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DEVISING A METHOD FOR THE FORMATION OF SUSTAINABLE CHAINS OF SUPPLY OF RAW MATERIALS FROM MERCANTILE EXCHANGE TO A TIMBER PROCESSING ENTERPRISE CONSIDERING UNCERTAINTIES AND RISKS

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The relevant problem of guaranteed supply of high-quality raw materials to a timber processing enterprise that does not have its own sources of raw materials is considered. A method for the formation of sustainable chains of supplying raw materials to a timber processing enterprise was proposed, taking into consideration uncertainties and risks associated with the purchase of raw materials on the mercantile exchange and the implementation of the circuit of delivery to a warehouse. A dynamic model, which is a problem of stochastic nonlinear programming, the objective function of which is the cost of purchasing raw materials, was developed. The model makes it possible to form a plan for purchasing raw materials on the timber section of the mercantile exchange on a given planning horizon, taking into consideration uncertainties when it comes to the number of daily offers, their volumes, and prices. The risk of cancellation of the concluded contract due to the loss of the quality of raw materials during delivery and non-fulfillment of delivery terms was also taken into consideration. To find a solution to the model, a two-stage circuit, in which the first stage involves a procurement plan that is close to optimal, was proposed. At the second stage, a plan that is closest to the basic one in terms of the volume of purchased raw materials and minimizing the total costs is chosen for each day of implementation of a random flow of applications. The numerical solution at the first stage is found using the heuristic algorithm that uses the branch and bound method and the genetic algorithm at certain steps. At the second stage, the multi-criteria problem of mathematical programming is solved numerically. An example of the formation by a timber processing enterprise in the Far East of a suboptimal procurement plan that ensures an increase in the efficiency and sustainability of economic activity in the long term is considered

Keywords: supply chains, timber industry, optimization of planning of raw material procurement, stochastic nonlinear programming

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1. Introduction

Under modern conditions, most enterprises of various industries cannot compete solely as separate facilities in a changing marketing environment. Supply Chain Management (SCM) is an integrated approach to modeling, forecasting, and planning the information flows and physical values between suppliers, distributors, providers, manufacturing enterprises, and end-users. Integrated supply chain management is recognized as one of the main opportunities for an industrial enterprise to create a competitive advantage. The main goal of the SCM is to obtain the economic effect of reducing costs and maximized meeting the demand for final products based on the optimization of the value-creating chain.

In the timber industry, for the effective and continuous operation of an enterprise, one of the basic tasks is to form sustainable supply chains of high-quality raw materials that ensure the non-stop technological process. However, many woodworking enterprises in the absence of their own raw material base acquire a significant part of raw materials in the domestic market of a country using the mechanism of mercantile exchanges. The procurement process at a mercantile exchange has great uncertainties associated with the stochastic flows of supply and demand both in terms of the number of lots and their parameters.

On the other hand, the logging sub-industry, which acts as a seller at the mercantile exchange, has much in common with the food industry in terms of the short shelf life of final products. In this regard, the contracts concluded based on trading on the mercantile exchange foresee the possibility of the buyer's refusal of raw materials if there is a loss of its quality in violation of the delivery terms stipulated in a contract. For a woodworking plant, this is another risk of a possible decrease in the amount of raw materials in a warehouse below the required daily consumption. This type of risk occurs quite often in the practice of delivery of forest lumber over a considerable distance.

The formation of the plans for purchasing raw materials that are optimal on the horizon of medium-term planning in terms of cost-effectiveness is a rather seriously developed problem. However, the stochastic processes of purchasing raw materials on the mercantile exchange and maintaining their quality when delivered over a considerable distance make most of them inapplicable in practice [1]. It is necessary to use the models of stochastic nonlinear programming and special methods for finding a solution. There are no universally accurate algorithms for finding the optimal solution to non-convex stochastic programming problems. Moreover, it is argued in papers [2–4] that such solutions do not exist, since the functioning of enterprises has a large number of probabilistic processes that are difficult to take into consideration. Therefore, it is acceptable to look for a suboptimal solution that differs from the optimal one by the fact that for most probabilistic outcomes such a solution is the best of all permissible ones.

Thus, the issue of developing economic and mathematical methods and models that make it possible to form an economically suboptimal supply chain of raw materials to a timber processing enterprise, taking into consideration the uncertainties and risks associated with the stochastic process, is relevant.

2. Literature review and problem statement

The problems of SCM class are in most cases complex ones from several points of view. Firstly, as the review articles [5–7] show, when resource suppliers, producers, and consumers of finished products interact, there are a large number of factors that need to be taken into consideration when finding solutions. A significant part of the parameters describing these processes has essential uncertainty. This requires the use of probabilistic approaches or fuzzy multiple logic when constructing models.

The COVID-19 pandemic, causing emergencies due to changing demand and shortage of supply, has a significant impact on the sustainability of supply chains (SCM). The study [8] indicates sharp jumps in demand in the manufacturing sector, including those associated with the actions of governments. It is noted that the pandemic has provided ample opportunities to bridge the gap between the results of conceptual research and the efforts in the industry. The key levers in mitigating the risks in a supply chain include the need to balance global supply sources with local ones and the increased use of information technologies to ensure the full and immediate availability of information. However, the paper does not consider the possibility of acquiring resources on the mercantile exchange. Paper [9] developed an SC management system, taking into consideration the high uncertainty of the situation between suppliers and manufacturers in terms of the supply of products and the size of supplies, which makes it possible to significantly neutralize the costly consequences of the pandemic. The optimal magnitude of the SC cost is found by solving a nonlinear mathematical model using the methodology of sequential quadratic programming with partially linear and partly exponential demand functions. However, this does not take into consideration such probabilistic situations as the deviation of the time of transportation of supplied components from the given one, which can significantly affect various outcomes in the course of production.

A popular trend around the world is multi-outsourcing driven by globalization. The OEM (original equipment manufacturer) enters contracts with the CM (contract manufacturer) which produce part of the products required in further production. However, in the face of uncertainty in profitability and demand, the agreement of decisions on the volumes and means of delivery of orders, including the SC formation, between the OEM and several CMs has not been sufficiently studied. There is a limited amount of research into multiple sources. Paper [10] studied the distribution of orders between several unreliable suppliers, but without taking into consideration the production optimization and channels coordination. Article [11] considers the issue of coordination of the assembly system with several unreliable suppliers and the distribution of profits between the levels of a supply chain. However, the article neither considers the game relationships when choosing the order volume size nor takes into account the uncertainty of demand. It should be noted that from the point of view of calculating effective performance, the assembly system is completely different from the outsourcing system.

In paper [12], the authors consider a decentralized outsourcing system consisting of one OEM with stochastic demand and several CMs with random prices. The OEM should consider the shortage when allocating orders, as the CM may choose production volumes other than order volumes so as to reduce the risk. This interaction is considered as a game situation, for which a generalized model of information distribution, including an arbitrary number of suppliers and randomness of profitability and demand, was developed. Optimal volumes of orders and production were found with the help of the Stackelberg game model. Using a centralized supply chain as a benchmark, it is demonstrated that OEMs can use revenue sharing in a surplus purchase contract to motivate the CM to increase their own production volumes to global optimums. However, at the same time, on a large planning horizon, such a model becomes computationally complex and, as a result, it is impossible to find a sustainable solution.

The study [13] constructed a model consisting of one supplier and one retailer and developed an appropriate mechanism of the SCC (supply chain coordination). The BWE (bullwhip effect) and stochastic demand are introduced into the model within DT (digital technologies), which are ignored in the existing literature on the supply chain coordination system but have real significance for the SC operation. The number of orders, the number of products, the profit of supply chain participants under the influence of DT are studied and the optimal DT application level is proposed. Cost-sharing agreements and revenue-sharing agreements are introduced to coordinate the supply chain. Analysis of the model shows that the Pareto improvements can be achieved in both SCC contracts. However, the problem of rapidly growing computational complexity at the growing number of constraints does not receive due attention.

Another important point that must be taken into consideration when forming sustainable supply chains of resources is the quality of supplied raw materials at the time of their receipt at the manufacturer's warehouse. Quality can significantly depend on the duration of transportation, season, and transportation conditions.

Study [14] considered a three-stage model: supplier-manufacturer-retailer. In each cycle, the task is to maximize the average profit of a manufacturer, taking into consideration the randomness of the volume of stock, delivery capabilities, and reliability of a supplier, both in terms of availability and defectiveness of the goods supplied. It is assumed that the demand and time interval between the sequential availability and unavailability of a supplier and a retailer follow some probabilistic distribution and a supplier may not be able to supply the exact magnitude for the time required by a manufacturer. Optimization variables are product quantity, re-order points and reliability factors. To find a solution, a genetic algorithm is used, which does not allow asserting the guaranteed optimality of the solution. Paper [15] proposes the general check plan to provide the required level of quality of critical components with several characteristics in a supply chain. The model contains stochastic arguments and minimizes the expected total costs associated with the acceptance of a defective component, incorrect classification of the component, and the cost of validation. The drawback of the model is its exponential complexity, which for the selected algorithm of solution search on a large sample of initial data will not make it possible to find a solution in the nearest time. Paper [16] proposed the investment model on quality improvement and explored the strategies for checking defective products in the model of one manufacturer with one supplier. In many ways, the choice of one supplier and one manufacturer as an object of research is due to the fact that the volume of calculations grows exponentially with the addition of participants. Four non-cooperative game models with varying degrees of information about the frequency of checking a player and assessment of the magnitude of investment in quality improvement were considered. To determine the policy of inventory of defectiveness of goods, the simulation model in paper [17] at each step uses the analytical expressions reflecting the economic characteristics of industries and types of supply chains. Defective products classified by an inspector and the products returned from the market stockpiled and sold at a reduced price at the end of each procurement cycle. When checking goods, errors of I and II kind are taken into consideration. The annual profit with verification errors was shown to remain concave in relation to the order size. Paper [18] proposes a simulation model of optimal inventory of goods of imperfect quality with inspection errors, planned delays, and sales returns. Numerical methods are used to find the suboptimal order size, the maximum number of items of a delayed order, and the suboptimal point of order. With an increase in the value of a company, it is profitable to reduce the size of the order and increase the maximum level of deficit. Moreover, if customers are willing to wait for the next delivery in the event of a shortage, it is advantageous to allow overdue orders, although this entails penalty costs. Study [19] examines a continuous quality monitoring model for the elements with exponential random service life. The process of demand formation is considered the Markovian process. The theorem of preserving the convergence rate is proved and it is argued that all other indicators of the performance of the system can be easily obtained through the expected cycle length. It was analytically found when the cost as a function of the re-order level is monotonous, concave, or convex. The results of the study demonstrate the degree of influence of various parameters on optimal policy and costs, but it was not taken into consideration that the distance covered by each order within a certain time interval may vary depending on seasonality. The analytical model using time intervals, rather than the volume of an order and the level of delay, was constructed in study [20] to analyze three different conditions of the optimal policy. The proposed model is used in the case when the optimal production time is less than the optimal time to eliminate overdue orders. Paper [21], in contrast to the traditional integrated model of coordination between a supplier and a buyer, considers intersecting deliveries, accounts for the defectiveness of goods and the possibility of the lack of time during batch inspections. It is noted that the discount when ordering more goods plays a significant role. The function of expected annual integrated total costs was obtained. A method for solving the model, which does not depend on the convexity of the functionality, was developed. The influence of five important parameters (frequency of inspections, annual demand, frequency of defects, cost of storage, and cost of obtaining) on the optimality of the solution was explored.

The performed analysis of literary sources makes it possible to talk about the existence of the shortage of tools that enable the reasonable formation of a suboptimal supply chain of raw materials on a given planning horizon for guaranteed provision of the technological process of a woodworking enterprise. At the same time, when finding a suboptimal procurement plan, uncertainties associated with the purchase of timber raw materials on the mercantile exchange and the risks of refusing the concluded contract should be taken into consideration. Unilateral termination of a purchase agreement may be associated with a significant loss of quality of purchased raw materials during transportation over long distances. This leads to the need to develop new methods and models.

3. The aim and objectives of the study

The purpose of the study is to develop an economic and mathematical method for the formation of sustainable supply chains of raw materials to a timber enterprise, taking into consideration the uncertainties and risks associated with the purchase of raw materials at the mercantile exchange and the implementation of the circuit of delivery to a warehouse.

To achieve the goal, the following tasks were set:

– to develop a model that makes it possible to form a plan for purchasing raw materials on the mercantile exchange on a given horizon, taking into consideration uncertainties in terms of the number of daily offers, their volumes, prices, and the risk of canceling the concluded contract due to the loss of the quality of raw materials;

– to develop a method for finding a suboptimal solution to the model to form a plan for the procurement of timber raw materials on the mercantile exchange;

– to test a model for one of the enterprises of the Far East with the justification of the economic feasibility of purchasing raw materials at the timber mercantile exchange and sustainability of providing production with the necessary raw materials.

4. Materials and methods of research

To achieve this goal, a database containing the characteristics of the flow of offers of the timber section of the mercantile exchange for the period of 01.01.2019–30.06.2020 was formed based on open information of the St. Petersburg International Mercantile Exchange. For all workdays of this period, a list of offers from timber enterprises of various regions for sale was formed. For each proposed lot, its volume, cost, and region were indicated.

According to a large woodworking enterprise in the Far East, firstly, a database of actual delivery times of the lots purchased on the exchange to the enterprise's warehouse, which makes it possible to assess the impact of seasonality on the throughput of the railway, was formed. Secondly, the base of unilateral refusals of an enterprise from the contract was formed.

The developed model is a problem of stochastic mixed-integer nonlinear programming, in which a significant part of the parameters describing the process of purchasing raw materials under consideration is given in the form of random magnitudes. Since the model requires a fairly large amount of calculations when finding a solution, it was decided to use the Python programming language. The heuristic algorithm for finding a solution at individual steps uses the Branch and Bound method and a genetic algorithm, which makes it possible to successfully search for a solution with a much larger number of variables. The software implementation of the algorithm uses the process of parallelization of calculations.

5. Results of the study on devising a method for the formation of sustainable chains of supply of raw materials to a woodworking enterprise

5. 1. A model for generating a long-term plan for purchasing raw materials at the mercantile exchange, taking into consideration uncertainties and risks

The task of forming sustainable chains of supply of raw materials to a woodworking enterprise that does not have timber production units and forest resources in its structure is considered. The company buys the raw materials necessary for production in a competitive market, using the capabilities of the mercantile exchange. The flow of offers at the mercantile exchange is significantly uncertain both in terms of the number of proposals from timber enterprises of various regions and in terms of the volume and cost of offers. To take into consideration the uncertainties and associated risks of possible shortages of providing the process with raw materials at certain intervals of time, we will use the probabilistic approach when modeling the supply process.

We will consider a woodworking plant, where the technological process requires a certain amount of raw materials daily. The technology of production of finished products makes it possible to use any type of raw materials from two (sawlogs or balance), as well as mix them in any proportion. On given planning horizon M, it is necessary to provide such stock of raw materials, which, on the one hand, guarantees non-stop work, on the other hand, minimizes the cost of its purchasing.

The company buys raw materials of two types at the mercantile exchange. Sales requests of certain lots come from several regions of the Russian Federation, each application is assigned by two parameters: volume and cost, taking into consideration delivery to a consumer. The peculiarity of the mercantile exchange operation is [22, 23] that a lot can be bought only as a whole. Thus, we assume that there is a flow of requests, each of which is assigned by a vector:

$$(m, r, i(m, r)v_i, c_i),$$

where m is the number by order of the day on the given planning horizon, $m=1, ..., M$; r is the number of the region, from where the request arrived $r=1, ..., R$; $i=g(m,r)$ is the number of request depending on the day m and region r, $i=0, ..., I$; I=const is the number of request of the entire planning horizon; v_i is the volume of raw materials in the i-th request (m^3); c_i is the price of purchasing the i-th request (rubles), including delivery cost. The number and distribution in time of the lots to sale $I(r,m)$, their volumes v_i, and costs c_i are random magnitudes.

The process of delivering raw materials to the consumer's warehouse contains two types of uncertainties: delivery time and quality of the supplied raw materials. The quality of raw materials can deteriorate significantly during warm periods with a significant increase in transportation time. In this regard, the company-consumer has the opportunity to terminate the contract for two reasons:

1) failure to meet the delivery terms,

2) discrepancy between the quality of supplied raw materials and the parameters stipulated in the contract.

When constructing the model, we will assume that for each lot, the distance covered by rail per day is a random magnitude assigned by some distribution law. Let's introduce function $f(t)$, which specifies the probability of termination of the contract for the above two reasons at time t.

Along with the procurement planning interval [0, M], it is necessary to consider some time interval of length $\underline{M}$ to the point of time $t=0$. This is due to the fact that under contracts concluded at this period, the goods will arrive at the warehouse on the days from the planning horizon (Fig. 1). The interval [M+1, $M+M$] contains the days on which the raw materials will arrive under the contracts concluded at the end of the planning interval (Fig. 1).

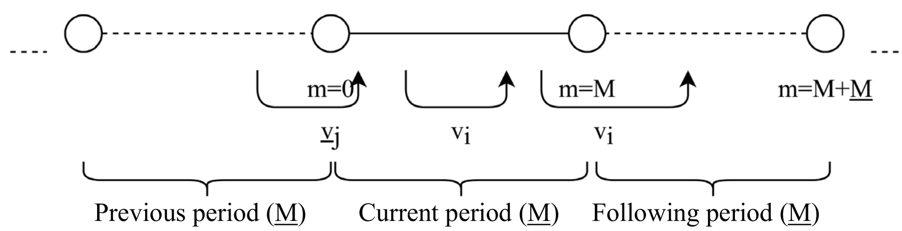


Fig. 1. Visualization of intervals of planning the formation of sustainable supply chains of raw materials

To construct a model, we introduce the following variables and designations:

– R – the number of regions from where sales requests arrive;

– u_m – the amount of raw materials in the warehouse per day m (m^3);

– $\tilde{u}_m$ – the volume of raw material required for production per day m (m^3);

– $\overline{u}$ – the maximum capacity of a warehouse (m^3);

– $\underline{u}$ – untouchable stock of raw materials in the warehouse (m^3);

– J – the number of requests satisfied within the previous period (up to m=1);

– $\underline{v}_j$ – the volume of raw materials in a request $j=j(r,n)$ from region r, purchased in within the previous period per day n (m^3);

– L_r – the distance from suppliers from region to warehouse of an enterprise by rail (km);

– T_i – the term of delivery of raw materials by the i-th request, fixed in the contract (days);

– *rand* – random magnitude evenly distributed on [0, 1];

– P_{im} – the counter of days from the moment of purchasing request i to day m (days);

– $t_{im}=\max(0;\ P_{im}-T_i)$ – the number of days, by which the agreed term of delivery of request i increases (similarly assigned for the case with requests j from the previous period) (days);

– $f(t_{im})$ – the probability of refusal depending on the number of days t_{im} and t_{jm}, respectively (days);

– s_{im} – the distance by day m (km) covered by request i;

– $\dot{s}_{jm}$ – the distance covered by request j purchased in the previous period by day m (km);

– τ_{imr}, $\dot{\tau}_{jmr}$ – the magnitudes assigning the excess of the distance covered by request i, j by day m relative to L_r (km);

– λ^2_{im}, $\dot{\lambda}^2_{jm}$ – technical variables;

– N – the technical rather big constant assigned by the program code executor and satisfying condition $N \geq L_r$;

– ξ – the random magnitude that assigns the distance covered by a request on any of the days of the period under consideration. It is distributed according to the lognormal law $LgN(\mu, \sigma^2)$, where μ, σ^2 are controlling parameters.

Optimization variables in the model are binary variables $y_i=\{0,1\}$ and $\dot{y}_j=\{0,1\}$ that assign the fact of satisfying a request in current and previous periods, respectively.

The model, which minimizes the total costs of purchasing raw materials on a given planning horizon, takes the following form:

$$f^* = \sum c_i \max_{m\in[1,M+1,5^*T_i]} \lambda^1_{im} \to \min, \tag{1}$$

$$u_{m+1} = u_m - \tilde{u}_m + \\ + \sum_j \left(\dot{\lambda}^1_{j(m+1)} - \dot{\lambda}^1_{jm}\right)\underline{v}_j + \sum_i \left(\lambda^1_{i(m+1)} - \lambda^1_{im}\right) v_i, \tag{2}$$

$$u_m \leq \overline{u}, m = 1:M, \tag{3}$$

$$u_m \geq \underline{u}, m = 1:M, \tag{4}$$

$$u_0 = \text{const}, \tag{5}$$

$$\lambda^1_{im} = \{0,1\}, \tag{6}$$

$$\dot{\lambda}^1_{jm} = \{0,1\}, \tag{7}$$

$$f(t_{im}) = \begin{cases} \dfrac{2}{\pi}\text{arctg}(\beta^* t_{im}), \beta = \text{const}, t_{im} > 0, \\ 0, t_{im} \leq 0, \end{cases} \tag{8}$$

$$f(t_{jm}) = \begin{cases} \dfrac{2}{\pi}\text{arctg}(\beta^* t_{jm}), \beta = \text{const}, t_{jm} > 0, \\ 0, t_{jm} \leq 0, \end{cases} \tag{9}$$

$$\left(1-\lambda^1_{im}\right)\left(f(t_{im}) - \text{rand}\right) \leq 1 - y_i, \tag{10}$$

$$\left(1-\dot{\lambda}^1_{jm}\right)\left(f(t_{jm}) - \text{rand}\right) \leq 1 - \dot{y}_j, \tag{11}$$

$$P_{im} = P_{i(m-1)} + y_i - \lambda^1_{im}, \tag{12}$$

$$P_{jm} = P_{j(m-1)} + \dot{y}_j - \dot{\lambda}^1_{jm}, \tag{13}$$

$$s_{i(m-1)} + \left(1-\lambda^1_{im}\right)^* y_i^* \xi - \tau_{imr} = \\ = \lambda^1_{im} L_r + \lambda^2_{im} s_{im}, \qquad r = g^{-1}(i,m), \tag{14}$$

$$\dot{s}_{j(m-1)} + \left(1-\dot{\lambda}^1_{jm}\right)^* \dot{y}_i^* \xi - \dot{\tau}_{jmr} = \\ = \dot{\lambda}^1_{jm} L_r + \dot{\lambda}^2_{jm} \dot{s}_{im}, \qquad r = g^{-1}(j,m), \tag{15}$$

$$\tau_{imr} = \lambda^1_{im}\left((s_{im}+\xi) - L_r\right) \geq 0, \quad r = g^{-1}(i,m), \tag{16}$$

$$\dot{\tau}_{jmr} = \dot{\lambda}^1_{jm}((\dot{s}_{jm}+\xi) - L_r) \geq 0, r = g^{-1}(j,m), \tag{17}$$

$$\lambda^1_{im} + \lambda^2_{im} = 1, \tag{18}$$

$$\dot{\lambda}^1_{jm} + \dot{\lambda}^2_{jm} = 1, \tag{19}$$

$$s_{im} \leq L_r - 10^{-17}, \quad r = g^{-1}(i,m), \tag{20}$$

$$\dot{s}_{jm} \leq L_r - 10^{-17}, \quad r = g^{-1}(j,m), \tag{21}$$

$$0 \leq s_{im} \leq N y_i, \tag{22}$$

$$0 \leq \dot{s}_{jm} \leq N \dot{y}_j, \tag{23}$$

$$y_i \geq \lambda^1_{im}, \tag{24}$$

$$\dot{y}_j \geq \dot{\lambda}^1_{jm}, \tag{25}$$

$$\lambda^2_{im}, \dot{\lambda}^2_{jm} \in \{0,1\}, \tag{26}$$

$$\lambda^1_{im} \geq \lambda^1_{i(m-1)}, \tag{27}$$

$$\dot{\lambda}^1_{jm} \geq \dot{\lambda}^1_{j(m-1)}, \tag{28}$$

$$s_{i0}, P_{i0} = 0, \tag{29}$$

$$\dot{s}_{j0}, P_{j0} = \text{const}. \tag{30}$$

We shall explain sense of the most important limitations of the model. The recurrent ratio (2) describes the amount of raw materials in the warehouse per day, taking into consideration their arrival and withdrawal for the production process. Variables λ^1_{im}, $\dot{\lambda}^1_{jm}$ reflect the fact of the arrival of a request at the warehouse and thereby the execution of the contract for this lot. In ratios (8), (9), sequentially, for each day beyond the delivery period fixed in the contract, there is a probability of failure, which increases with an increase in the day of delay. This is due to an increase in the risk of deterioration in the quality of the supplied raw materials and possibly with the absence of the need for these raw materials on overdue days. Constraints (10), (11) for the request undelivered on a given day (beyond the agreed period) and when deciding to cancel the contract, transfer variable y_i to the "request not bought" state. Constraints (14), (15) assign the distance covered by the cargo taking into consideration uncertainty by the magnitude of the covered daily distance. Ratios (18), (19) assign that the goods can be simultaneously either in transit or in the warehouse.

Thus, the proposed model is a problem of stochastic nonlinear integer programming *F*.

5. 2. The method for finding a suboptimal solution of the model of formation of a plan for procuring timber raw materials on the mercantile exchange

To find a suboptimal solution of the constructed model, the following two-step algorithm was used:

1. Using the method presented in [23], we find a procurement plan that is close to optimal (at a given level of accuracy) for a fixed flow of requests at the exchange. We will call it "basic". Note that the model at this stage contains random variables that specify the uncertainty of the covered daily way, and accordingly, the probability of canceling the contract.

2. At the second stage, starting from the first day (m=1), we play out a daily set of requests at the mercantile exchange every day. From the available set of requests, we choose such a procurement plan for this day, which is the closest in terms of raw materials to the "basic" one and minimizes total costs. Model (31) is used to find this procurement plan. Note that for each following day, accumulated deviation of purchased volumes from the "basic" plan is taken into consideration. When there are critical deviations in volumes or accumulated total costs from the "basic" plan, the given day is taken as the starting point of planning and the planning process is again launched for the next M days.

$$\begin{cases} m = 1:M \\ \sum_i c_i x_i \to \min, \\ \sum_r \alpha_{mr} \to \min, \\ (1-\alpha_{mr})(v^{\Pi}_{mr}+\Delta_{mr}) \le \sum_i x_i v_i \le (1+\alpha_{mr})(v^{\Pi}_{mr}+\Delta_{mr}), \\ u_m = u_{m-1} + \sum_i x_i v_i - \tilde{u}_m, \\ \alpha_{mr} \ge 0, \\ x_i \in \{0;1\}, \\ \Delta_{mr} = \Delta_{(m-1)r} + v^{\Pi}_{(m-1)r} - \sum_{i:i(m-1,r)} x_i v_i, \\ \Delta_{0r} = 0, \\ u_m \ge \underline{u}, \\ u_m \le \overline{u}, \end{cases} \tag{31}$$

where c_i is the cost of request i, including delivery costs;

x_i is the variable reflecting the fact of including request i in the procurement plan;

α_{mr} is the degree of deviation of the volume of raw materials, purchased on day m from region r, from the planned ("basic") one taking into consideration the accumulated deviation;

v^{Π}_{mr} is the planned ("basic") volume of raw material which is necessary to be purchased on day m from region r;

Δ_{mr} is the deviation of the volume of raw materials, purchased in region r, from the basic one (m^3), accumulated by day m.

The constructed model (31) is a multi-criteria problem of mathematical programming. To find its solution, assign some value α_{mr} and find the solution of the model according to the first criterion. Next, we will consistently reduce values $\alpha_{mr} \ge 0$ until the following condition is met:

$$\forall m, r > 0 \left| \alpha^{iter}_{mr} - \alpha^{iter-1}_{mr} \right| \le \varepsilon, \tag{32}$$

where α^{iter}_{mr} is the value of α_{mr} on iteration $iter$, ε is the assigned accuracy.

5. 3. Testing the model of formation of a cost-effective plan of purchasing raw materials

Consider the application of the above model of the formation of sustainable supplies of raw materials for its purchases at the St. Petersburg International Mercantile Exchange (hereinafter referred to as the exchange) by the timber industry company of Primorsky Krai, which does not have its own plots for forest raw materials.

To test the model based on the data of 2019 2020, first of all, we will set the "basic" flow of proposals for the sale of forest resources, which will be considered deterministic. Secondly, construct the estimates of characteristics of probabilistic distributions that assign daily values of deviations in the number of lots-offers from different regions, their volumes, and cost, taking into consideration the time dynamics, from the "basic" option on the horizon under consideration. Let us take a week as a window, for which statistical estimates of parameters are constructed. As a planning horizon, consider six months from January to June.

Modeling of the probabilistic flow of offers at the mercantile exchange (m, r, i (m, r) v_i, c_i) is carried out as follows: for each day m on the planning horizon, we play out the implementation of random magnitudes that specify the deviations in the number of requests, volumes, and cost from the "basic" option. The flow of requests constructed in this way will be considered one implementation. As the distribution law, we consider a uniform law with mathematical expectation 0 (since this is a deviation) and the interval width determined by the sample variance for a given week.

Expressions (33) to (38) reflect the generation process in more detail.

$$n_{mr} = \max\left(0; n^*_{mr} + U_{discrete}\begin{pmatrix} -\alpha^{(1)}(month, r), \\ \alpha^{(1)}(month, r) \end{pmatrix}\right),$$

$$\forall m \in month, \tag{33}$$

$$\alpha^{(1)}(month, r) = \sqrt{3D_n(month, r)}, \tag{34}$$

where $month$ is the name of the month, r is the number of region, $D_n(\bullet)$ is the sample variance of the number of orders, $U_{discrete}(-\alpha^{(1)}, \alpha^{(1)})$ is the discrete random magnitude evenly distributed on interval $[-a^{(1)}, a^{(1)}]$.

If for fixed m *and* r: $n_{mr}>0$, then

$$a^{(2)}(month, r) = \sqrt{3D_v(month, r)}, \tag{35}$$

$$v_{i(m,r)} = \begin{cases} \max\left(0; v_{(m,r)} + U\begin{pmatrix} -\alpha^{(2)}(month, r), \\ \alpha^{(2)}(month, r) \end{pmatrix}\right), i \le n_{mr}, \\ \max\begin{pmatrix} 0; \dfrac{\sum_{m \in month} \sum_{i(m,r)} v_{i(m,r)}}{M^{(1)}(month)} + \\ +U\begin{pmatrix} -\alpha^{(2)}(month, r), \\ \alpha^{(2)}(month, r) \end{pmatrix} \end{pmatrix}, i > n_{mr}, \end{cases} \tag{36}$$

where $month$ is the name of the month, r is the number of region, $D_v(\bullet)$ is the sample variance of the volumes of raw materials in requests, $U(-a^{(2)}, a^{(2)})$ is the evenly distributed continuous magnitude on interval $[-a^{(1)}, a^{(1)}]$, $M^{(1)}(month)$ is the number of days in $month$.

$$\alpha^{(3)}(month, r) = \sqrt{3D_p(month, r)}, \tag{37}$$

$$p_{i(m,r)} = v_{i(m,r)} * U\left(\max\left(0; \frac{p_{i(m,r)}}{v_{i(m,r)}} - \alpha^{(3)}\right), \frac{p_{i(m,r)}}{i(m,r)} + \alpha^{(3)}\right), \tag{38}$$

where *month* is the name of the month, r is the number of the region, $D_p(\bullet)$ is the sample variance of prices for raw materials, $U(-\alpha^{(2)},\alpha^{(2)})$ is the evenly distributed continuous random magnitude on interval $[-\alpha^{(1)}, \alpha^{(1)}]$, $M^{(1)}(month)$ is the number of days in month *month*.

The source data of the model are represented in Table 1.

The following regions are represented: the Republic of Udmurtia, Irkutsk Region, Moscow Region, Perm Krai. The Republic of Buryatia is not under consideration due to rare requests at the Mercantile Exchange for the entire period taken as the basis for forming the initial database.

The time of algorithm operation was assigned by three hours. During this time, the algorithm managed to find 18 acceptable solutions. A description of the interpretation (tracing) of the best solution is presented below.

The solution obtained for the "basic" flow of requests will be called the "basic" solution. We will conduct 100 implementations of the probabilistic flow of offers at the mercantile exchange. The obtained solutions for these implementations and average values of the main parameters are shown in Fig. 2–5.

We used the following designations in Fig. 2–5: I – the "basic" solution, II – the solution of the problem on one of the generated samples, III – the average value for all solutions for all generated samples. The cut-off on the Ox axis means the end of the corresponding designated month.

Fig. 2 shows the volume of accumulated costs for purchasing raw materials that guarantee sustainable functioning of an enterprise for each implementation of the flow of requests, and Fig. 3 shows the deviations of the received decisions from the "basic" volume of accumulated costs, accepted as "zero". It should be noted that in January and in the second half of March, there is a significant deviation in the volume of costs on average and in terms of sales. In other periods, and importantly, at the end of the planning period under review, the observed deviations are not large.

The second important parameter is the daily volume of raw materials in a warehouse. Fig. 4 visualizes the volume of raw materials in the warehouse, and Fig. 5 shows the relative magnitude of the deviation of the volume of raw materials in the warehouse from the "basic" solution.

It is worth noting that February – March is quite a difficult period for planning. Serious deviations are observed during it for lengthy periods. In the first two-thirds of February, the problem is the lack of sufficient raw materials in the market, so it is not possible to return from the mark of 10 % for the deviation up to 0. A similar picture can be observed when considering deviations from the planned amount of costs (Fig. 3).

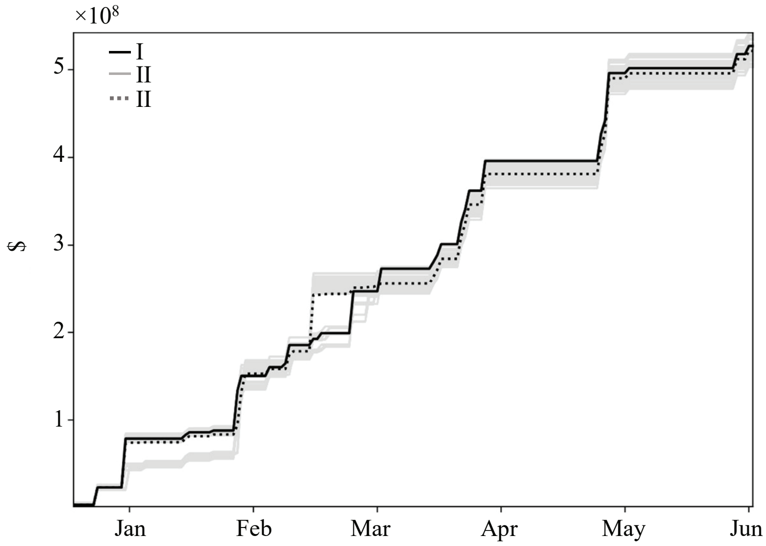


Fig. 2. Accumulated volumes of costs of raw material costs

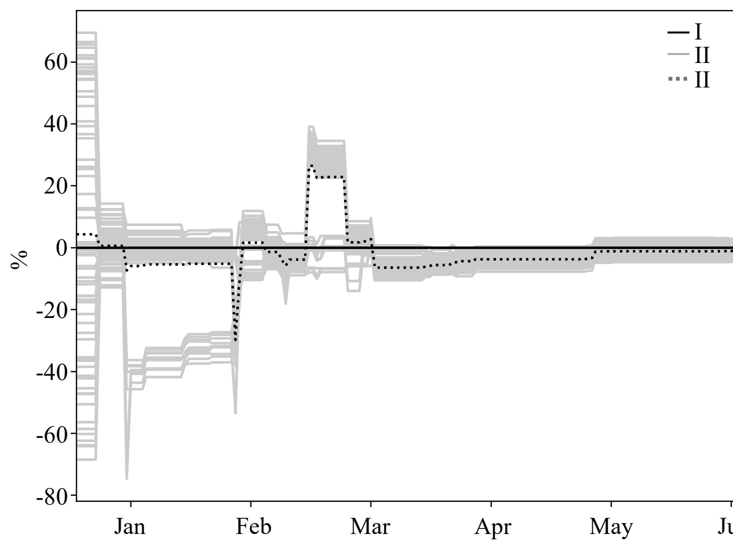


Fig. 3. Relative deviation of accumulated costs of raw material from the "basic", %

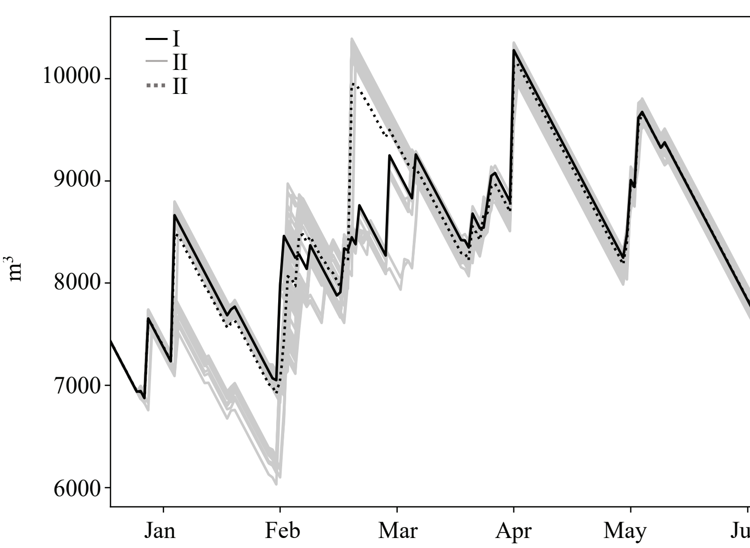


Fig. 4. Volume of raw materials in the warehouse, m^3

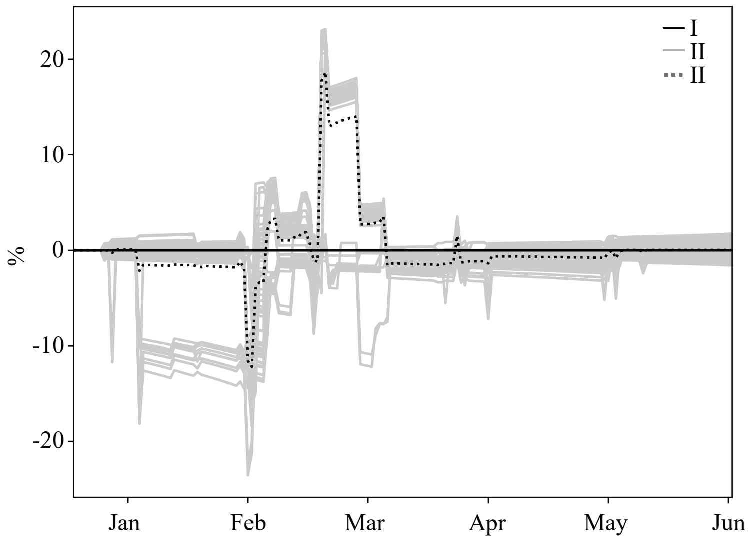


Fig. 5. Relative deviation of raw materials in the warehouse from the "basic" level, %

Consider the volume of purchases in the context of months and regions. Tables 2, 3 show the values of the number of obtained requests and the volume of purchased raw materials. Note that in addition to June, the bulk of supplies is made from the Irkutsk region. The most "stable" supplier is the Republic of Udmurtia.

Table 1

Values of source data

No	Parameters, measurement units	Values
1	$u^{\max}$, m^3	12750
2	$u^{\min}$, m^3	9
3	L_r, km	[3253, 7243, 8211, 7893]
4	ξ, km	$\sim LN(0.26, 0.25)$
5	$\tilde{u}$, m^3	183
6	M, days	180
7	$\underline{M}$, days	15
8	B	3

Table 2

Structure of purchases of raw materials for regions and months (number of requests)

Month	Jan	Feb	Mar	Apr	May	Jun
Number of requests at the stock, units	16.2	40.9	78.8	31.2	29.2	18
Bought lots, units	3.2	10	3.2	12.6	12	3
Irkutsk region, %	62.5	62	43.75	53.97	41.67	0
Perm Krai, %	0	0	0	15.87	0	66.67
Udmurtia, %	37.5	28	31.25	7.94	58.33	33.33
Moscow region, %	0	10	25	22.22	0	0

Sources: compiled by Authors

An interesting issue is the influence of the parameters of modeling the stochastic time of delivery of raw materials to an enterprise and the risk of cancellation of the concluded contract due to the loss of quality of raw materials during delivery and non-fulfillment of delivery terms.

The models (1) to (30) use random variable ξ, which specifies the distance covered by a request on any day of the period under consideration. To adequately assign its distribution law, we will use, firstly, the following consideration: possible deviations of the covered distance from the normative towards the larger and smaller sides are asymmetrical. The deviation to the larger side cannot be significant due to technical reasons, and the deviation to the smaller side can appear to be significant due to periodically occurring traffic congestions on the railway in the Far East. The database on the implementation of delivery of purchased raw materials formed on the basis of the information of a large timber enterprise includes tracking the cargo transition by rail. A mirror image of the empirical distribution of daily covered distances relative to the vertical straight line passing through the normative value was constructed. Verification of the hypothesis about the correspondence of the constructed mirror empirical distribution to the lognormal law at the level of significance of 0.05, using Pearson agreement criterion, showed that the hypothesis is not rejected.

Table 3

The region's contribution by months to the volume of purchases (volumes of raw materials)

Month	Jan	Feb	Mar	Apr	May	Jun
There was at the mercantile exchange, m^3	8725	11470	28199	8267	6166	3555
Bought, m^3	2268.53	2417.97	2654.72	2927.58	1983.47	672.52
Irkutsk region, %	95.09	73.66	79.64	69.85	49.63	0
Moscow region, %	0	2.47	1.59	5.33	0	0
Perm Krai, %	0	0	0	8.58	0	43.86
Udmurtia, %	4.91	23.88	18.77	16.24	50.37	56.14

Sources: compiled by Authors

To assign parameters μ and σ of the lognormal distribution, it was accepted that the distribution mode is equal to the normative value of the daily covered distance:

$$x^{(1)} = \arg\max\left(\frac{1}{\left(\alpha^{(4)} - x\right)\sigma\sqrt{2\pi}} e^{-\frac{\left(\ln\left(\alpha^{(4)} - x\right) - \mu\right)^2}{2\sigma^2}}\right), \qquad (39)$$

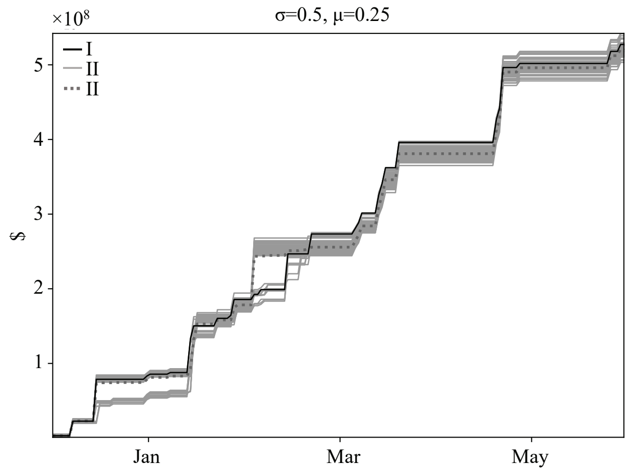
where $x^{(1)}$ is the normative daily distance covered by a request, $a^{(4)}$ is the maximum distance that a cargo can cover in one day.

Values $x^{(1)}$ and σ were assigned, and μ was found from (40) considering that condition (41) is satisfied (41)

$$\mu = \sigma^2 + \ln\left(x^{(1)}\right), \qquad (40)$$

$$0 \le \frac{1}{\left(\alpha^{(4)} - x\right)\sigma\sqrt{2\pi}} e^{-\frac{\left(\ln\left(\alpha^{(4)} - x\right) - \mu\right)^2}{2\sigma^2}} \le 1. \qquad (41)$$

Fig. 6–9 present the results of solving the problem for different values of the parameters of the law of probability distribution, which simulates the path covered in a day.



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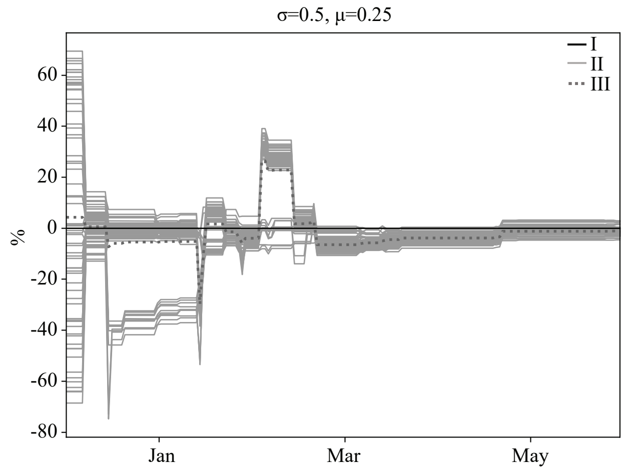

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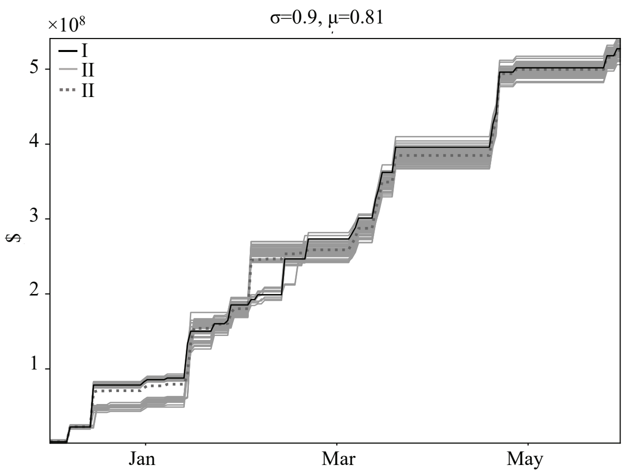

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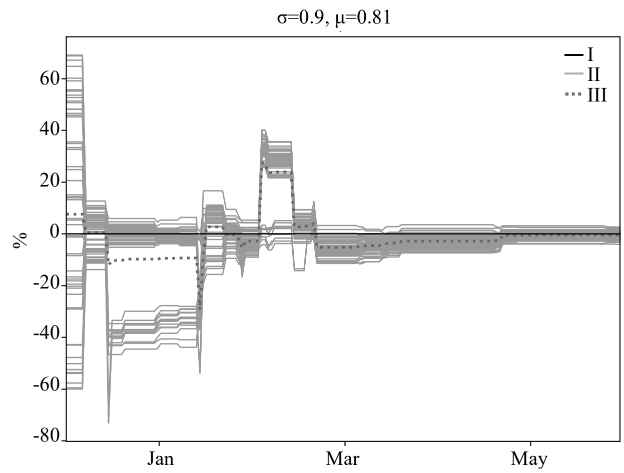

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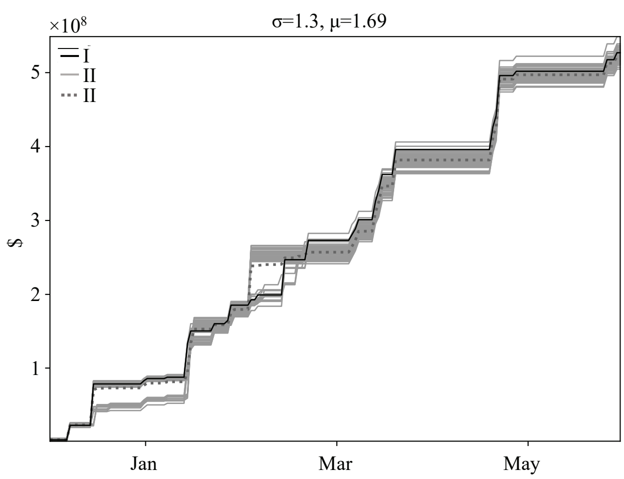

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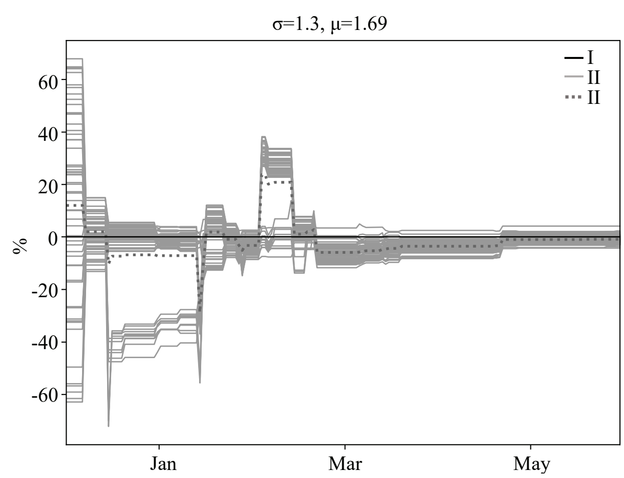
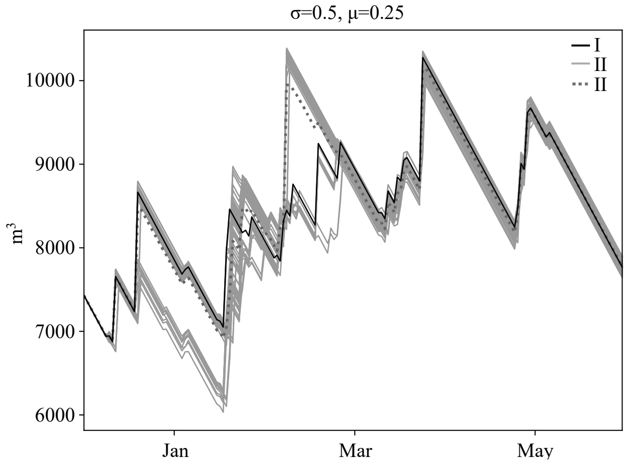


c

Fig. 6. Accumulated volumes of costs of raw materials at solving a problem for generated samples with parameters, $: *a* – μ=0.5, σ=0.25; *b* – μ=0.9, σ=0.81; *c* – μ=1.3, σ=1.69; I – "basic" solution; II – solution of the problem of one of the generated samples; III – average for solutions of all generated samples

Fig. 7. Relative deviation of accumulated costs of raw materials from the "basic" option, at solving the problem for generated samples with parameters, %: *a* – μ=0.5, σ=0.25; *b* – μ=0.9, σ=0.81; *c* – μ =1.3, σ=1.69; I – "basic" solution; II – solution to the problem on one of the generated samples; III – average for solutions for all generated samples



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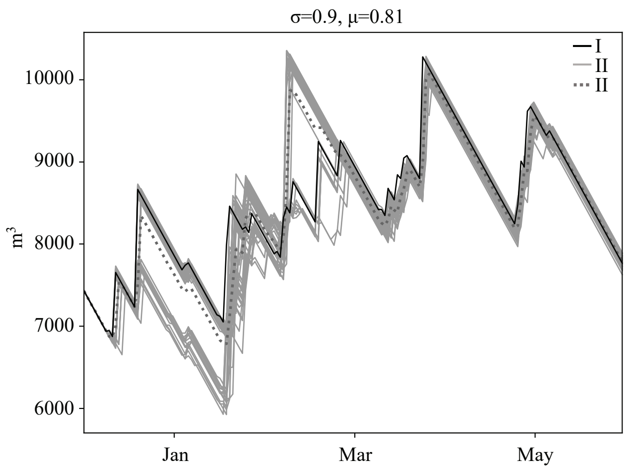

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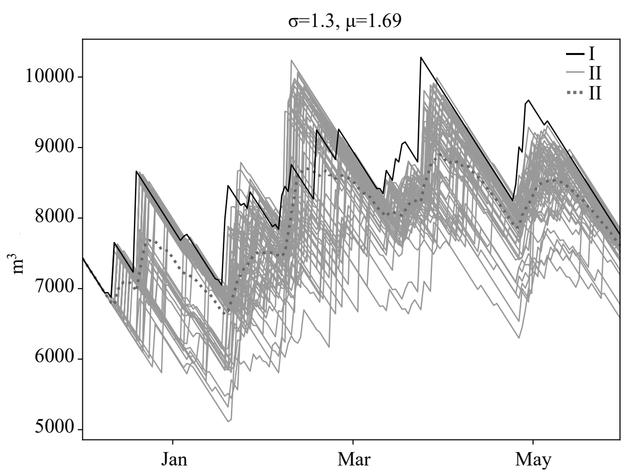

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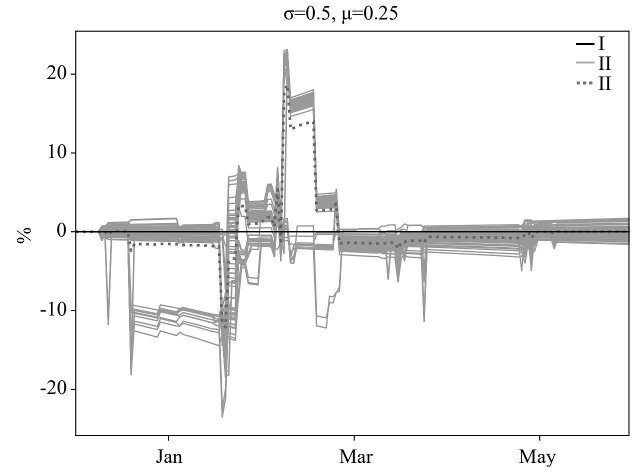
Fig. 8. The volume of raw materials in a warehouse at solving the problem for generated samples with parameters, m^3, *a* – μ=0.5, σ=0.25; *b* – μ=0.9, σ=0.81; *c* – μ=1.3, σ=1.69; I – "basic" solution; II – solution of the problem on one of the generated samples; III – average for solutions for all generated samples



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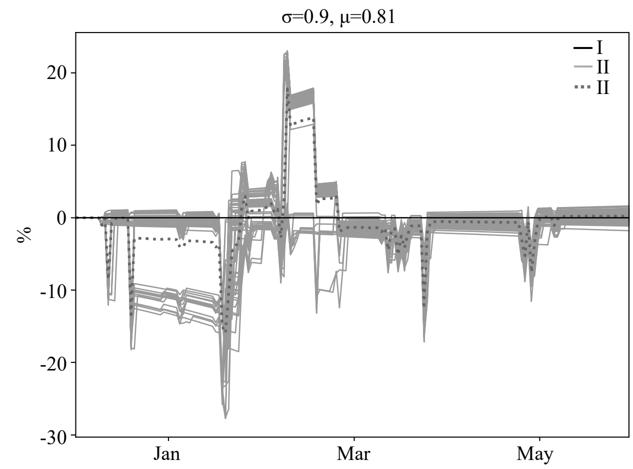

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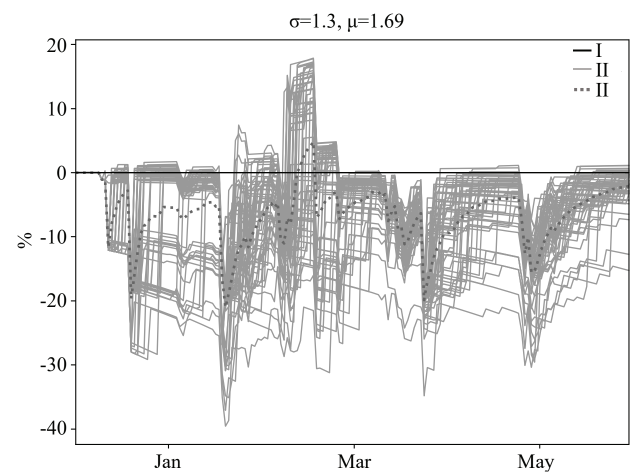

c

Fig. 9. Relative deviation of raw materials in the warehouse from the "basic" level at solving the problem for generated samples with parameters, %: *a* – μ=0.5, σ=0.25; *b* – μ=0.9, σ=0.81; *c* – μ=1.3, σ=1.69; I – "basic" solution; II – solution of the problem on one of the generated samples; III – average for solutions for all generated samples

It should be noted that with an increase in σ, that is, an increase in the asymmetry of the density function and at an increase in the weight of the tail, modeling a decrease in the distance covered per day, the spread of deviation of the volume of raw materials in the warehouse from the "basic" for different implementations increases significantly. Nevertheless, the volume of raw materials in the warehouse for all implementations does not fall below the "non-burnt" residue and ensures the non-stop operation of the technological complex of an enterprise. At the same time, the spread for different implementations of accumulated costs for purchasing raw materials changes slightly when the distribution parameters change.

6. Discussion of results of studying the formation of sustainable supply chains of raw materials, taking into consideration uncertainties and risks

The issue of cost-effective provision of the technological process at a timber processing enterprise with raw materials of the required quality in the required volumes was considered. The method for the formation of sustainable supply chains of raw materials, allowing the guarantee of the uninterrupted operation of the technological complex of an enterprise, was developed. The method is based on dynamic model (1) to (30) of the formation of a suboptimal plan for procurement of raw materials of a given specification at the mercantile exchange, which makes it possible to hedge the risks associated with both the flow of offers on the mercantile exchange and the logistics of delivery.

The main characteristics of the model are:

1) taking into consideration uncertainties and risks when purchasing raw materials at the mercantile exchange, associated with the stochastic flow of applications both in terms of the number of daily offers for sale of lots by timber enterprises from different regions, and in terms of the volumes and prices of each offer. Stochastic offers at the mercantile exchange leads to possible deviations of the main characteristics (accumulated costs, the volume of raw materials in a warehouse) for each played out implementation of the flow of applications in comparison with the "basic" plan (Fig. 2–5). There are intervals of time at which serious deviations are observed. This is due to the small number of proposals in these periods and the narrowing of the choice in purchasing raw materials. However, the adaptability of the model makes it possible to level these deviations on the long-term horizon;

2) taking into consideration uncertainties in the time of delivery of raw materials to a consumer (ratio (14), (15)) and risks associated with possible deterioration in its quality when failing to meet the deadline established in the contract. Loss of quality of raw materials, for this reason, can lead to unilateral cancellation of the contract (ratios (8), (9)) and the emergence of a shortage of raw materials in the warehouse. Setting parameter β in (8), (9) requires the use of the data of a particular enterprise in the practice of using this option provided for in contracts. Unjustified overestimation of β can significantly narrow the permissible set of solutions and, as a result, worsen the characteristics of the constructed solution;

3) two-stage formation of a suboptimal procurement plan that minimizes the cost of purchasing raw materials on the planning horizon under consideration. At the first stage, the "basic" procurement plan is constructed based on a fixed flow of proposals on the exchange, constructed on the average indicators of the exchange functioning for the previous period. At the second stage, the daily implementation of deviations in the flow of requests from the considered one that was fixed at the first stage is simulated, and based on the second optimization model (31), we find the procurement plan that makes it possible to minimally deviate from the "basic" plan. The deviation of the volume of raw materials in the warehouse from the "basic" one (Fig. 8) is sensitive to the size of the spread of the daily distance covered by cargo ξ. To increase the reliability of the formed procurement plan, it makes sense to overstate the value of parameter σ, which determines the variance of random magnitude ξ.

It should be noted that the process of finding a suboptimal solution to the problem is complicated by its large dimensionality, integer limitations, and rapidly growing load on RAM. Additional studies will make it possible to determine the limit from above on the dimensionality of the problem, for which the proposed method is able to find a solution in an acceptable computational time.

Computational experiments have shown that the proposed model and the method for finding its solution make it possible to build a stable suboptimal procurement plan. For each implementation of both a random flow of requests at the mercantile exchange and accidents in delivery to a consumer, the two main indicators (accumulated costs for the purchase of raw materials and the volume of raw materials in the warehouse) lie in some confident corridor near the "basic" procurement plan (Fig. 2–5). The width of the corridor at the confidence level of 0.95 allows avoiding downtime of production with an acceptable deviation in costs from the average value.

It is worth noting that the research has practical significance, which is expressed in the formation of an applied tool that makes it possible to increase the efficiency of decision-making by the management of a timber enterprise on the organization and implementation of the raw materials procurement system, taking into consideration the uncertainties of external conditions and the production plan.

In addition, one of the advantages of the model is the two-stage algorithm for finding a solution, which makes it possible to hedge the risks of the external environment based on daily accounting for the stochastic flow of applications when making decisions on concluding a contract for purchasing a particular lot.

Subsequent development of the proposed model is possible in several directions. First, it makes sense to add to the model a dynamically changing plan to produce each type and consideration of the norms of raw material costs to manufacture each production unit. This will affect the daily consumed volumes of raw materials at an enterprise and, thus, can change the structure of the vector of purchases of raw materials. Secondly, in order to find a reasonable plan to produce each type, it is worth adding a retailer of finished products to the considered chain "seller of raw materials – manufacturer". This will enable simulating the situation in the market and form a plan for purchasing raw materials based on the optimization of the production plan.

7. Conclusions

1. We devised the dynamic model that makes it possible to form a suboptimal plan for purchasing raw materials by

a timber processing enterprise at the mercantile exchange, taking into consideration uncertainties of the flow of sales requests. The model is a problem of stochastic nonlinear programming, the objective function of which is the value of accumulated costs at an assigned planning horizon. The input data of the model is the flow of sale requests, which has uncertainties in the number of daily offers, their volumes, and prices. The restrictions of the model also include a random magnitude that simulates the possibility of cancellation of the concluded contract due to the loss of quality of raw materials during delivery due to non-fulfillment of delivery time. The model makes it possible to hedge the risks associated with both the flow of offers on the mercantile exchange and the logistics of delivery.

2. To find a solution to the model, we devised a two-stage circuit, consisting of finding a "basic" procurement plan at the first stage and then choosing a random flow of requests for each day of implementation, which is closest by the volume of purchased raw materials to the "basic" one and minimizes total costs. The numerical solution at the first stage is a hybrid heuristic algorithm using the Branch and Bound method and the genetic algorithm, while at the second stage a two-criteria problem is solved numerically. The proposed algorithm makes it possible to find a suboptimal solution of some class of the problems of stochastic nonlinear programming. From the practical point of view, the model is a tool enabling the management of an enterprise to achieve maximum economic efficiency in ensuring the production of raw materials of the necessary quality and continuity of the technological process at an enterprise.

3. The model was tested on the example of a timber processing complex from Primorsky Krai. The computational aspects of the formation of the supply chain of the required raw materials, which ensures the minimization of costs and sustainability of the enterprise operation, were considered. Based on the performed calculations and the found solution of the model, recommendations for the company management on cooperation with the St. Petersburg Mercantile Exchange were generated. Analysis of the decision revealed that, despite the territorial proximity of the Irkutsk region to Primorsky Krai, it is worth paying attention to purchasing raw materials from the Moscow region and the Republic of Udmurtia, since they, firstly, have sufficient potential for extracted raw materials, and secondly, the pricing policy of logging enterprises is more acceptable. Analysis of the impact of uncertainties during transportation and the risks of termination of contracts on the sustainability of raw materials supply was performed. Computational experiments have shown the possibility for the management of an enterprise to use the proposed tool for long-term procurement planning and to enhance the efficiency and sustainability of the economic activity.

Acknowledgment

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