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Mathematical Model for Searching for an Optimal Solution to the Problem of Forming Supply Chains for Raw Materials of Forestry Enterprises under Conditions of Uncertainty

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ABSTRACT

This paper examines important aspects related to the problems of forming supply chains and production volumes at forest processing enterprises. The main emphasis is on assessing the optimality of decisions made. The study focuses on enterprises that do not have their own sources of raw materials and that are seeking to find the most appropriate solution based on the planning horizon based on data on transactions carried out on the commodity exchange. The **purpose** of the study is to create a mathematical model that allows us to establish the optimal volume of production of goods based on the formed supply chains of raw materials from the commodity exchange, considering the share of its useful volume, the time the lots are in transit and the uncertainty associated with supply and logistics. The following research methods were proposed: mathematical modeling, theory and optimization methods. Testing the model using data from the St. Petersburg Stock Exchange and enterprises of the Primorsky Territory made it possible to determine the optimal trajectories of profit, production volume and other important indicators. The work also raises issues of planning supply chains and production volumes, analyzes regions — sources of raw materials and presents the advantages and disadvantages of the presented mathematical model. The **results** obtained are of interest to the top management of forestry enterprises seeking to improve the efficiency of their activities and can be the basis for assessing the rationality of commodity transactions on the Russian Commodity and Raw Materials Exchange.

Keywords: formation of supply chains; production volumes; timber processing enterprises; optimality of decisions; mathematical model; commodity and raw material exchange; share of useful volume of raw materials; time of lots in transit; rational raw material transactions; efficiency improvement

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INTRODUCTION

In today's global economy and rapidly changing business environment, the effective development of raw material supply chains (SC) is becoming a strategically important factor in the success of forestry companies. The management of supply chains directly affects the competitiveness and profitability of enterprises, since the raw material base is an integral component of the production process.

However, the procedure for creating optimal SCs currently faces a number of difficulties. Factors such as fluctuations in demand, changes in the volume and quality of raw materials, transport restrictions and geographical features cause risks and uncertainty. In such a situation, it is necessary to develop a mathematical model that would take into account the above circumstances and allow one to find optimal solutions.

The relevance of this study is due not only to the rapid changes taking place in the business environment, but also to the existing need to reduce costs, increase production efficiency, optimize the use of resources and improve the competitiveness of companies as a whole. The mathematical model proposed in this article can become a valuable tool for organizing the process of managing the formation of raw material supply chains, taking into account the problems that enterprises face in their activities.

GOALS, OBJECTIVES AND RESEARCH HYPOTHESIS

This work takes into account two stages of the activities of companies in the timber industry: the purchase of raw materials on the exchange (and their delivery), as well as the production of a certain volume of products based on the existing timber stock. It is necessary to explain what is the algorithm for the receipt of raw materials on the stock exchange. It, as an organizer of auctions, enters into contracts with plot tenants from various regions, allowing them to use its site. After completing a transaction between the enterprise (customer) and the seller (plot) for processing raw materials, the latter in the amount specified in the contract is sent to the customer. Typically, businesses receive orders from customers well in advance and (as one might assume) plan their activities for the long term.

It should be noted that the demand for forest products is seasonal, which complicates the work of companies. During the study, a mathematical model was formed, with the help of which it was suggested to estimate the maximum profit of the enterprise over the entire planning horizon.

To achieve the goal of the work, the author set the following tasks:

• to review scientific literature on the research topic.

• to create an economic and mathematical model for the formation of SC and calculate the optimal volume of production of goods in the timber industry, taking into account events that have already occurred, namely:

- distribution of orders over time;
- delivery of consignments of goods to the enterprise warehouse.

• to analyze the model's testing results.

LITERATURE REVIEW

Existing academic works related to the field of raw material supply chain management in uncertain environment is often driven by the use of empirical methods and heuristic approaches, which limits its accuracy and applicability.

The author has analyzed a significant number of works that are relevant to the problems discussed in the article. So, A.A. Tsai and N. Agrawal assessed a supply chain consisting of one supplier and two competing retailers, focusing on service and price competition; their findings showed that, under certain scenarios, retailers favored increased competition [1]. The same authors studied the symbiosis of cooperation and competition in a supply chain that includes retail and direct channels [2].

F. Bernstein and A. Federgruen described the development of a general stochastic equilibrium inventory structure including service and price competition as key factors [3]. D.K. Yao, S. Yue and J. Liu focused on the impact of information sharing on optimal strategies for a retailer [4]. T. Xiao and D. Yang compared the impact of retail risk sensitivity on channel members' strategies in two different supply chains, showing that retailers with higher risk sensitivity have optimal service levels and lower prices, and also presented a competitive price and service framework, based on demand uncertainty [5].

D. Wu considered service and pricing in different channels, where service levels can be adjusted by both parties (both sellers and merchants) either sequentially or simultaneously [6]. C.H. Wu studied two-level SC, examined the impact of service and price competition between established manufacturers and those introducing new products, and showed that the degree of this competition determines the costs of processing and investment in services (especially for manufacturers introducing new products) [7].

S. Rezapour and R.Z. Farahani presented a two-tier supply chain model that takes into account price competition and service level of retailers [8]. The authors of the study [9] analyzed an SC model subject to demand disruptions, and Z. Pi, W. Fang and B. Zhang, when estimating a two-channel model, applied game theory approaches to achieve a Stackelberg-Nash equilibrium, since two competing retailers and a supplier supplied the product through a direct online channel [10].

The authors of [11] examined the distribution of a single product by a single manufacturer to multiple retailers within an SC, focusing on replenishment and pricing policies based on Bertrand and Cournot competition; Further, scientists expanded their research to include retailers' behavior in relation to competition and cooperation [12].

K. Chen and T. Xiao developed a supply chain model based on demand uncertainty, with a decentralized structure involving one supplier and several competing retailers, and a form of contracts that allows SCs to exhibit centralized behavior [13]. G.P. Cachon found an approximate solution to the inventory problem in a two-tier SC model with one manufacturer and several retailers, where the latter could compete or cooperate [14]. A team of scholars in [15] analyzed decentralized and centralized supply chain models and presented a model that considers a single supplier and multiple differentiated retailers, emphasizing that the former seeks to maximize the quantity of the latter [16].

Numerous studies are devoted to inventory management issues [17–36]. Their authors evaluate the coordination and sharing of inventory among retailers in SC with independent determination of order quantities and joint inventory allocation [22]; build supply chain models with both a decentralized structure (one monopolist manufacturer and several dependent retailers) [32] and one manufacturer and two retailers [33].

From the above one can conclude that the problems of supply chain management in the context of commodity exchanges are relevant and described in detail in a large number of scientific works. However, it is important to note such features of the studies as the relatively little attention paid to the conditions of uncertainty and risks that arise, in particular, on commodity stock exchanges. Typically, commodity transactions occur in B 2B format (directly between sellers and buyers). However, in the timber industry, especially in Russia, many companies continue to operate outside the official system and evade taxes. As a result, the process of connecting buyers and sellers can be time-consuming, limiting the potential number of customers and affecting commodity prices, as well as creating losses for the national budget, which does not receive sufficient tax revenue. The use of commodity exchange tools will contribute to the transparency of transactions and increase the number of potential clients for sellers, since even foreign companies in need of raw materials will be able to contact the latter without the need to seek direct contact. This will ultimately lead to competitive prices and more efficient sales of raw materials.

The literature typically examines issues relevant to supply chain management. These works describe mathematical models that help to effectively form SC taking into account the characteristics of the industry, and also explore management problems associated with organizing production and creating supply chains. Basic approaches are often used, such as Lean Logistics,[1] Six Sigma,[2] etc. However, scientific sources have little coverage of the issue of analyzing possible profits in a situation of uncertainty, although this task is useful for assessing the effectiveness of IT solutions and the quality of management. A feature of the timber industry is the reduction in the volume of wood during transportation, and this property of raw materials must be taken into account when developing a production plan and supply chains to the enterprise warehouse.

DEVELOPMENT OF A MATHEMATICAL MODEL

Any production, be it timber industry or otherwise, cannot function without the necessary supply of raw materials. The work uses data on its sale provided by the St. Petersburg International Commodity and Raw Materials Exchange[3] (hereinafter referred to as the exchange), which is publicly available. Every day, information on the number of transactions, prices and volume of raw materials sold is published on the exchange website. It provides services for the delivery of raw materials to the consumer (which are included in the cost of raw materials) from many regions, so that the buyer has a choice. According to the rules of the exchange, you can only purchase the entire lot of raw materials. Timber production is organized as follows: raw materials are delivered to a warehouse, then they are processed into dust and pressed into OSB[4] boards, i.e. into finished products. Each type of raw material corresponds to certain OSB. Transportation of boards is carried out by rail (including along the Trans-Siberian Railway) at the expense of the sender, who includes all costs for delivery of the lot in the price of the product.

Before moving on to the description of the model, we introduce the following notation for parameters and variables.

Parameters:

p_{km} — is price for goods of type k on day m;

c_{ilrm} — is the price of lot i with raw material type l from region r, which appeared on the exchange on day m;

[1] Lean logistics is a pull system that includes all organizations in the value stream for the end customer, when inventory is replenished according to the needs of internal and external consumers in small quantities.

[2] Six Sigma is a methodology for setting up business processes to reduce all types of defects, losses and costs.

[3] St. Petersburg International Commodity and Raw Materials Exchange (SPICRME) (official website). URL: https://spimex.com/markets/wood/trades/results/

[4] Oriented strand board (OSB) is a multilayer (3–4 or more layers) sheet consisting of wood chips (thin chips).

A_{lk} — is the rate of consumption of raw materials of type l for the production of a unit of goods of type k;

$\gamma_{\tilde{m}m}$ — is coefficient of spoilage of raw materials purchased on day $\tilde{m}$ to day m ($m \geq \tilde{m}$);

V_{ilrm} — is volume of raw materials in lot i with raw material type l from region r, which appeared on the exchange on day m;

H_{km} — is the maximum production volume of goods of type k on day m;

$\underline{b}$ — is the emergency level of raw material reserves;

$\overline{b}$ — is maximum storage capacity;

B_0 — is initial budget;

FC — are fixed costs;

M — is planning horizon;

$T_{r\tilde{m}}$ — is the time it takes for a lot purchased on day $\tilde{m}$ from region r to reach the warehouse;

L_r — is distance from the warehouse to region r;

S_m — is distance traveled by the application on day m;

β — is a constant;

$\varepsilon^{(1)}$ — is noise;

left and *right* — are the minimum and maximum values of a random variable distributed according to a uniform law;

$LN(a_m, \delta_m)$ — is lognormal distribution of a random variable with parameters (a_m, δ_m) respectively;

E — is the number of different sets of input parameters $\{V_{ilrm}(e), c_{ilrm}(e), T_{r\tilde{m}}(e)\}$.

Variables:

x_{km} — is the volume of production of goods of type k on day m;

λ_{ilrm} — is decision to purchase lot i with raw material type l from region r, which appeared on the exchange on day m;

b_{lm} — is the stock level of raw materials of type l in the warehouse on day m.

Let us denote the problem to be solved for each set of parameters e (the list of parameters is given above) as $F^{(1,1)}(e)$. The model will look:

$$\sum_{k,m} p_{km} x_{km} - \sum_{i,l,r,m} c_{imrl} \lambda_{imrl} \to \max, \quad (1)$$

$$b_{lm} = b_{lm-1} - \sum_k A_{lk} x_{km} + \gamma_{\tilde{m}m} \sum_{i,r} V_{i\tilde{m}rl} \lambda_{i\tilde{m}rl}, \quad (2)$$

where the condition $\tilde{m} = m - T_{r\tilde{m}}$ is satisfied.

$$x_{km} \in N, \quad (3)$$

$$\lambda_{imrl} = \{0;1\}, \quad (4)$$

$$0 \leq \sum_l b_{lm} \leq \overline{b}, \quad (5)$$

$$0 < \underline{b} \leq b_{lm}, \quad (6)$$

$$B_0 + \sum_{\underline{m}=1}^{m} \left(\sum_k p_{km} x_{km} - \sum_{i,l,r} c_{i\tilde{m}rl} \lambda_{i\tilde{m}rl} - FC \right) \geq 0, \underline{m} = 1:M, \quad (7),$$

where $\tilde{m} = m - T_{r\tilde{m}}$.

$$T_{r\tilde{m}} = m^* : \begin{cases} \left| L_r - \sum_{m=\tilde{m}}^{m^*} S_m \right| \to \min \\ L_r - \sum_{m=\tilde{m}}^{m^*} S_m \leq 0, \end{cases} \quad (8)$$

$$S_m \sim LN(a_m, \delta_m), \quad (9)$$

$$\gamma_{\tilde{m}m} = \min\left(1; \max\left[0; 1 - \frac{2}{\pi} arctg\left(\beta(m - \tilde{m})\right) + \varepsilon^{(1)}\right]\right), \quad (10)$$

$$\varepsilon^{(1)} \sim U(left, right), \quad (11)$$

$$0 \leq x_{km} \leq H_{km}. \quad (12)$$

Let us explain that in expressions (2) and (7) the values $V_{ilr(m-T_{r\tilde{m}})}$ are written into the system of restrictions if and only if the condition $\tilde{m} = m - T_{r\tilde{m}}$ is satisfied.

Problem $F^{(1,1)}(e)$ is solved for all $e = 1:E$.

Let's consider expressions (1–12) in more detail. Objective function (1) is aimed at obtaining the maximum profit value on the last day of the planning horizon. The level of raw material stock on day m is calculated according to formula (2), based on the volume of raw materials spent on production $\sum_k A_{lk} x_{km}$, the stock of raw materials at the end of the previous day b_{lm-1}, as well as the amount of raw materials received at the warehouse on the current day day adjusted for travel time $\tilde{m}$ and, accordingly, for the share of the useful volume of raw materials $\gamma_{\tilde{m}m}$.

Production volume (3) has only integer and non-negative values. The fact of making a decision on the purchase of a lot is given by relation (4). The volume of raw materials in the warehouse is limited by the maximum warehouse capacity (5) at the top and (6) at the bottom, since this value cannot have a negative value. Any enterprise has a certain budget, beyond which it cannot go (7). The travel time of each request is calculated from relations (8–9). In formula (9), the assumption was introduced that the random variable of the distance traveled by the lot on day m has a lognormal distribution. This is due to the seasonality of rail transportation, through which products are delivered to the buyer's warehouse. These data can be found in detail in [25, 27, 29].

The coefficient of useful volume of raw materials is given by formulas (10)–(11). Let us assume that $\varepsilon^{(1)}$ has a uniform distribution, since there are no estimates of how exactly the working volume of raw materials changes over time. The number of goods produced (12) is also limited from above for physical reasons.

As follows from the description of the model $F^{(1,1)}(e)$, it is a problem of nonlinear and stochastic programming. To solve it, it is necessary to consider an algorithm, namely:

Play values (8)–(9) and $\gamma_{\tilde{m}m}$ taking into account (11).

Solve mixed-integer programming problem (1)–(7), (12) for each data set e.

CALIBRATION

The model was tested on the basis of data, on the one hand, obtained at the LLC DNS-Les enterprise,[5] located in Spassk-Dalny, Primorsky Territory, and on the other hand, generated by the authors.

Let's look at how data related to the distribution of lots over time was generated. For this purpose, information from the exchange website was used for 120 days starting from 02/01/2021. Every 30 days, the mathematical expectation and dispersion of the number of applications, the volume of raw materials in each of them and the average price per 1 m3 were calculated. Next, according to the normal law, E sets of data were generated with the calculated characteristics. The remaining values of the parameters of logistics and production processes $\left(\bar{b}, \underline{b}, B_0, FC, a_m, \delta_m, \beta, L_r\right)$ were obtained at the above-mentioned enterprise in accordance with its estimates.

To be specific, we will use the following parameters: $K = 4$ (types of goods); $M = 100$ days (length of the planning horizon); $L = 2$ (types of raw materials); $R = 4$ (number of regions); $0 \le I \le 6$ (number of lots every day in the range); $E = 400$ (number of different sets of input parameters).

The exchange is represented by four regions: Irkutsk region ($R = 1$), Perm region ($R = 2$), Republic of Buryatia ($R = 3$), Moscow region ($R = 4$). The planning horizon lies between February 1, 2021 and mid-May 2021. The main input data characterizing the enterprise are presented in *Tables 1, 2.*

To carry out the calculations, we will use the high-level programming language Matlab and the built-in Intlinprog[6] function to find solutions to mixed-integer linear optimization problems. This function uses the branch and bound algorithm.

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[5] LLC DNS-Les (official web-site). URL: http://dns-les.ru/

[6] Website MathWorks. URL: https://www.mathworks.com/help/optim/ug/intlinprog.html

Table 1

Main input parameters of the enterprise

Option	Value
$\forall m > 0 : p_{km}, k = 1 : K$, RUB.	$(1,1.49,1.61,1.71)*10^4$
$\bar{b}$, m³	3000
$\underline{b}$, m³	21
B_0, rub.	3,01*106
$left(m)$, c.u.	$-\frac{100}{m*10^5}$
$right(m)$,	$\frac{100}{m*10^5}$
$\forall m, k > 0 : H_{km}$	4
$L_r, r = 1 : R$, KM	$(3741, 7561, 3251, 9021)$

Source: compiled by the author based on LLC "DNS-Les" data. URL: http://dns-les.ru/; SPIMEX. URL: https://spimex.com/markets/wood/trades/results

Table 2

Cost of raw materials for the production of a unit of good, m³

A_{lk}	$k = 1$	$k = 2$	$k = 3$	$k = 4$
$l = 1$	2	3	4	3
$l = 2$	1	3	3	5

Source: compiled by the author based on LLC "DNS-Les" data. URL: http://dns-les.ru/

INTERPRETATION

Let's look at *Fig. 1*. It shows the volume of goods produced each day (from the 1st to the 100th day). Gray color indicates the production volumes of each individual data set e, black color indicates the average value. Despite the higher price for goods 3 and 4, the calculation results show that the most frequently produced goods are types 1 and 2. However, as can be seen from the averages, all goods are almost always produced.

Figure 2 shows the profit indicators $\pi_m(e)$, received every day (from the 1st to the 100th day). Gray color indicates the profit volumes for each individual data set e, black color indicates their average value.

As follows from *Fig. 2*, the most financially difficult period (from the point of view of the

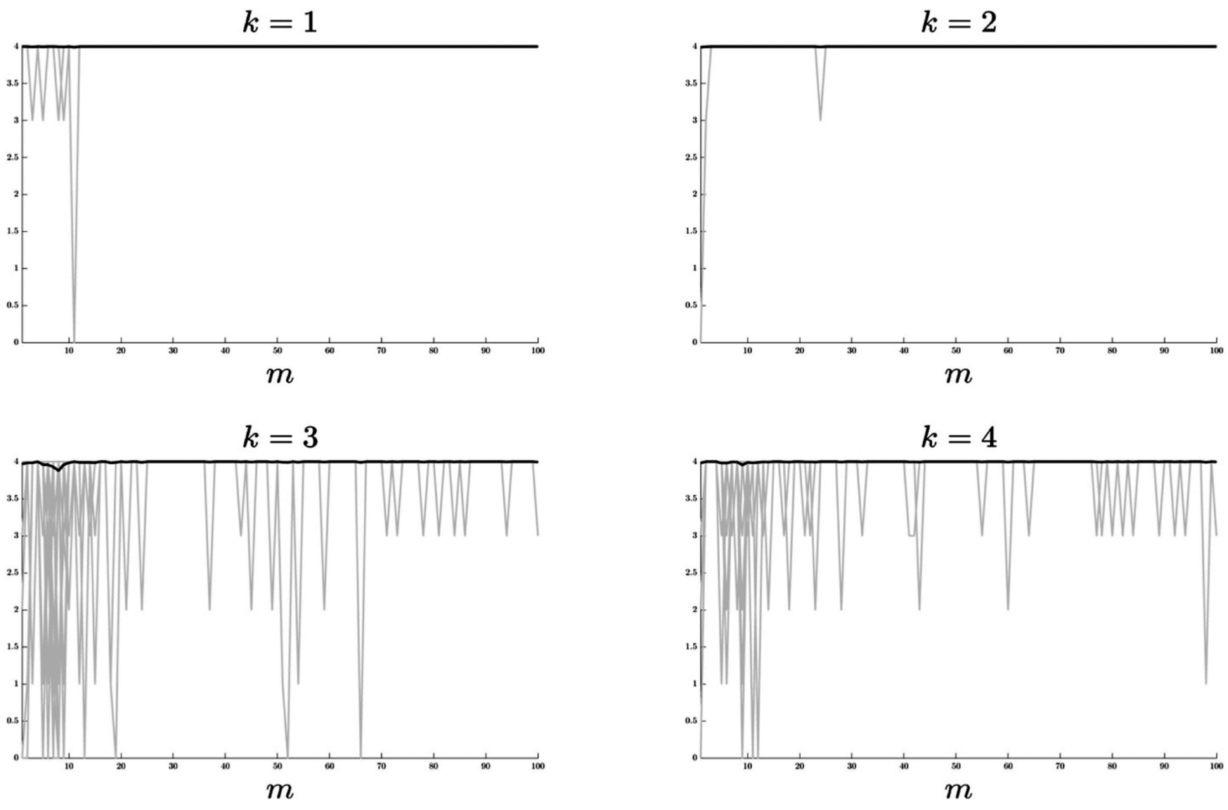

Fig. 1. **Visualization of production volumes**

Source: developed by the authors.

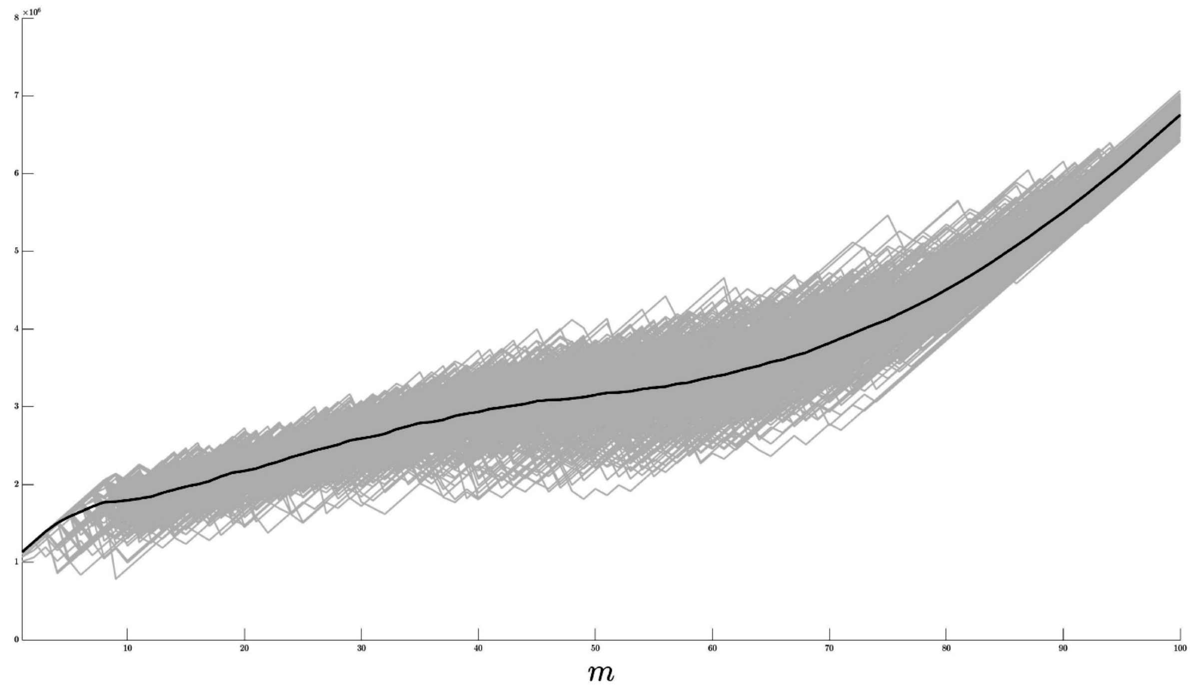

Fig. 2. **Visualization of profit values**

Source: developed by the authors.

management approach) falls on the interval from the 40th to the 60th day of planning — this can be said based on the almost stabilized and unchanged value of the profit indicator with the *optimal solution*.

Let's consider the positive and negative aspects of the designed model.

Negative aspects:

1. In real production during the planning stage, it is hardly possible to imagine a situation where managers responsible for making decisions can know the practical distribution of lots over time with all their characteristics. Therefore it is important:

a) collect data related to the task at hand over a large period of time; however, firstly, information is available on the exchange website only starting from the 2010s, and secondly, the exchange website is protected by anti-bot technology to reduce the load on the site in case the data is read using bots, which makes the process extremely complicated generating a sufficient sample size for analysis. It is worth noting that over time this problem becomes less relevant, as the volume of reports on completed transactions grows.

b) build complex mathematical models for the most accurate forecast of the distribution of requests over time. However, it has long been known that predicting situations on stock exchanges is not an easy task, since as private investors (in the context of the current task — small enterprises) are admitted to them, the influence of sentiment increases, and the latter are very difficult to predict. Based on this circumstance, the relevance of developing methods for forecasting situations not only on securities exchanges, but also on commodity exchanges sharply increases.

2. A rapidly growing number of limitations due to the linearity of the model [24].

3. For each day, it is necessary to know the parameters a_m, δ_m, which can change over time.

4. There is no clear explanation for the validity of using a lognormal distribution for the distance traveled by a lot.

5. The parameter β should also change over time, because in summer the useful volume of raw materials decreases faster under the influence of temperature, moisture and the mechanical impact of insects [29].

6. In real conditions, constraint (12) should include the value $\min(H_{km}, Q_{km})$, as an upper estimate, where Q_{km} — is the demand for goods of type k on day m, which will significantly specify the solution to the problem.

7. The model does not imply a choice of risk tolerance, which is extremely important when determining the strategy for forming a "commodity portfolio" in modern conditions.

8. Enterprises in the timber industry do not always use only the exchange as a source of raw materials; direct B 2B agreements are often concluded, which mitigate risks. This feature is not provided in the model.

Positive aspects:

1. For an upper estimate of the profitability of production (even of such a scale as the largest company in the timber industry sector of the Russian Federation — PJSC Segezha[7]) with sufficiently large values of the number of raw materials, lots and regions on the stock exchange, this model can be effective with a planning horizon of 1 year, the most common at enterprises in this industry [23–26].

2. Conceptual simplicity of the model.

3. It contains the possibility of recording the time of the lot in transit.

4. Availability of a coefficient of useful volume of raw materials for production.

5. The presence of well-known optimization methods for linear programming problems [29].

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[7] PJSC Segezha Group (official website). URL: https://segezha-group.com/about/

CONCLUSION

The developed model determines the upper limit of the profit of an enterprise in the timber industry and takes into account the time of lots in transit and their useful volume; it allows to create supply chains for raw materials and production volumes using the enterprise budget and just-in-time policy. The structure of the model covers production, budget status, supply chains and inventory levels — it is useful for top management of forestry enterprises and complements the economic and mathematical theory of decision making.

Testing the model at a timber processing enterprise made it possible to formulate recommendations for cooperation with the commodity exchange. The analysis showed that purchasing raw materials in the Moscow region and Perm region may be advisable, despite the proximity of other regions. However, it is recommended to purchase raw materials from the Irkutsk region and the Republic of Buryatia only under certain conditions. Calculations confirm the possibility of rational commodity transactions on the Russian stock exchange.

REFERENCES

1. Tsay A. A., Agrawal N. Channel dynamics under price and service competition. *Manufacturing & Service Operations Management*. 2000;2(4):372–391. DOI: 10.1287/msom.2.4.372.12342
2. Tsay A. A., Agrawal N. Channel conflict and coordination in the e-commerce age. *Production and Operations Management*. 2004;13(1):93–110. DOI: 10.1111/j.1937–5956.2004.tb00147.x
3. Bernstein F., Federgruen A. A general equilibrium model for industries with price and service competition. *Operations Research*. 2004;52(6):868–886. DOI: 10.1287/opre.1040.0149
4. Yao D.-Q., Yue X., Liu J. Vertical cost information sharing in a supply chain with value-adding retailers. *Omega*. 2008;36(5):838–851. DOI: 10.1016/j.omega.2006.04.003
5. Xiao T., Yang D. Price and service competition of supply chains with risk-averse retailers under demand uncertainty. *International Journal of Production Economics*. 2008;114(1):187–200. DOI: 10.1016/j.ijpe.2008.01.006
6. Wu D. Joint pricing-servicing decision and channel strategies in the supply chain. *Central European Journal of Operations Research*. 2011;19(1):99–137. DOI: 10.1007/s10100–009–0133-z
7. Wu C.-H. Price and service competition between new and remanufactured products in a two-echelon supply chain. *International Journal of Production Economics*. 2012;140(1):496–507. DOI: 10.1016/j.ijpe.2012.06.034
8. Rezapour S., Farahani R.Z. Supply chain network design under oligopolistic price and service level competition with foresight. *Computers & Industrial Engineering*. 2014;72:129–142. DOI: 10.1016/j.cie.2014.03.005
9. Ali S.M., Rahman M.H., Tumpa T.J., Rifat A.A.M., Paul S.K. Examining price and service competition among retailers in a supply chain under potential demand disruption. *Journal of Retailing and Consumer Services*. 2018;40:40–47. DOI: 10.1016/j.jretconser.2017.08.025
10. Pi Z., Fang W., Zhang B. Service and pricing strategies with competition and cooperation in a dual-channel supply chain with demand disruption. *Computers & Industrial Engineering*. 2019;138:106130. DOI: 10.1016/j.cie.2019.106130
11. Bernstein F., Federgruen A. Pricing and replenishment strategies in a distribution system with competing retailers. *Operations Research*. 2003;51(3):409–426. DOI: 10.1287/opre.51.3.409.14957
12. Bernstein F., Federgruen A. Decentralized supply chains with competing retailers under demand uncertainty. *Management Science*. 2005;51(1):18–29. DOI: 10.1287/mnsc.1040.0218

13. Chen K., Xiao T. Pricing and replenishment policies in a supply chain with competing retailers under different retail behaviors. *Computers & Industrial Engineering*. 2017;103:145–157. DOI: 10.1016/j.cie.2016.11.018
14. Cachon G.P. Stock wars: Inventory competition in a two-echelon supply chain with multiple retailers. *Operations Research*. 2001;49(5):658–674. DOI: 10.1287/opre.49.5.658.10611
15. Anderson E.J., Bao Y. Price competition with integrated and decentralized supply chains. *European Journal of Operational Research*. 2010;200(1):227–234. DOI: 10.1016/j.ejor.2008.11.049
16. David A., Adida E. Competition and coordination in a two-channel supply chain. *Production and Operations Management*. 2015;24(8):1358–1370. DOI: 10.1111/poms.12327
17. Adida E., DeMiguel V. Supply chain competition with multiple manufacturers and retailers. *Operations Research*. 2011;59(1):156–172. DOI: 10.1287/opre.1100.0863
18. Konur D., Geunes J. Supplier wholesale pricing for a retail chain: implications of centralized vs. decentralized retailing and procurement under quantity competition. *Omega*. 2016;65:98–110. DOI: 10.1016/j.omega.2016.01.002
19. Shenoy P.P. Competitive inventory models. *RAIRO — Operations Research*. 1987;21(1):1–19. URL: http://www.numdam.org/article/RO_1987__21_1_1_0.pdf
20. Yang S.-L., Zhou Y.-W. Two-echelon supply chain models: Considering duopolistic retailers' different competitive behaviors. *International Journal of Production Economics*. 2006;103(1):104–116. DOI: 10.1016/j.ijpe.2005.06.001
21. Zhang P., He Y., Shi C.V. Transshipment and coordination in a two-echelon supply chain. *RAIRO — Operations Research*. 2017;51(3):729–747. DOI: 10.1051/ro/2016052
22. Yan X., Zhao H. Inventory sharing and coordination among *n* independent retailers. *European Journal of Operational Research*. 2015;243(2):576–587. DOI: 10.1016/j.ejor.2014.12.033
23. Rogulin R.S., Mazelis L.S. Algorithm and mathematical model of supply chain management for raw wood from the regions in Russia: Comparison and analysis. *Vestnik Permskogo universiteta. Seriya: Ekonomika = Perm University Herald. Economy*. 2020;15(3):385–404. (In Russ.). DOI: 10.17072/1994–9960–2020–3–385–404
24. Rogulin R.S. Modeling of promising interaction between a timber industry enterprise and a commodity exchange in Russia. *Journal of Applied Economic Research*. 2020;19(4):489–511. (In Russ.). DOI: 10.15826/vestnik.2020.19.4.023
25. Rogulin R.S. A model for optimizing plans for procurement of raw materials from regions of Russia in a timber-processing enterprise. *Business Informatics*. 2020;14(4):19–35. DOI: 10.17323/2587–814X.2020.4.19.35 (In Russ.: *Biznes-informatika*. 2020;14(4):19–35. DOI: 10.17323/2587–814X.2020.4.19.35).
26. Rogulin R.S. The place of ICT and entrepreneurship in forming sustainable supply chains. *Ekonomicheskaya politika = Economic Policy*. 2021;16(4):84–103. (In Russ.). DOI: 10.18288/1994–5124–2021–4–84–103
27. Rogulin R.S. A mathematical model for the formation of the pricing policy and the plan of the production and transport system in a timber-processing enterprise. *Business Informatics*. 2021;15(3):60–77. (In Russ.: *Biznes-informatika*. 2021;15(3):60–77. DOI: 10.17323/2587–814X.2021.3.60.77).
28. Rogulin R.S. The role of ICT and entrepreneurship in forming sustainable supply chains: Before and after the COVID-19 pandemic. *Journal of Applied Economic Research*. 2021;20(3):461–488. (In Russ.). DOI: 10.15826/vestnik.2021.20.3.019
29. Mazelis L., Rogulin R. 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. *Eastern-European Journal of Enterprise Technologies*. 2021;5(3–113):6–18. DOI: 10.15587/1729–4061.2021.242960
30. Tarasov V.B. From multi-agent systems to intelligent organizations: Philosophy, psychology, computer science. Moscow: Editorial URSS; 2002. 352 p. (In Russ.).

31. Kantorovich L.V. Mathematical methods of organizing and planning production. Leningrad: Leningrad State University; 1939. 96 p. (In Russ.).
32. Shao J., Krishnan H., McCormick S.T. Incentives for transshipment in a supply chain with decentralized retailers. *Manufacturing & Service Operations Management*. 2011;13(3):361–372. DOI: 10.1287/msom.1110.0326
33. Huang H., Ke H., Wang L. Equilibrium analysis of pricing competition and cooperation in supply chain with one common manufacturer and duopoly retailers. *International Journal of Production Economics*. 2016;178:12–21. DOI: 10.1016/j.ijpe.2016.04.022
34. Glock C.H., Kim T. The effect of forward integration on a single-vendor-multi-retailer supply chain under retailer competition. *International Journal of Production Economics*. 2015;164:179–192. DOI: 10.1016/j.ijpe.2015.03.009
35. Chen K., Xiao T. Pricing and replenishment policies in a supply chain with competing retailers under different retail behaviors. *Computers & Industrial Engineering*. 2017;103:145–157. DOI: 10.1016/j.cie.2016.11.018
36. Karimi M., Khademi-Zare H., Zare-Mehrjerdi Y., Fakhrzad M.B. Optimizing service level, price, and inventory decisions for a supply chain with retailers' competition and cooperation under VMI strategy. *RAIRO — Operations Research*. 2022;56(2):1051–1078. DOI: 10.1051/ro/2022039

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