{Fend}}^{+}} q_{\text{F}k}^{+H}(t)\, dt = \int_{t_{\text{Fst}}^{-}}^{t_{\text{Fend}}^{-}} q_{\text{F}k}^{-H}(t)\, dt, \quad k = \overline{1, L}, \tag{7}$$

where Δt_{RM}^{+}, Δt_{RM}^{-}, Δt_{F}^{+}, Δt_{F}^{-} are periods of wood raw material and fuel replenishing and consuming respectively, hence:

$$t_{RMst}^{+} + \Delta t_{RM}^{+} = t_{RMend}^{+}, \tag{8}$$

$$t_{RMst}^{-} + \Delta t_{RM}^{-} = t_{RMend}^{-}, \tag{9}$$

$$t_{Fst}^{+} + \Delta t_{F}^{+} = t_{Fend}^{+}, \tag{10}$$

$$t_{Fst}^{-} + \Delta t_{F}^{-} = t_{Fend}^{-}. \tag{11}$$

Let us introduce the restrictions on the amount of stock at warehouses taking into account raw material humidity:

$$0 \le \int_{t_{\text{RMst}}^{+}}^{t} \beta_1 q_{\text{RM}i}^{+RMAP}(\tau)\, d\tau - \int_{t_{\text{RMend}}^{-}}^{t} \beta_2 q_{\text{RM}i}^{-RMAP}(\tau)\, d\tau \le V_{\text{RM}i}^{\text{RMAP}}, \quad i = \overline{1, M}, \tag{12}$$

$$0 \le \sum_{i=1}^{M} \int_{t_{\text{RMst}}^{-}}^{t} q_{\text{RM}i}^{-RMAP}(\tau)\, d\tau - \int_{t_{\text{RMst}}^{-}}^{t} q_{\text{RM}}^{-FPP}(\tau)\, d\tau \le \frac{V_{\text{RM}}^{\text{FPP}}}{\beta_2}, \tag{13}$$

$$0 \le \int_{t^-_{\text{RMst}}}^{t} q_{\text{F}}^{+FPP}(\tau)\,d\tau - \sum_{j=1}^{L}\int_{t^+_{\text{Fst}}}^{t} q_{\text{F}j}^{+H}(\tau)\,d\tau \le \frac{V_{\text{F}}^{\text{FFP}}}{\beta_2}, \qquad (14)$$

$$Q_{\text{H}j}^{\text{F}r} \le \int_{t^+_{\text{Fst}}}^{t} q_{\text{F}j}^{+H}(\tau)\,d\tau - \int_{t^-_{\text{Fst}}}^{t} q_{\text{F}j}^{-H}(\tau)\,d\tau \le \frac{V_{\text{H}j}^{\text{F}}}{\beta_2}, \quad j = \overline{1, L}, \qquad (15)$$

where β_1, β_2 are ratios that define the number of bulk cubic meters of wood raw material per ton of standard fuel, bulk cub. m./t. of n. f.; $V_{\text{RM}i}^{\text{RMAP}}$ is the volume of wood raw material warehouse in i th RMAP, bulk cub. m.; $V_{\text{RM}}^{\text{FPP}}, V_{\text{F}}^{\text{FPP}}$ are volumes of wood raw material and fuel warehouses at FPP, bulk cub. m; $Q_{\text{H}j}^{\text{F}r}$ is the size of reserve fuel supply in j th heat source, t. of n. f.; $V_{\text{H}j}^{\text{F}}$ is the volume of fuel warehouse in j th heat source, bulk cub. m.

Thus, equations (1)–(15) describe fuel supply logistic system.

Operational risks in regional fuel supply system may depend primarily on the malfunctioning of logistic system components. So three types of risks can be distinguished: emergencies occurred due to RMAP breakdown; emergencies occurred due to FPP breakdown; emergencies occurred due to heat sources breakdown.

This paper does not take into account the problem of optimal management of fuel supply system in case of emergency related to heat sources breakdown because heat sources are consumers of the fuel supply system's end product. The problem of increasing the level of energy security must be dealt with prevention measures aimed at reducing the likelihood of risk occurrence.

2.1. Optimal management in case of emergency related to RMAP breakdown

Let us assume at the time t_{br} m RMAPs broke down and these accumulation points supplied raw materials to n FPPs.

To be specific, suppose that broken RMAPs have indexes $1, 2, 3, \ldots, m,$ and corresponding FPP indexes are $1, 2, 3, \ldots, n.$

Optimal management boils down to the supply redistribution of raw materials from $M - m$ RMAPs left to all FPPs, so that total expenditures in the system over the period of RMAP recovery t_{rec} are minimum.

During the period t_{rec} the volume of raw materials that must be delivered from m broken RMAPs to corresponding FPPs can be calculated as follows:

$$Q_{\text{RM}}^{\text{rec}} = \sum_{k=1}^{m} \int_{t_{\text{bt}}}^{t_{\text{br}}+t_{\text{rec}}} q_{\text{RM}k}^{-RMAP}\,dt.$$

As long as all wood raw materials at RMAP are consumed without remainder after each period, then, when broken RMAPs are recovered, raw materials need to be distributed in the volume of $Q_{\text{RM}}^{\text{rec}}$ from their warehouses between FPP that received less resources than expected because of emergencies. Moreover, raw materials are successfully transported from one of $M - m$ working RMAPs to one of n FPPs which needs raw materials only if raw materials volume in this RMAP warehouse exceeds the amount needed during the period t_{rec}. Thus, the amount of raw materials which can be transported from i th working RMAP to FPP in need of raw materials can be calculated as follows:

$$Q_i^h = \tilde{Q}_{\text{RM}i}^{\text{RMAP}} + \int_{t_{\text{br}}}^{t_{\text{br}}+t_{\text{rec}}} q_{\text{RM}i}^{+RMAP}\,dt - \int_{t_{br}}^{t_{\text{br}}+t_{\text{rec}}} q_{\text{RM}i}^{-RMAP}\,dt, \quad i = \overline{m+1, M}.$$

The essence of optimal management of fuel supply in case of emergency related to RMAP breakdown is to minimize total expenditures during the recovery period of RMAP:

$$F(q_{\mathrm{RM}_{(m+1)}}^{-RMAP}, q_{\mathrm{RM}_{(m+2)}}^{-RMAP}, \ldots, q_{\mathrm{RM}_M}^{-RMAP}) \to \min, \tag{16}$$

where $q_{\mathrm{RM}i}^{-RMAP}(t)$ are control functions.

Additional expenses on fuel supply related to RMAP breakdown consist of two parts:

$$F = F^I + F^{II}.$$

1. The costs of raw material transportation from working RMAPs to FPPs in need of the materials:

$$F^I = \sum_{i=m+1}^{M} \sum_{j=1}^{n} s_{ij}^{RM} Q_i^h,$$

where s_{ij}^{RM} are specific transportation costs on wood raw material delivery from i^{th} RMAP to j^{th} FPP, rub./ t. of n. f.

2. The costs of raw material transportation from recovered RMAPs to FPP received less raw materials than expected:

$$F^{II} = \sum_{i=1}^{m} \sum_{j=n+1}^{N} s_{ij}^{RM} Q_i^h,$$

$$\sum_{i=m+1}^{M} Q_i^h = \sum_{i=1}^{m} Q_i^h.$$

2.2. Optimal management in case of emergency related to FPP breakdown

Let us assume that at the time t_{br} fuel preparation stopped at n FPPs. These production points were provided with raw materials from m RMAPs and supplied fuel to l heat sources.

To be specific, suppose that broken FPPs have indexes $1, 2, 3, \ldots, n,$ corresponding RMAPs have indexes $1, 2, 3, \ldots, n,$ and heat sources have indexes $1, 2, 3, \ldots, l.$

The objective of optimal management is to redistribute the supply of raw materials from m RMAPs to $N - n$ working FPPs, and redistribute fuel supply to l heat sources, so that total expenditures in the system during the period of FPP recovery t_{rec} are minimum.

At the time t_{br} the volume of fuel located at FPP is equal to:

$$\sum_{j=1}^{n} \tilde{Q}_{\mathrm{F}j}^{\mathrm{FPP}} = \begin{cases} \left(t_{\mathrm{br}} - t_{\mathrm{RMst}}^{-}\right) \sum\limits_{j=1}^{n} p_j, & \text{if } t_{\mathrm{br}} \le t_{\mathrm{Fst}}^{+}, \\ \left(t_{\mathrm{br}} - t_{\mathrm{RMst}}^{-}\right) \sum\limits_{j=1}^{n} p_j - \left(t_{\mathrm{br}} - t_{\mathrm{RMst}}^{+}\right) \sum\limits_{j=1}^{n} q_{\mathrm{F}j}^{-H}(t), & \text{if } t_{\mathrm{br}} > t_{\mathrm{Fst}}^{+}, \end{cases}$$

and the volume of fuel at corresponding heat sources is defined as follows:

$$\sum_{k=1}^{l} \tilde{Q}_{\mathrm{F}k}^{\mathrm{H}} = \begin{cases} 0, & \text{if } t_{\mathrm{br}} \le t_{\mathrm{Fst}}^{+}, \\ \left(t_{\mathrm{br}} - t_{\mathrm{Fst}}^{+}\right) \sum\limits_{k=1}^{l} p_k, & \text{if } t_{\mathrm{br}} \le t_{\mathrm{Fst}}^{-}, \\ \left(t_{\mathrm{br}} - t_{\mathrm{Fst}}^{+}\right) \sum\limits_{k=1}^{l} p_k - \left(t_{\mathrm{br}} - t_{\mathrm{Fst}}^{-}\right) \sum\limits_{k=1}^{l} q_{\mathrm{F}k}^{-H}(t), & \text{if } t_{\mathrm{br}} > t_{\mathrm{Fst}}^{-}. \end{cases}$$

Then the volume of fuel needed to power heat sources during FPP recovery time t_{rec} is equal to:

$$\sum_{k=1}^{l} Q_{\text{F}k}^{\text{rec}} = t_{\text{rec}} \sum_{k=1}^{l} p_k - \sum_{k=1}^{l} \tilde{Q}_{\text{F}k}^{\text{H}}.$$

The essence of optimal management of fuel supply in case of emergency related to FPP breakdown is to minimize total expenditures during FPP recovery period:

$$F(q_{\text{RM}1}^{-RMAP}, q_{\text{RM}2}^{-RMAP}, \ldots, q_{\text{RM}m}^{-RMAP}, q_{\text{F}1}^{+H}, q_{\text{F}2}^{+H}, \ldots, q_{\text{F}l}^{+H}) \to \min, \qquad (17)$$

where $q_{\text{RM}i}^{-RMAP}(t)$, $q_{\text{H}k}^{+F}(t)$ are control functions.

Total expenditures (17) consist of four parts: stock costs, organizational costs related to stock registration, its loading, discharging etc., storage costs and costs of shipping FPP raw materials and fuel to a certain heat source:

$$F = F^{\text{I}} + F^{\text{II}} + F^{\text{III}} + F^{\text{IV}}.$$

1. Stock costs:

$$F^{\text{I}} = \sum_{k=1}^{l} c_{\text{F}k} \int_{t_{\text{br}}}^{t_{\text{br}}+t_{\text{rec}}} q_{\text{F}k}^{+H}(t)\, dt,$$

where $c_{\text{F}k}$ is the cost of fuel deliver from FPP to k th heat source, rub./ t. of n. f.

2. Organizational costs:

$$F^{\text{II}} = \sum_{i=1}^{m} z_{\text{RM}i} n_{\text{RM}i} + \sum_{k=1}^{l} z_{\text{F}k} n_{\text{F}k},$$

where $z_{\text{RM}i}$ is organizational costs of one raw material shipment from i th RMAP, rub./shipment; $z_{\text{F}k}$ is organizational costs of one fuel shipment to k th heat source, rub./shipment; $n_{\text{RM}i}, n_{\text{F}k}$ are numbers of wood raw material shipments from i th RMAP and fuel shipments to k th heat source during FPP recovery time.

Let us introduce the functions $\eta_{\text{RM}i}(t)$, $i = \overline{1, m}$, and $\eta_{\text{F}k}(t)$, $k = \overline{1, l}$, so that:

$$\eta_{\text{RM}i}(t) = \begin{cases} 1, \text{ if } q_{\text{RM}i}^{-RMAP}(t) > 0, \\ 0, \text{if } q_{\text{RM}i}^{-RMAP}(t) = 0, \end{cases} \quad i = \overline{1, m};$$

$$\eta_{\text{F}k}(t) = \begin{cases} 1, \text{ if } q_{\text{F}k}^{+H}(t) > 0, \\ 0, \text{if } q_{\text{F}k}^{+H}(t) = 0, \end{cases} \quad k = \overline{1, l}.$$

Then

$$n_{\text{RM}i} = \sum_{t_{\text{rec}}} \eta_{\text{RM}i}(t), \quad i = \overline{1, m};$$

$$n_{\text{F}k} = \sum_{t_{\text{rec}}} \eta_{\text{F}k}(t), \quad k = \overline{1, l}.$$

3. Bulk storage costs:

$$F^{\text{III}} = h_{\text{C}} \int_{t_{\text{отк}}}^{t_{\text{отк}}+t_{\text{рем}}} \tilde{Q}_{\text{C}}^{\text{ППТ}}(t)\, dt + h_{\text{T}} \int_{t_{\text{отк}}}^{t_{\text{отк}}+t_{\text{рем}}} \tilde{Q}_{\text{T}}^{\text{ППТ}}(t)\, dt + \sum_{k=1}^{l} h_{\text{T}k} \int_{t_{\text{отк}}}^{t_{\text{отк}}+t_{\text{рем}}} \tilde{Q}_{\text{T}k}^{\text{T}}(t)\, dt,$$

where $h_{\text{RM}}, h_{\text{F}}$ are unit costs of wood raw material and fuel storage at FPP, rub./(t. of n. f.·day); $h_{\text{F}k}$ is unit costs of fuel storage in k^{th} heat source, rub./(t. of n. f.·day). Unit costs include warehouse lease costs, amortization costs during the storage etc.

4. Costs of raw material and fuel shipping:

$$F^{\text{IV}} = \sum_{j=n+1}^{N}\left(\sum_{i=1}^{m} Q_{\text{RM}ij}^{\text{RMAP}} s_{ij}^{\text{RM}} + \sum_{k=1}^{l} Q_{\text{F}jk}^{\text{H}} s_{jk}^{\text{F}}\right) + \sum_{a=1}^{n}\sum_{b=1}^{l} Q_{\text{F}ab}^{\text{FPP}} s_{ab}^{\text{F}},$$

$$\sum_{i=1}^{m} Q_{ij}^{\text{RM}} \le \gamma p_j t_{\text{rec}},$$

$$\sum_{j=1}^{N} Q_{jk}^{\text{F}} = q_k^{-\text{H}} t_{\text{rec}}.$$

3. Algorithm for solving the problem of optimal management of fuel supply system

Often, when solving optimization problems, the use of exact methods is very difficult due to the large number of variables and constraints, and therefore various heuristic methods are used to solve them, in particular, genetic algorithms that allow to obtain close to optimal solutions in a reasonable time [Tenenev, Yakimovich, 2010].

To solve the problem of optimal management of regional fuel supply system in case of emergency related to breakdown of the logistic system's objects genetic optimization algorithms adjusted to the current problems are used [Ruszczyński, 2006; Bozkaya et al., 2006; Huang et al., 2011].

Let us take a look at the algorithm for solving the problem in case of RMAP breakdown.

The volumes of wood raw material shipping from RMAP to FPP are assumed to be constant and must meet the conditions of continuous fuel preparation process taking into account the performance of equipment $p_j^{\max}(t)$ (t. of n. f./day) in j^{th} FPP:

$$q_{\text{RM}ij}^{-RMAP}(t) = \begin{cases} x_{ij}, \text{ if } \tilde{Q}_{\text{RM}j}^{\text{FPP}}(t) \le Q_{\text{RM}j}^{*}, \\ 0, \text{ if } \tilde{Q}_{\text{RM}j}^{\text{FPP}}(t) > Q_{\text{RM}j}^{*}, \end{cases} \quad i = \overline{1,M}, \quad j = \overline{1,N},$$

where $q_{\text{RM}ij}^{-RMAP}$ is a speed of wood raw material shipping from i^{th} RMAP to j^{th} FPP, t. of n. f./day; $\tilde{Q}_{\text{RM}j}^{\text{FPP}}$ is the current volume of wood raw material in j^{th} FPP, tons of standard fuel; $Q_{\text{RM}j}^{*}$ is the volume of wood raw material replenishing in j^{th} FPP (tons of standard fuel) during the period of shipment $t_{\text{ship}}^{\text{FPP}}$ (days) which is defined by formula:

$$Q_{\text{RM}j}^{*} = p_j(t)\, t_{\text{ship}}^{\text{FPP}}, \quad j = \overline{1,N}.$$

Let $X = \left(x_{11}, x_{21}, \ldots x_{N1}, x_{12}, \ldots, x_{MN}\right)$ be the vector of volumes of wood raw material shipments from RMAP to FPP which are the parameters of the problem of optimal management of fuel supply in case of RMAP breakdown. Then the target function of the optimal management problem (16) introduced in the problem statement will be as follows:

$$F\left(X\right) \to \min. \tag{18}$$

The problem of fuel supply optimal management in case of RMAP breakdown boils down to the search of optimization parameters $X = \left(x_{11}, x_{21}, \ldots x_{N1}, x_{12}, \ldots, x_{MN}\right)$ that meet the conditions (12)–

(15), (18). The process of problem solving consists of two stages. At the first stage the parameter values $x_{(m+1)1}, x_{(m+2)1}, \ldots, x_{MN}$ defining raw material shipment from working RMAPs to all FPPs are determined. At the second stage the parameters $x_{11}, x_{21}, \ldots, x_{mN}$ defining raw material shipment from recovered RMAPs to FPPs received less resources than expected due to emergency. The given problem belongs to the class of mathematical programming problems and its solution is based on using genetic optimization algorithms at every stage of its solving process. The operation of genetic algorithms at both stages is identical.

When using genetic algorithms optimization parameters are represented as encoded values (genes). The set of genes is organized into a chromosome. The set of chromosome forms a population. At the first stage a chromosome represents a set of $N\left(M-m\right)$ numbers that determine what RMAP raw materials are transported and to what FPP they are transported as well as their shipping volumes. First $M-m$ numbers describe the relationship between the first FPP and working RMAPs, next $M-m$ numbers relate to the second FPP etc. An example of the chromosome for the given problem is shown in Figure 2.

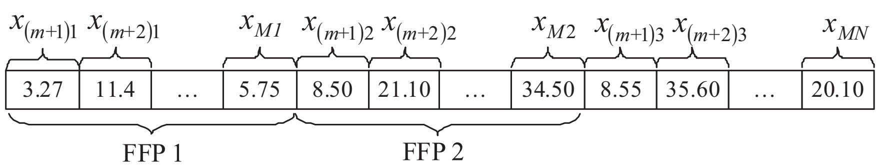

Fig. 2. An example of a vector of controlled variables in a genetic algorithm to solve an optimal control problem in case of RMAP breakdown

To assess the quality of solution described by each individual in the population each chromosome is assigned a value of a fitness function which describes how close a given problem's solution is to the optimal one. In our case the fitness function is the target function (18). The evolution of initial population, i.e. the improvement of the fitness function value, is caused by using genetic operators that change information in chromosomes.

As each chromosome contains not only information about the required parameter values, but also the information about the links between the system's elements, initial population of individuals can't be formed by filling chromosome genes with arbitrary structures because it may cause the appearance of infeasible individuals. When solving the problem of fuel supply optimal management in case of RMAP breakdown new population is generated as follows: a raw material accumulation point is randomly chosen and linked to the nearest fuel preparation point providing the former with the highest possible amount of raw materials, then next RMAP is chosen and the iteration repeats. RMAPs with no resources and FPPs received enough raw materials are excluded from consideration. The individual's generation process ends when the need for raw materials at all FPPs is met. After that the fitness function value is calculated for each chromosome.

Then, as every individual is assigned the fitness function value (18), selection operator is applied to the population. Selection operator selects chromosomes based on their fitness function values so that they can participate in the generation of new population. Tournament selection was chosen as a selection operator with tournament size m_s.

After the generation of parent population genetic crossover and mutation operators are applied to it.

Crossover operator leads to the generation of child individuals based on the gene values of parent individuals. As a parametric structural optimization problem is being solved, links and relations between the value of genes in the chromosome must be taken into consideration. Therefore, using of standard crossover and operators is unacceptable for this problem solving because in this case the problems related to the generation of infeasible chromosomes emerge.

Let us take a look at the method of how crossover operator adjusted to the given problem works. Crossover operator should be applied if the sums of values of chromosome genes that determine a state of some FPP are equal. Suppose we have two individuals $X^1 = \left(x^1_{(m+1)1}, x^1_{(m+2)2}, \ldots, x^1_{MN}\right)$ and $X^2 = \left(x^2_{(m+1)1}, x^2_{(m+2)2}, \ldots, x^2_{MN}\right)$, and suppose this condition holds true:

$$\sum_{i=m+1}^{M} x^1_{ij} = \sum_{i=m+1}^{M} x^2_{ij}, \quad j = \overline{1,N}. \tag{19}$$

In this case these chromosomes exchange a set of genes that meet the condition (19). As a result, following chromosomes are obtained:

$$X^1 = \left(x^1_{(m+1)1}, \ldots, x^1_{M1}, \ldots, x^2_{(m+1)i}, \ldots, x^2_{Mi}, \ldots, x^1_{MN}\right),$$
$$X^2 = \left(x^2_{(m+1)1}, \ldots, x^2_{M1}, \ldots, x^1_{(m+1)i}, \ldots, x^1_{Mi}, \ldots, x^2_{MN}\right).$$

After we get new chromosomes the feasibility of obtained solutions must be verified. If there is an unfeasible chromosome, its gene values that don’t meet the condition (19) are redistributed. The gene values redistribution method is identical to the chromosome generation method. Then best individuals are chosen among parent and child ones to join the population.

Mutation operator is designed to produce arbitrary changes in information in a chromosome. In this case mutation operator can be applied with a certain probability to a set of numbers defining the state of some FPP. The operator redistributes gene values while keeping the same amount of their sum and satisfying the constrains.

Aforementioned crossover and mutation operators are of probabilistic nature. When genetic operators are used in practice a certain fixed number p_f is set. Then a random number p from the interval $[0;1]$ is generated. If $p \le p_f$, then the operator is executed. In case of crossover operator $p_f \in [0.5;1]$, in case of mutation operator $p_f \in [0;0.1]$.

After the parameter values $x_{(m+1)1}, x_{(m+2)1}, \ldots, x_{MN}$ are defined, the volumes of raw materials consumed by working RMAPs are calculated as well as what FPP will not receive enough raw materials and in what quantities. After that the second stage begins and its result is the parameter values $x_{11}, x_{21}, \ldots, x_{mN}$.

After all the parameters in question are determined, total expenditures in the fuel supply system for RMAP recovery period are calculated.

Thus, a general algorithm for solving the problem of optimal management of fuel supply system in case of emergency related to RMAP breakdown can be described as a flow chart in the Figure 3.

Let us take a look at the algorithm for the same problem solving in case of FPP breakdown.

The volumes of wood raw material shipping from RMAP to FPP are assumed to be constant and must meet the conditions of continuous fuel preparation process taking into account the highest performance of equipment $p_j^{\max}(t)$ (t. of n. f./day) in j^{th} FPP:

$$q^{-RMAP}_{\mathrm{RM}ij}(t) = \begin{cases} x_{ij}, & \text{if } \tilde{Q}^{\mathrm{FPP}}_{\mathrm{RM}j}(t) \le Q^*_{\mathrm{RM}j}, \\ 0, & \text{if } \tilde{Q}^{\mathrm{FPP}}_{\mathrm{RM}j}(t) > Q^*_{\mathrm{RM}j}, \end{cases} \quad i = \overline{1,M}, \quad j = \overline{1,N},$$

where $q^{-RMAP}_{\mathrm{RM}ij}$ is a speed of wood raw material shipping from i^{th} RMAP to j^{th} FPP, t. of n. f./day; $\tilde{Q}^{\mathrm{FPP}}_{\mathrm{RM}j}$ is a current volume of wood raw materials in j^{th} FPP, tons of standard fuel; $Q^*_{\mathrm{RM}j}$ is a volume of wood raw material processing in j^{th} FPP (tons of standard fuel) during the shipment period $t^{\mathrm{FPP}}_{\mathrm{ship}}$

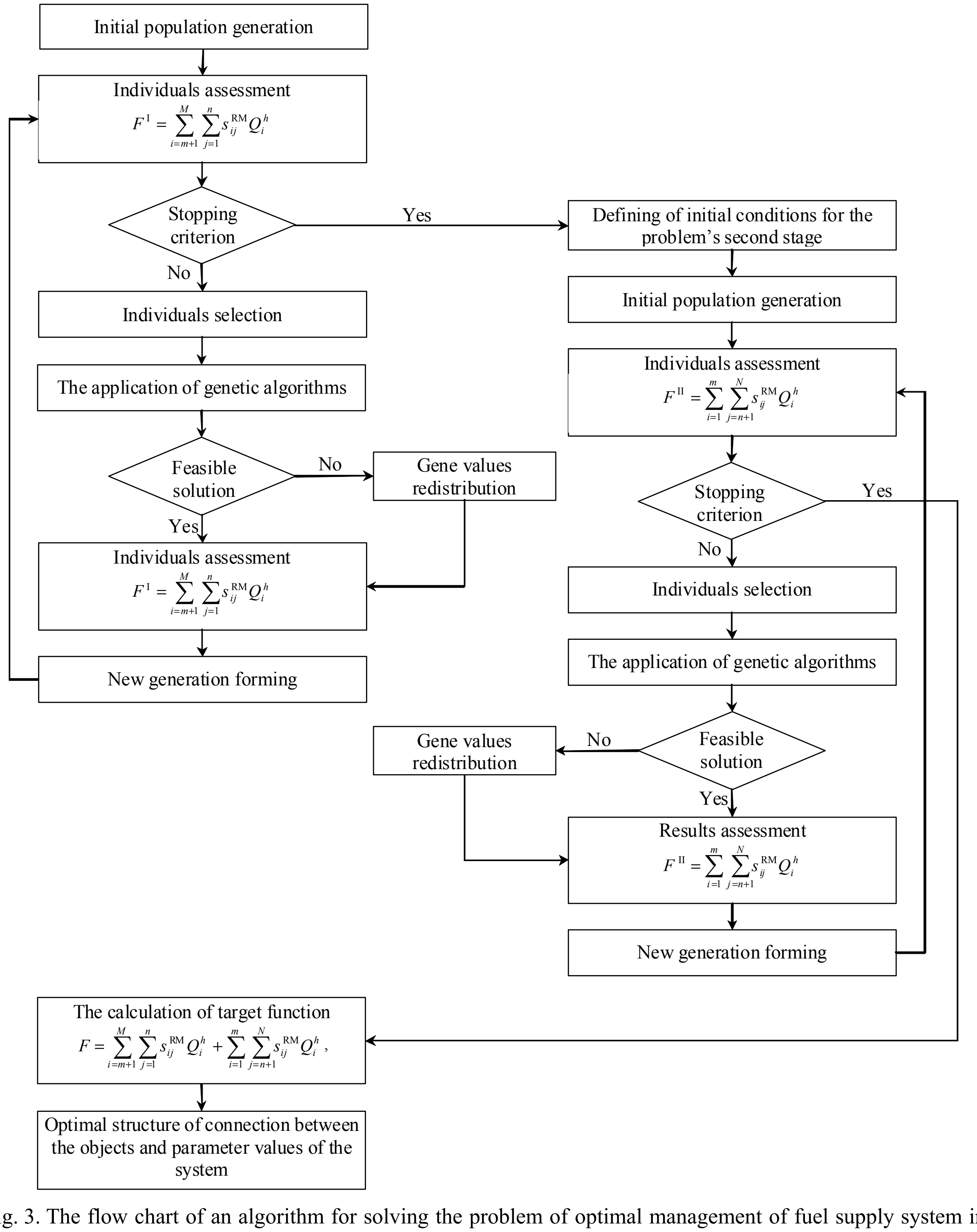

Fig. 3. The flow chart of an algorithm for solving the problem of optimal management of fuel supply system in case of emergency related to RMAP breakdown

(days) defined by the formula:

$$Q_{\mathrm{RM}j}^{*} = p_j^{\max}(t)\, t_{\mathrm{ship}}^{\mathrm{FPP}}, \quad j = \overline{1, N}.$$

The volumes of the fuel batch delivered to heat sources during the heating season are constant and determined based on reserve fuel supplies $Q_{\mathrm{F}}^{\mathrm{H}r}$ (tons of standard fuel) in warehouses at heat sources:

$$q_{\mathrm{F}jk}^{+H}(t)=\begin{cases} x_{jk}^{(2)}, & \text{if } \tilde{Q}_{\mathrm{H}k}^{\mathrm{F}}(t)\le Q_{\mathrm{H}k}^{\mathrm{F}r}, \\ 0, & \text{if } \tilde{Q}_{\mathrm{H}k}^{\mathrm{F}}(t)> Q_{\mathrm{H}k}^{\mathrm{F}r}, \end{cases} \qquad j=\overline{1,N}, \quad k=\overline{1,L},$$

where $q_{\mathrm{F}jk}^{+\mathrm{H}}$ is a speed of fuel shipping from j^{th} FPP to k^{th} heat source (t. of n. f./day); $\tilde{Q}_{\mathrm{H}k}^{\mathrm{F}}$ is a current volume of fuel in k^{th} heat source (t. of n. f.).

Let $X_1=\left(x_{1(n+1)}^{(1)}, x_{2(n+1)}^{(1)},\ldots, x_{m(n+1)}^{(1)}, x_{1(n+2)}^{(1)},\ldots, x_{mN}^{(1)}\right)$ and $X_2=\left(x_{(n+1)1}^{(2)}, x_{(n+2)1}^{(2)},\ldots, x_{N1}^{(2)}, x_{(n+1)2}^{(2)},\ldots, x_{Nl}^{(2)}\right)$ be the vectors denoting the volumes of wood raw material shipping from unclaimed RMAPs to working FPPs and fuel shipping to heat sources in need of shipping. These vectors are the parameters in the problem of fuel supply optimal management in case of FPP breakdown. Hence, the target function of optimal management problem (17) introduced in the problem statement can be rewritten as follows:

$$F\left(X_1, X_2\right)\to \min. \tag{20}$$

The problem of fuel supply optimal management in case of FPP breakdown boils down to the search of optimization parameters $X_1=\left(x_{1(n+1)}^{(1)}, x_{2(n+1)}^{(1)},\ldots, x_{mN}^{(1)}\right)$ and $X_2=\left(x_{(n+1)1}^{(2)}, x_{(n+2)1}^{(2)},\ldots, x_{Nl}^{(2)}\right)$ that meet the conditions (12)–(15), (20).

The solving of this problem is also based on using genetic optimization algorithms. In this case a chromosome is represented as a set of $(N-n)(m+l)$ numbers that define the structure of fuel supply system in case of FPP breakdown and the volumes of raw material and fuel supply between the system's elements. Each $m+l$ numbers describe the state of one of $N-n$ working FPPs with the first m numbers from each set defining what RMAP a given fuel preparation point obtains resources from and in what quantities, and next l numbers define what heat sources are provided with fuel from the given FPP and in what quantities. An example of a chromosome for the problem in question is shown in Figure 4.

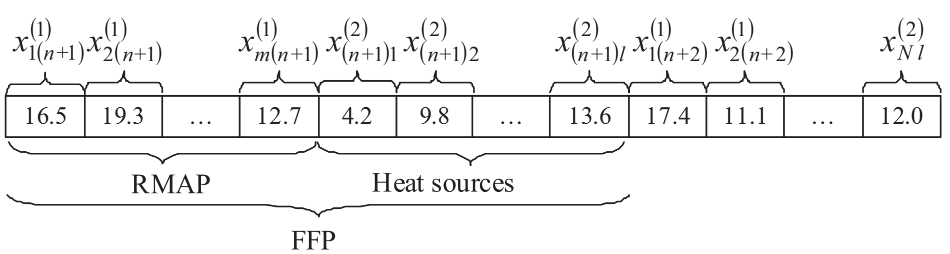

Fig. 4. An example of a vector of controlled variables in a genetic algorithm to solve an optimal control problem in case of FPP breakdown

To assess the quality of solution described by each individual in the population each chromosome is assigned a value of a fitness function. In our case the fitness function is the target function (20).

Initial population is generated given the structural features of fuel supply system. In order to avoid infeasible individuals being generated in the population the algorithm takes into account the restrictions related to FPP work equipment capacity.

When solving the problem of fuel supply optimal management in case of FPP breakdown new population is generated in two stages. At the first stage one of l heat sources is randomly chosen and linked to the nearest fuel preparation point. Given that, a maximum amount of fuel is written into the chromosome cell corresponding to the connection between these objects. While the chromosome being filled, heat sources with resources depleted and FFPs with no reserved capacity are excluded from consideration. The process runs until all needs of heat sources are met. After that, at the second stage, the chromosome cells corresponding to the volumes of raw material shipping from RMAPs to FPPs are filled. The process is analogous: one RAMP is randomly chosen and linked to the nearest fuel preparation point with the volume of raw materials delivered from RMAP to FPP being determined based on how loaded this FPP will be after the first stage of the chromosome formation. While the chromosome being filled FPPs with resources depleted and RMAPs with no raw materials are excluded from consideration. The process runs until all needs of FPPs are met.

After that the fitness function values is calculated for each chromosome. The selection operator is applied to population. When solving this problem tournament selection is applied as a selection operator. After parent population being generated crossover and mutation operators are applied to it.

Crossover operator is applied if the sums of values of chromosome genes that determine a state of some FPP are equal. Suppose we have two individuals $X^1 = \left(x_{1(n+1)}^{11}, x_{2(n+1)}^{11}, \ldots, x_{N\,l}^{12}\right)$ and $X^2 = \left(x_{1(n+1)}^{21}, x_{2(n+1)}^{21}, \ldots, x_{N\,l}^{22}\right)$, and suppose this condition holds true:

$$\sum_{i=1}^{m} x_{ij}^{11} + \sum_{k=1}^{l} x_{jk}^{12} = \sum_{i=1}^{m} x_{ij}^{21} + \sum_{k=1}^{l} x_{jk}^{22}, \quad j = \overline{(n+1), N}. \tag{21}$$

In this case these chromosomes exchange a set of genes that meet the condition (21). As a result, following chromosomes are obtained:

$$X^1 = \left(x_{1(n+1)}^{11}, x_{2(n+1)}^{11}, \ldots, x_{1j}^{21}, x_{2j}^{21}, \ldots, x_{mj}^{21}, x_{j1}^{22}, x_{j2}^{22}, \ldots, x_{jl}^{22}, \ldots, x_{N\,l}^{12}\right),$$
$$X^2 = \left(x_{1(n+1)}^{21}, x_{2(n+1)}^{21}, \ldots, x_{1j}^{11}, x_{2j}^{11}, \ldots, x_{mj}^{11}, x_{j1}^{12}, x_{j2}^{12}, \ldots, x_{jl}^{12}, \ldots, x_{N\,l}^{22}\right).$$

After we get new chromosomes the feasibility of obtained solutions must be verified. If there is an unfeasible chromosome, its gene values that don't meet the condition (21) are redistributed. The gene values redistribution method is identical to the chromosome generation method. Then the fitness function of obtained chromosomes is calculated and best individuals are chosen among parent and child ones to join the population.

Mutation operator, in this case, can be applied with a certain probability to a set of numbers defining the state of some FPP. The operator redistributes gene values while keeping the same amount of their sum and satisfying the constrains. The mutation method is identical to the chromosome generation method.

After all the parameters in question are determined, total expenditures in the fuel supply system for FPP recovery period are calculated.

Thus, a general algorithm for solving the problem of optimal management of fuel supply system in case of emergency related to FPP breakdown can be described as a flow chart in Figure 5.

3.1. Testing of the algorithm for solving the problem of optimal management of fuel supply system

In order to adjust optimization parameters and check the accuracy of developed algorithms their testing was conducted.

While testing the algorithm for solving the problem of optimal management of fuel supply in case of emergency the characteristics such as the performance of an algorithm and the accuracy of solution obtained were tested. The performance is defined as the time needed to obtain a solution T (seconds). The accuracy of obtained solution is defined based on the estimated deviation of the fitness function value ΔF from the reference value F_{opt}.

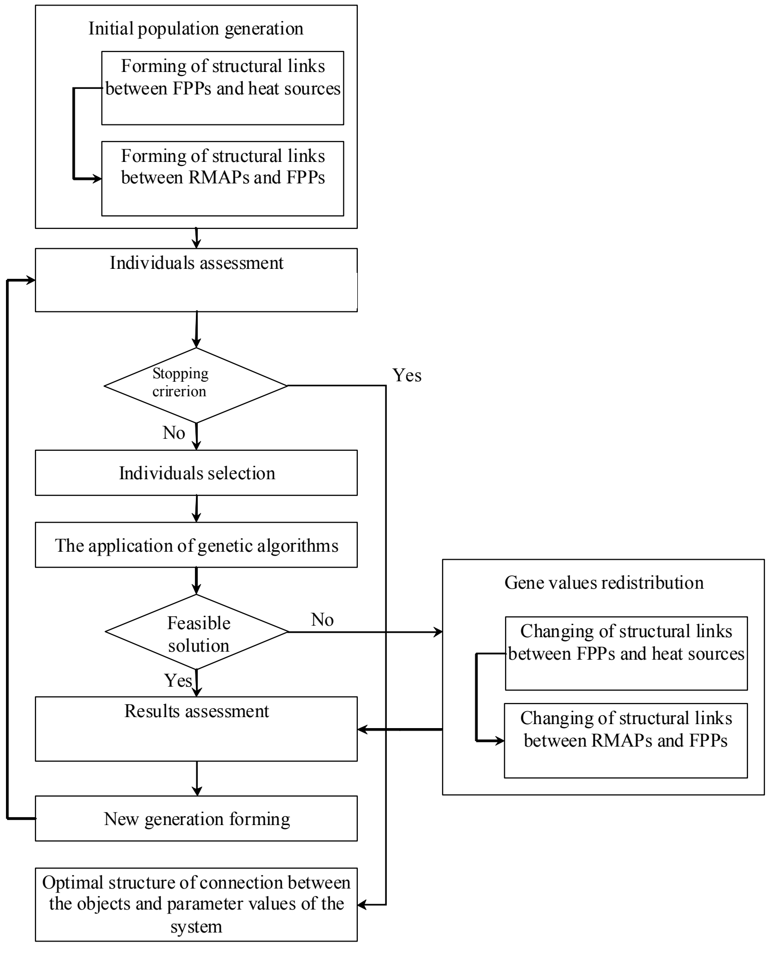

Fig. 5. The flow chart of an algorithm for solving the problem of optimal management of fuel supply system in case of emergency related to FPP breakdown

When developing the algorithm for solving the optimal management problem three parameters were distinguished: the number of individuals in the population N, the probability of crossing p_{c} and the probability of mutation p_{m}.

N is a prescribed number of individuals making up a population of genetic algorithm, $N \in [5; 100]$, the parameter values varied by $\Delta N = 5$.

The probability of crossing $p_{\text{c}} \in [0.5; 1]$, the parameter values varied by $\Delta p_{\text{c}} = 0.05$.

The probability of mutation $p_{\text{m}} \in [0.05; 0,5]$, the parameter values varied by $\Delta p_{\text{m}} = 0.05$.

The reference value of target function the results obtained with optimal management algorithm compared with was determined with a number of individuals in the population $N = 300$.

While testing the algorithms emergency modeling was conducted using the example of Igra region, the Udmurt Republic. This region is located in the center of the Udmurt republic, so that if emergency occurs, there are many ways to mitigate it by the neighboring regions. Seven RMAPs and two FPPs are planned to be established in this region to supply overall 37 regional heat sources with fuel.

While testing the algorithm of optimal management of fuel supply in case of emergency related to several FPPs breakdown a case of breakdown of all FPPs in Igra region was considered.

As mentioned earlier, the probability of finding a global extremum and the performance of the algorithm were evaluated. Optimal parameters for the operation of the algorithm are adjusted during the test.

Comparative analysis over each parameter within its range (other parameter values considered to be fixed) was conducted.

Figure 6 shows the results of the testing of fuel supply optimal management algorithm in case of emergency related to FPP breakdown with different parameter values N. The diagrams below show how the algorithm performance and accuracy of obtained solution depend on the parameter N.

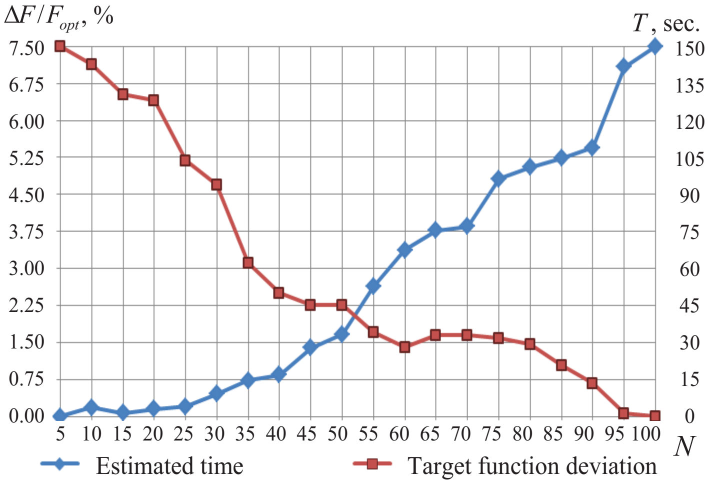

Fig. 6. Dependence of the algorithm performance T and accuracy of obtained solution $\Delta F / F_{opt}$ on the on the number of individuals in the population N

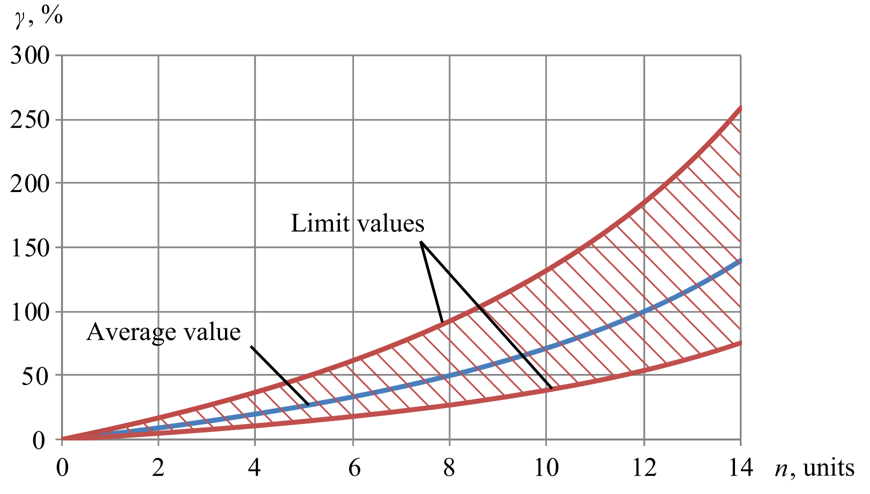

Fig. 7. Average and limit values of FPPs reserve capacity γ in case of different number of FPPs break-down n

As the diagrams in Figure 7 show, the more the number of individuals in the population the higher the accuracy of obtained solution and the lower the performance of an algorithm. So the number of individuals making up a population of genetic algorithm with the deviation of the target function value from the reference value not more than 3 % is 40.

The study was conducted for the remaining parameters of the genetic algorithm. Optimal probability of crossover operator application for genetic algorithm adjusted to the given problem is 0.8. Given that, the deviation of the target function value from the optimal value is 2 %. Optimal probability of mutation was chosen to be $p_{\mathrm{m}} = 0.3$, the deviation of the target function from the optimal value is not more than 2.5 %.

Furthermore, to assess the limits of applicability of developed optimal management models a research on the parameter γ which defines the reserve capacity of FPP equipment powering the fuel supply system in case of emergency was conducted.

As the lack of capacity in case of some FPPs breakdown is mitigated by increasing the capacity of working FPP, the following balance equation holds true:

$$n\overline{p} = (N-n)\,\overline{p}(1+\gamma),$$

where $\overline{p}$ is the average FPP performance, n is the number of broken FPPs, N is the overall number of FPPs. So the parameter γ can be assessed according to the following formula:

$$\gamma = \frac{n}{N-n}.$$

As the capacity of FPPs are different, the deviation of real FPP capacity from the average value must be taken into account as well as the cases of FPP breakdown with maximum or minimum capacity. The range of γ variation in case of different types of FPP breakdown is shown in Figure 7.

As the number of broken FPPs grows, the reserve capacity built in the system rises irregularly. In order to make up for the next FPP breakdown a value of γ needs to be higher.

The number of FPPs which breakdown can be made up for by the system with different values of γ is shown in Figure 8.

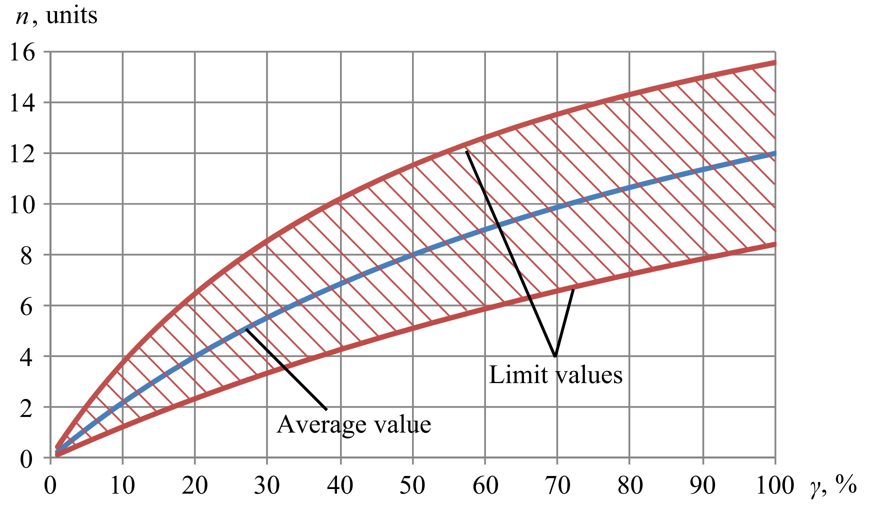

Fig. 8. Average and limit values of number FPPs n which breakdown can be fixed by the system with different value of FPPs reserve capacity γ

As rising value of γ results in an increase of FPP equipment price, recommended value of γ should be within the range $0 < \gamma < 20\,\%$. 20 % capacity reservation will allow to balance simultaneous breakdown of two to six FPPs.

3.2. Results of optimal management of regional fuel supply system in case of emergency

Considering the case of emergency in the regional fuel supply system information-analytical system redefines structural links between objects and calculates the parameters of changed system in accordance with mathematical models introduced in analytical subsystem of the program complex. The results of calculations are plotted on the electronic map of the Udmurt Republic as new routes of raw material and fuel movement. Quantitative characteristics of changed system are depicted in the information bar as well as in the control table of fuel supply system stock.

An example of visual representation of optimal management of regional fuel supply system in case of FPP breakdown is shown in Figures 9–12. Figures 9, 10 demonstrate the initial map of fuel supply in Vavozh region, the Udmurt Republic.

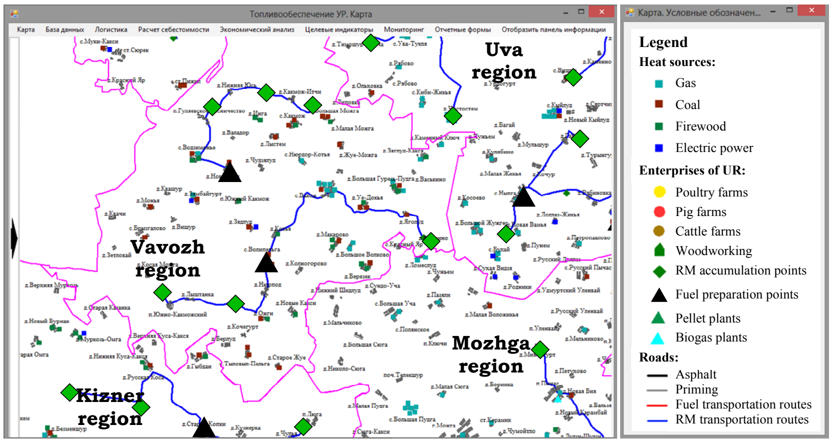

Fig. 9. Wood raw material transportation routes in Vavozh region, the Udmurt Republic

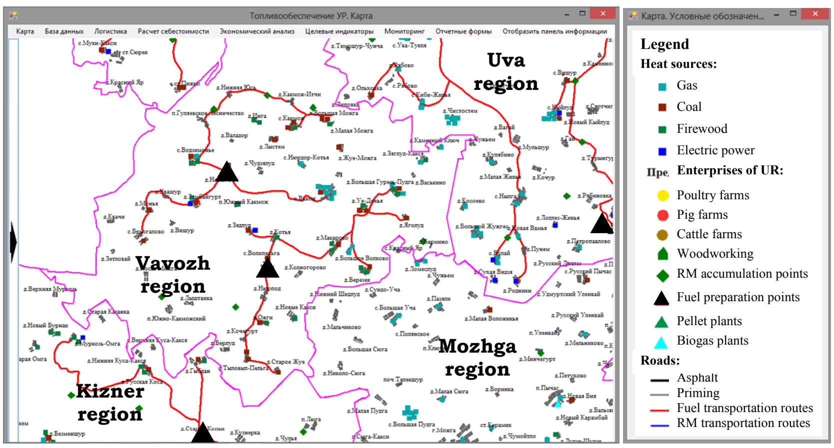

Fig. 10. Fuel transportation routes in Vavozh region, the Udmurt Republic

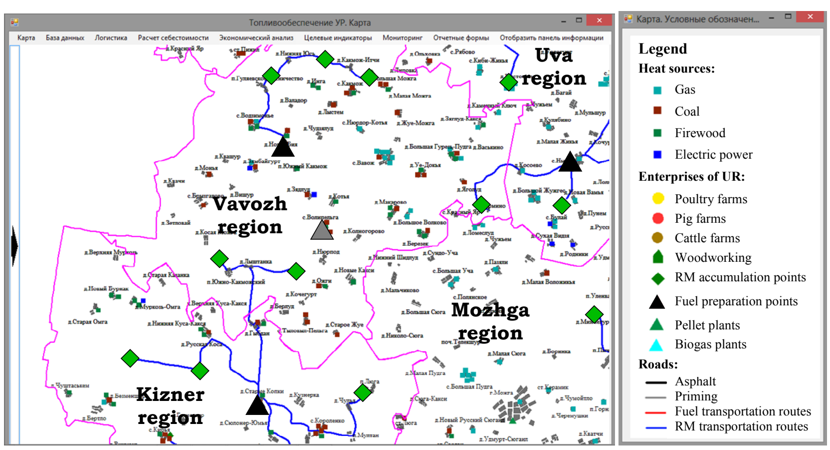

Fig. 11. Raw material transportation routes in Vavozh region, the Udmurt Republic, in case of FPP breakdown in Volipelga village

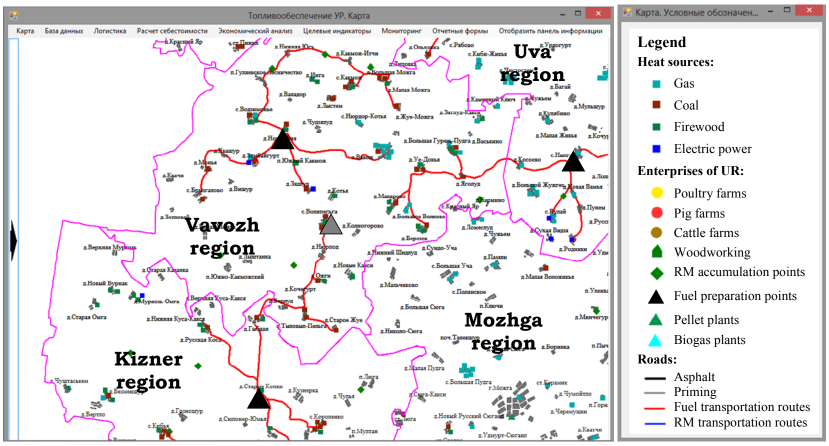

Fig. 12. Fuel transportation routes in Vavozh region, the Udmurt Republic, in case of FPP breakdown in Volipelga village

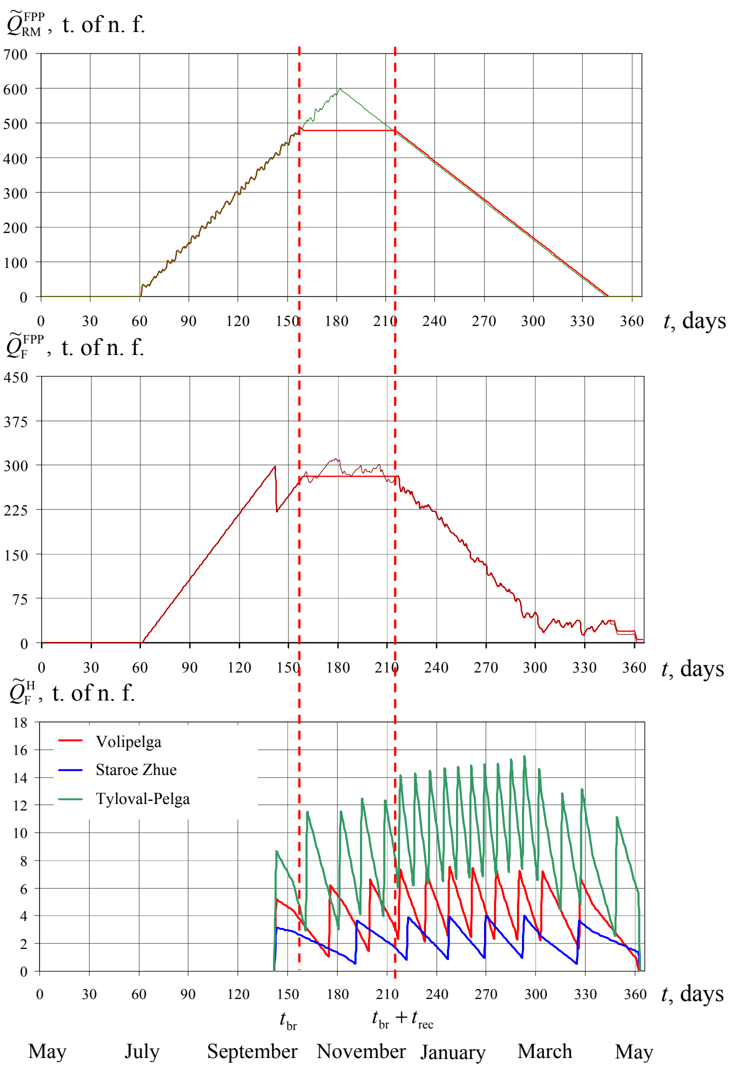

Fig. 13. Graphs of changes in stocks of wood raw materials $\tilde{Q}_{RM}^{FPP}$ and fuel $\tilde{Q}_{F}^{FPP}$ at FPP in Volipelga and changes in fuel reserves at heat sources $\tilde{Q}_{F}^{H}$ supplied with this FPP, during the year under normal conditions and in case of emergency at FPP in Volipelga

It's planned to establish two fuel preparation points in villages Volipelga and Novaya Biya in Vavozh region, the Udmurt Republic. These FPPs will be provided with raw materials from six accumulation points and they will supply fuel to about ten regional heat sources.

If a FPP in Volipelga village breaks down, raw material and fuel transportation routes in the system will rearrange. The result of the calculation of links between fuel supply system's objects in case of emergency is shown in Figures 11, 12.

Figure 13 shows the diagrams depicting the change of wood raw material and fuel volumes at FPP located in Volipelga village as well as at heat sources being powered by this FPP in case of fuel supply system operating under normal conditions. In case of FPP breakdown raw materials are redistributed to neighboring fuel preparation points which will supply fuel to heat sources for a FPP repairing period providing the compliance with fuel delivery schedule.

Figure 14 shows the diagrams depicting the change of wood raw materials and fuel at FPP located in Starye Kopki village in case of FPP breakdown in Volipelga village. Former FPP will supply fuel to a part of heat sources of broken FPP.

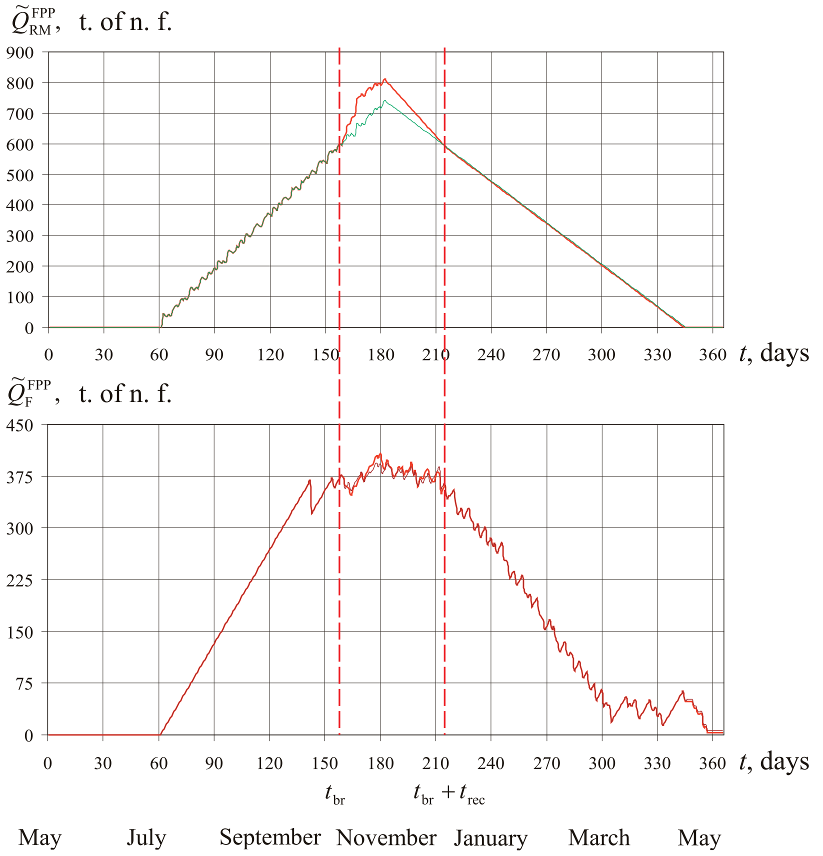

Fig. 14. Graphs of changes in stocks of wood raw materials $\tilde{Q}_{RM}^{FPP}$ and fuel $\tilde{Q}_{F}^{FPP}$ at FPP in Starye Kopki during the year under normal conditions and in case of emergency at FPP in Volipelga

4. Conclusion

The article presents a mathematical model of optimal management of logistic fuel supply system with wood fuel, which consists of three interconnected levels: raw material accumulation points, fuel preparation points and heat sources. This model is introduced in information-analytical system of regional alternative fuel supply management, which is implemented in the Ministry of Industry and Energy of the Udmurt Republic and is used for the operational management of region's fuel and energy complex. The information-analytical system implements a logistic fuel supply system of the Udmurt Republic, consisting of 94 raw material accumulation points and 24 fuel preparation points, as well as of 297 heat sources located in remote settlements of the republic and which are planned to be supplied with wood fuel.

For the operational management of logistic fuel supply system, mathematical models and algorithms for the optimal control have been developed in case of emergency related to RMAP breakdown and FPP breakdown. In mathematical models, the target criterion is minimization of costs associated with the functioning of logistic system in case of emergency. The proposed optimal control algorithms are based on the use of genetic algorithms adapted to solve problems. During the test of developed algorithms optimal values of its parameters were found so that needed proportion between the algorithm's performance and accuracy of obtained solution is reached. The use of genetic algorithms allows you to quickly respond to emergency situations, due to the high speed of the algorithm without losing accuracy in the calculations. The application of genetic algorithms enables to respond quickly to emergency situations due to high performance of the algorithm without accuracy losses.

The influence of the reserve capacity of FPP equipment on the conditions for the stable operation of the regional fuel supply system has been investigated. So, 20 % capacity reservation will allow to balance simultaneous breakdown of two to six FPPs. For various values of reserve capacity, computer simulation of emergency in the fuel supply system of the Udmurt Republic was carried out: optimal routes for wood raw material and fuel transportation between different levels of the logistic scheme were built, optimal volumes and time of wood raw material and fuel deliveries were calculated.

Thus, the proposed mathematical models and algorithms for optimal fuel management in case of emergency are a contribution to the mathematical tools of logistic control of multi-level organizational systems. The developed information and analytical system allows to solve interactively the problems of operational planning and control of fuel supply of a regional heat supply distributed management system.

References

Беляев Л. С., Подковальников С. В. Рынок в электроэнергетике. Проблемы развития генерирующих мощностей. — Новосибирск: Наука, 2004. — 220 с.

Belyaev L. S., Podkovalnikov S. V. Electricity Market. Problems in Expansion of Generation Capacities [Rynok v elektroenergetike: problemy razvitiya generiruyushchih moshchnostei]. — Novosibirsk: Nauka, 2004. — 220 p. (in Russian).

Воропай Н. И. Системные исследования проблем энергетики. — Новосибирск: Наука, 2000. — 558 с.

Voropai N. I. System Research in the Energy Sector [Sistemnye issledovaniya problem energetiki]. — Novosibirsk: Nauka, 2000. – 558 p. (in Russian).

Гранберг А. Г. Основы региональной экономики. — М.: ГУ ВШЭ, 2004. — 495 с.

Granberg A. G. Foundations of Regional Economy [Osnovy regionalnoi ekonomiki]. — Moscow: GU VShE, 2004. — 495 p. (in Russian).

Ишаев В. И. Экономическая реформа в регионе. Тенденции развития и регулирование. — Владивосток: Дальнаука, 1998. — 178 с.

Ishaev V. I. Economic Reform in the Region. Development Trends and Regulation [Ekonomicheskaya reforma v regione. Tendentsii razvitiya i regulirovaniye]. — Vladivostok: Dalnauka, 1998. — 178 p. (in Russian).

Кетова К. В., Трушкова Е. В. Решение логистической задачи топливоснабжения распределенной региональной системы теплоснабжения // Компьютерные исследования и моделирование. — 2012a. — Т. 4, № 2. — С. 451–470.

Ketova K. V., Trushkova E. V. The Solution of the Logistics Task of Fuel Supply for the Regional Distributed Heat Supply System [Resheniye logisticheskoi zadachi toplivosnabzheniya raspredelyonnoi regionalnoi sistemy teplosnabzheniya] // Computer Research and Modeling. — 2012. — Vol. 4, No. 2. — P. 451–470 (in Russian).

Кетова К. В., Трушкова Е. В. Построение алгоритма поиска оптимальных маршрутов в региональной системе топливоснабжения // Вестник ИжГТУ. — Ижевск: ИжГТУ, 2012b. — № 2. — С. 157–162.

Ketova K. V., Trushkova E. V. Postroenie algoritma poiska optimal'nyh marshrutov v regional'noj sisteme toplivosnabzheniya [Construction of the search algorithm of optimal routes in a regional system of fuel supply] // Vestnik IzhGTU, 2012. — No. 2. — P. 157–162 (in Russian).

Кетова К. В., Трушкова Е. В., Кривенков Р. Ю. Применение кластерного анализа для решения задачи оптимального распределения топливно-энергетических ресурсов // Интеллектуальные системы в производстве. — 2010. — № 2. — С. 207–213.

Ketova K. V., Trushkova E. V., Krivenkov R. Yu. Primenenie klasternogo analiza dlya resheniya zadachi optimal'nogo raspredeleniya toplivno-energeticheskikh resursov [Application of cluster analysis to solve the problem of energy resources optimal allocation] // Vestnik IzhGTU. — 2010. — No. 2. — P. 207–213 (in Russian).

Кулешов В. В., Розин К. Б., Радченко В. В. Перспективное отраслевое планирование: экономико-математические методы и модели. — Новосибирск: Наука, 1986. — 358 с.

Kuleshov V. V., Rozin K. B., Radchenko V. V. Perspective Industry Planning: Econonomic-mathematical Methods and Models [Perspectivnoye otraslevoye planirovaniye: ekonomiko-matematicheskiye metody i modeli]. — Novosibirsk: Nauka, 1986. — 358 p. (in Russian).

Макаров А. А., Мелентьев Л. А. Методы исследования и оптимизация энергетического хозяйства. — Новосибирск: Наука, 1973. — 276 с.

Makarov A. A., Melentyev L. A. Methods of Studying and Optimizing the Energy Sector [Metody issledovaniya i optimizacya energeticheskogo sektora]. — Novosibirsk: Nauka, 1973. — 276 p. (in Russian).

Русяк И. Г., Касаткина Е. В., Сайранов А. С. Информационно-аналитическая система управления топливоснабжением региона альтернативными видами топлива // Информационно-управляющие системы. — СПб.: ГУАП, 2013. — Т. 65, № 4. — С. 83–87.

Rusyak I. G., Kasatkina E. V., Sairanov A. S. An Information-Analytical System of Regional Alternative Energy Sources Fuel Supply Management [Informatsionno-analiticheskaya sistema upravleniya toplivosnabzheniyem regiona alternativnymi vidami topliva] // Informacionno-upravlyayushchie sistemy. — St. Petersburg: IUS, 2013. — Vol. 65, No. 4. — P. 83–87 (in Russian).

Русяк И. Г., Кетова К. В., Королев С. А., Трушкова Е. В. Разработка концепции топливообеспечения распределенной региональной системы теплоснабжения местными возобновляемыми видами топлива // Энергобезопасность и энергосбережение. — 2010. — № 5. — С. 14–20.

Rusyak I. G., Presnukhin V. K., Ketova K. V., Korolev S. A., Trushkova E. V. Development of the Concept of Fuel Supply Distributed Regional Heating System of Local Renewable Fuels [Razrabotka contseptsii toplivoobespecheniya raspredelyonnoi regionalnoi sistemy teplosnabzheniya mestnymi vozobnovlyaemymi vidami topliva] // Energobezopasnost i energosberezheniye. — 2010. — No. 5. — P. 14–20 (in Russian).

Русяк И. Г., Кетова К. В., Королев С. А., Трушкова Е. В. Логистика топливоснабжения региона возобновляемыми видами топлива, получаемыми из древесного сырья. — Ижевск: Изд-во ИжГТУ, 2011. — 184 с.

Rusyak I. G., Ketova K. V., Korolev S. A., Trushkova E. V. Logistics of Regional Renewable Fuel Supply from Wood Raw Materials [Logistika toplivoshabzheniya regiona vozobnovlyaemymi vidami topliva, polychaemymi iz drevesnogo syrya]. — Izhevsk: Izd-vo IzhGTU, 2011. — 184 p. (in Russian).

Русяк И. Г., Кетова К. В., Нефедов Д. Г. Математическая модель и метод решения задачи оптимального размещения производства древесных видов топлива // Известия Российской академии наук. Энергетика. — 2017. — № 2. — С. 177–187.

Rusyak I. G., Ketova K. V., Nefedov D. G. Matematicheskaya model' i metod resheniya zadachi optimal'nogo razmeshcheniya proizvodstva drevesnyh vidov topliva [Mathematical Model and Method for Solving Problem of Optimal Location of Wood Fuels Facility] // Proceedings of the Russian Academy of Sciences. Power Engineering. — 2017. — No. 2. — P. 177–187 (in Russian).

Тененев В. А., Якимович Б. А. Генетические алгоритмы в моделировании систем. — Ижевск: Изд-во ИжГТУ, 2010. — 306 с.

Tenenev V. A., Yakimovich B. A. Genetic algorithms in systems' modeling [Geneticheskie algoritmy v modelirovanii sistem]. — Izhevsk: Izd-vo IzhGTU, 2010. — 306 p. (in Russian).

Трушкова Е. В. Задача оптимального управления запасами в распределенной системе теплоснабжения региона // Вести высших учебных заведений Черноземья. — 2011. — № 3. — С. 44–50.

Trushkova E. V. Zadacha optimal'nogo upravleniya zapasami v raspredelennoi sisteme teplosnabzheniya regiona [Problem of optimal reserves management in a distributed system of heat supply of the region] // Vesti vysshikh uchebnykh zavedenii Chernozem'ya. — 2011. — No. 3. — P. 44–50 (in Russian).

Трушкова Е. В. Опыт применения генетического алгоритма для оптимизации системы топливоснабжения // Математическое моделирование. — 2013. — Т. 25, № 1. — С. 99–112.
Trushkova E. V. Opyt primeneniya geneticheskogo algoritma dlya optimizatsii sistemy toplivosnabzheniya [Attempt of genetic algorithm application for optimization of fuel supply system] // Mathematical Models. — 2013. — Vol. 25, No. 1. — P. 99–112 (in Russian).

Bozkaya B., Zhang J., Erkut E. An Efficient Genetic Algorithm for the p-median Problem. Facility Location: Application and Theory. — Berlin: Springer, 2006. — P. 179–205.

Bramel J., Simchi-Levi D. A location bases heuristic for general routing problems // Operations research. — 1995. — Vol. 43. — P. 649–660.

Daskin M. S. What You Should Know about Location Modeling. — Naval Research Logistics, Economics and Information Technology. — 2008. — No. 55. — P. 283–294.

Huang C. Y., Chiang B. Y., Chang S. Y., Tzeng G. H., Tseng C. C. Predicting of the Short Term Wind Speed by Using a Real Valued Genetic Algorithm Based Least Squared Support Vector Machine // Proceedings of the 3rd International Conference on Intelligent Decision Technologies (IDT′ 2011). — Springer-Verlag Berlin Heidelberg, 2011. — P. 567–575.

Li X., Zhao Z., Zhu X., Wyatt T. Covering Models and Optimization Techniques for Emergency Response Facility Location and Planning: a Review // Mathematical Methods of Operations Research. — Springer-Verlag, 2011. — Vol. 74. — P. 281–310.

Orlov V., Detina E., Kovalchuk O. Mathematical Modeling of Emergency Situations at Objects of Production and Gas Transportation // VI International Scientific Conference “Integration, Partnership and Innovation in Construction Science and Education” (IPICSE-2018). — EDP Sciences, 2018. — Vol. 251. — P. 04012.

Revelle C., Cohon J., Shobrys D. Simultaneous siting and routing in the disposal of hazardous wastes // Transportation Science. — 1991. — Vol. 25. — P. 138–145.

Ruszczyński A. Nonlinear Optimization. — Princeton, NJ: Princeton University Press, 2006. — 464 p.

Shen Z.-J., Coullard C., Daskin M. S. A joint location-inventory model // Transportation science. — 2003. — Vol. 37. — P. 40–55.

Tlili T., Abidi S., Krichen S. A. Mathematical Model for Efficient Emergency Transportation in a Disaster Situation // American Journal of Emergency Medicine. — Elsevier Inc., 2018. — P. 1585–1590.

Wu G., Wu B., Qin L., Chen X., Qian F., Fan Y. Multi-Agent System-Based Emergency Control Scheme for Power System // Computer Modelling and New Technologies. — 2013. — Vol. 17, No. 3. — P. 56–62.